Study on Low-carbon Transport Scheme of Express Freight Based on Space-time Network

Yuzhao Zhang, Zhenjiang Zhang, Zhimo Jiang, Xiaorong Wang, Muchen Ye

Abstract—**The determination of transport schemes represents a critical facet of operational management in express freight logistics and constitutes a significant scientific challenge within the domain of freight transportation. Globally, there is an escalating focus on adopting low-carbon transit strategies, and it has been established that multimodal transport methods can significantly diminish carbon emissions associated with freight transportation. Moreover, the scheduled arrival and departure times for railway and aviation are pivotal in shaping the selection of transport schemes. Regrettably, these critical considerations are frequently neglected in the prevailing body of research. This paper endeavors to bridge this research gap by advocating for a low-carbon transport scheme for express freight through the utilization of an integrated transportation system. It undertakes a collaborative optimization study concerning transportation modes and routes. This document proposes an optimization framework for the selection of express freight transport schemes that incorporates considerations for carbon emissions and fixed timetables. A three-layer service network is developed, integrating the fixed schedules of railway and aviation to formulate a space-time shortest path problem aimed at minimizing the generalized transportation cost. Three models are formulated to reduce the transportation costs and carbon emissions of logistics enterprises, taking into account diverse carbon emission policies. Subsequently, a two-stage heuristic algorithm is introduced to address this complex problem. The findings reveal that by accounting for customers' transportation time constraints and judiciously selecting transportation modes and routes, it is feasible to effectively minimize transportation costs and carbon emissions.**

Index Terms— **Express freight, Transport scheme, Space-time network, Carbon emission, Heuristic algorithm**

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I. INTRODUCTION

With the evolution of socio-economic conditions and consumer behavior, there is an escalating demand for express freight delivery services that offer enhanced value addition and efficiency. Consequently, numerous transportation enterprises are exploring a variety of strategies to augment their competitive edge in the express freight market. Each mode of freight transportation is characterized by distinct technical and economic features, catering to the wide-ranging demands of diverse express freight customers or shippers. In light of the ongoing advancements in integrated transportation systems, it becomes imperative for logistics companies to devise express freight transport schemes that are not only comprehensive and well-coordinated but also efficient, convenient, safe, and environmentally sustainable.

As an integral element of the economy, the challenge of freight transportation has garnered significant interest over recent decades. The primary focus of research within this domain is the Freight Service Network Design Problem (FSNDP), which bifurcates into two main streams: the design and optimization of service networks, and the selection of transportation products. The former addresses the execution of transportation tasks by introducing service arcs that incorporate cost, time, service type, and other attributes between nodes, thereby satisfying the constraints imposed by the transportation network's structural framework [1]. The latter involves the selection of transportation products based on the offerings of transportation companies, encompassing choices related to freight mode, routing, and the distribution of freight flows, among others [2].

The selection of transportation products for express freight is a pivotal aspect that has garnered significant interest. Typically, various transport attributes and capacity constraints are factors that are frequently considered [12, 25]. Given that the freight transport process involves multiple stakeholders, previous studies have often accounted for the collective interests of transportation companies, customers, and society by developing a multi-objective optimization model for transport scheme selection [16]. With environmental concerns increasingly coming to the fore, and considering that the transportation sector is a major contributor to carbon emissions, adopting appropriate multimodal transport modes has been identified as a viable approach to reduce carbon emissions [20]. However, the influence of diverse carbon emission policies on the selection of transport schemes has been largely overlooked in current research. Express freight is inherently timesensitive, necessitating the consideration of the impact of fixed departure times on transportation decisions. Regrettably, there is a scarcity of research focusing on the selection of freight transportation modes and routes, taking into account the influence of fixed departure times.

Optimal selection of transportation modes and routes significantly enhances the utilization of transportation resources, enabling logistics enterprises to reduce both transportation costs and carbon emissions while simultaneously increasing customer satisfaction. Previous research on the Freight Service Network Design Problem (FSNDP) has shown success. However, the fixed arrival-departure times of railway and aviation remain critical factors that cannot be overlooked, as they substantially influence the selection of feasible routes and the overall efficiency of the transport system. Moreover, the consideration of varying carbon emission policies plays a pivotal role in the decision-making process for transport scheme selection. To date, the integration of express freight transport schemes across multiple modes of transportation has been scantily explored in this domain. This paper introduces a space-time network approach and formulates 0-1 integer programming models aimed at minimizing both transportation costs and carbon emissions. Additionally, a two-stage heuristic algorithm is developed to address this complex problem, facilitating the determination of a transport scheme that satisfies the express freight requirements.

The structure of this paper is meticulously organized as follows: Section 2 embarks on a comprehensive review of prior research achievements pertaining to the transport schemes of express freight. Section 3 delineates the specific problem under investigation. In Section 4, we construct the space-time-mode network and introduce a customer satisfaction function, alongside the development of optimization models that take into account various carbon emission policies. Section 5 is dedicated to the design of a two-stage heuristic algorithm. A practical numerical example to demonstrate the application and efficacy of the developed models and algorithm is presented in Section 6. Finally, Section 7 draws conclusions from the study's findings and outlines potential directions for future research, suggesting areas where further investigation could yield significant contributions to the field.

II. Literature review

Freight transportation route planning and mode selection are foundational elements of the Freight Service Network Design Problem (FSNDP), a quintessential challenge within the realm of traffic and transportation. Over the past decades, there have been substantial research advancements regarding FSNDP. The transportation modes in question encompass railway, highway, aviation, and multimodal transport, among others. Reference [3] addressed the design of a railway freight train network, formulating a linear binary programming model aimed at minimizing the aggregate costs of train accumulation and car classification. Furthermore, a tree-based decomposition algorithm was introduced to enhance both the efficiency and quality of solutions. Reference [14] unveiled a three-phase approach for converting an optimized service network into a comprehensive set of vehicle routes within the highway network. Meanwhile, reference [26] developed an integrated model that combines cargo flight network design with fleet routing selection for air cargo transportation, showcasing the breadth of approaches and strategies devised to tackle various facets of FSNDP.

Integrated transport systems are heralded as a sophisticated platform for enhancing the efficiency, reliability, flexibility, and sustainability of freight transportation, garnering increasing interest. Reference [16] introduced a multi-objective integer programming model for a multimodal transportation network, factoring in the critical delivery time windows for freight. In the realm of discrete intermodal freight transportation network design, reference [11] developed a nonlinear mixed-integer programming model to analyze the route choice behavior of intermodal operators, incorporating congestion effects, piecewise linear cost functions, and a fixed-point constraint. The design of the intermodal container service network also took center stage, with reference [27] addressing penalties for delayed deliveries and the integration of self-operated and subcontracted slots. Reference [23] crafted a bi-objective optimization model aimed at minimizing both costs and transit times for the strategic planning of intermodal container flows, under the constraints of carbon emissions. Embracing a comprehensive approach, reference [8] proposed deterministic and robust optimization strategies for the Freight Service Network Design Problem (FSNDP) to curtail overall costs. Furthermore, with the ambitious goal of minimizing costs, time, and carbon emissions, a significant body of research has thoroughly explored the multifaceted dimensions of multimodal FSNDP [9-11].

In the context of optimizing express freight transport networks, factors such as cost, time, service frequency, and transport capacity are frequently highlighted [21]. It is notable that preferences for transportation time and reliability from the perspective of service network owners are also taken into account during the design phase of express freight service networks [25]. Given the inherent uncertainty associated with express freight transportation, several scholars have developed service network design models that incorporate uncertain elements. To address elastic demand within multimodal transport networks, [28] formulated a bi-level programming model. In scenarios of transportation disruptions, [30] established a stochastic mixed-integer programming model to facilitate the selection of a multi-commodity freight transport scheme. Additionally, [10,31] delved into planning intermodal networks to manage mixed uncertainty challenges. With the surge in e-commerce transactions, the necessity of studying e-commerce freight service network design has become evident. [29] created an integer programming model for the e-commerce transportation service trading issue, unveiling that network dynamics are significantly influenced by demand fluctuations and holding costs. The high-speed railway, evolving as a pivotal mode for express freight transportation, has also drawn attention regarding its service network design [5-6]. [32] conducted analyses on competitive relationships and transportation distances among various express goods transportation modes. These studies collectively contribute to a deeper understanding of the fundamental theories and mechanisms influencing the express freight transport scheme.

In recent years, environmental concerns have increasingly come to the forefront, with low-carbon transportation becoming a focal point of global attention [4]. A judicious mix of transportation modes has been proven to effectively reduce both costs and CO2 emissions. Research [33] has demonstrated that, compared to a singular reliance on highway transportation, a composite approach involving public and railway transport can achieve both low-carbon and cost-effective outcomes. Moreover, the integration of low-carbon transport schemes in multimodal transportation is essential for fostering the development of sustainable transportation systems [20,22]. Reference [24] successfully integrated carbon emissions into the multimodal transport path optimization model, facilitating the achievement of minimal carbon emissions while ensuring optimal timeliness. Reference [15] delved into the carbon emission dilemma within multimodal transport and developed a multi-objective path optimization model geared towards low-carbon multimodal transport. Reference [34] explored the network design optimization problem for water-land multimodal transportation, incorporating low-carbon subsidy schemes and established a bi-level programming model that considers the strategic interplay between government and logistics users. Reference [35] proposed a low-carbon multimodal route optimization model that also accounts for passenger comfort and the punctuality rate of travel time.

Punctuality is a key attribute of express freight transportation, necessitating the consideration of precise departure and arrival times for freight transportation products. Space-time networks are widely utilized to articulate time-dependent challenges. In the context of railway freight transportation, a three-layer space-time network encompassing service, block, and car layers has been developed to address the scheduled Freight Service Network Design Problem (FSNDP) with a focus on time-dependent issues [17]. The technique of space-time network modeling is further applied to address the route selection dilemma for both vehicle routes and travelers [18-19]. These models are frequently decomposed into smaller sub-problems, which are more tractable using the Lagrange relaxation method. Incorporating multiple time windows, reference [13] devised a mathematical model tailored to multimodal transportation challenges, accommodating both flexible-time and scheduled services.

Based on the foregoing analysis, current research has made noteworthy contributions to the theoretical and practical aspects of the transport scheme for express freight. Nonetheless, considerations for the fixed timetable and varying carbon emission policies within the integrated transport system are often overlooked. Indeed, these elements significantly influence the decision-making process for express freight transport schemes. Hence, our research endeavors to address these gaps. Initially, we articulate the problem concerning the express freight transport scheme and develop a space-time-transportation mode network that accounts for the impact of fixed arrival-departure times. Subsequently, we construct express freight transport scheme selection models aimed at minimizing generalized transportation costs, taking into account various carbon emission policies. In response to the complexity of the issue, we formulate a two-stage heuristic algorithm to tackle the problem, validating our approach through numerical examples.

III. Problem Statement

For different express freight items and shippers, transportation demands vary significantly. The express freight transport scheme involves selecting appropriate transport modes and routes within an integrated transport network to cater to the requirements of multiple batches of express freight. Given the critical timeliness demands of express freight, four transportation modes are considered: highway, general-speed railway, high-speed railway, and aviation. The virtual transport network for a batch of express freight is depicted in Fig.1, where nodes O and D denote the origin and destination of the express freight, respectively, with additional nodes serving as intermediaries. Express freight may transition from one mode of transportation to another at these intermediate nodes, with transit arcs representing these transfer processes. Moreover, multiple transportation modes exist between any two nodes, each potentially offering several routes. Express freight is required to utilize a single mode and route for transportation, highlighted by transportation arcs illustrating the movement process. Different modes of transportation vary in terms of transportation cost and time, departure schedules, carbon emissions, and capacity. Similarly, the transit operation within nodes varies across modes, affecting transit time, cost, and carbon emissions. Logistics companies must weigh factors such as cost, time, and emissions when selecting the optimal freight mode and route combination, given the available transportation options. The transport scheme is effectively represented by compiling transportation and transit arcs from the origin node O to the destination node D.

$$T_{total}^{1} = t_{operation} + t_{AB} + t_{transit} + t_{BC} \tag{1}$$

$$T_{total}^{2} = t_{operation} + t_{waiting} + t_{AB} + t_{transit} + t_{waiting} + t_{BC} \tag{2}$$

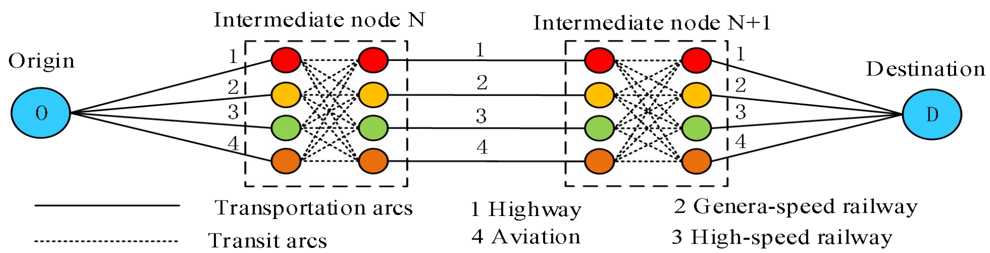


Fig. 1. Virtual express freight network

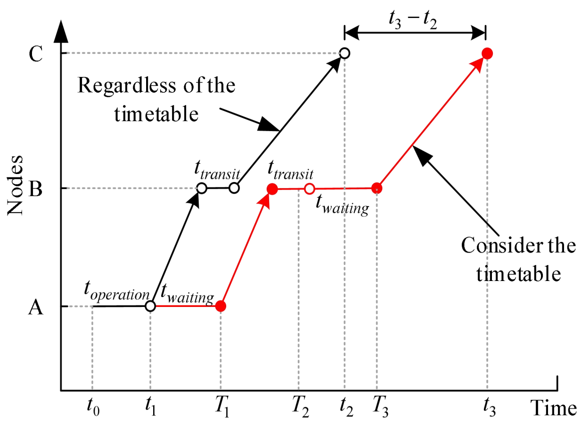


Fig. 2. Influence of timetable on transport scheme

The incorporation of fixed schedules for railway and aviation significantly influences transportation time, particularly through the accrual of waiting time prior to departure, which in turn impacts the decision-making processes of enterprises. Illustratively, consider a scenario depicted in Fig.2, where a batch of express goods is handed over to the carrier at an initial time t_0, and there exist three predetermined departure times T_1, T_2, and T_3. Ignoring the timetable, the goods, upon completion of the departure procedure, would depart at t_1 and arrive at their destination at t_2 , with the total transportation time represented by equation (1). However, when the timetable is taken into account, the actual departure occurs at T_1 , modifying the entire duration as indicated in equation (2). This adjustment reveals that equation (2) incurs additional waiting time compared to equation (1). Moreover, the selection of transport services is contingent upon meeting transit time constraints at intermediate nodes. For instance, at node B, T_3 satisfies the timing requirements whereas T_2 does not, leading to the selection of T_3 for transportation. This example underscores the significance of timetables in shaping transportation scheme decisions, necessitating the use of a space-time network to accurately describe and address these complexities. This approach enables enterprises to more effectively plan and implement transportation schemes, taking into account the critical role of timetables in optimizing overall transportation efficiency and minimizing unnecessary waiting times.

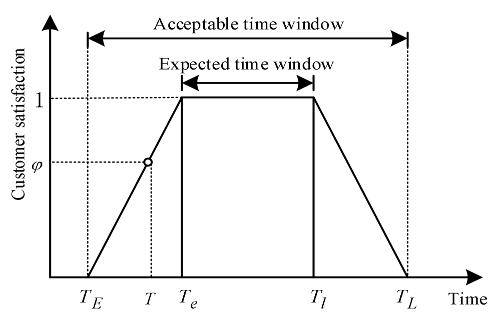


Fig. 3. The relationship between customer satisfaction and time

Customer satisfaction plays a pivotal role in evaluating the service levels of logistics companies. In this study, we delineate the expectations of varying customer service levels through the concept of a customer-expectation time window. From the perspective of transportation companies, deliveries completed within the customer's expected time window incur no penalties. Conversely, deliveries executed either before or after the anticipated time window will attract penalty costs. Viewed from the shippers' standpoint, timely deliveries that align with the expected time window maintain customer satisfaction levels; however, deliveries that fall outside this time frame result in diminished satisfaction. The dynamic interaction between customer satisfaction and temporal variations is illustrated in Fig.3.

Customer satisfaction function $\varphi(t)$ is as follows.

$$\varphi(t)=\begin{cases} 0 & T \notin [T_E, T_L] \\ \dfrac{T-T_E}{T_e-T_E} & T \in [T_E, T_e) \\ 1 & T \in [T_e, T_l] \\ \dfrac{T_L-T}{T_L-T_l} & T \in (T_l, T_L] \end{cases} \tag{3}$$

IV. Problem Statement

A. Space-time-transportation Mode network

To facilitate the description of the problem and the formulation of the mathematical model, the sets and parameters employed in this study are presented in Tab.1, while the decision variables are delineated in Tab.2.

Leveraging the physical network as a foundation, the time dimension and the transportation mode selection dimension are incorporated to develop a three-dimensional space-time-transportation mode network (STTM); the nodes and arcs are represented by N and A, respectively. Fig. 4 illustrates a simplified depiction of a space-time-transportation mode network.

B. The Basic Model

To facilitate the modeling process, we adopt several assumptions, summarized as follows:

(1) The transportation of express freight between two nodes is restricted to a single mode of transport, and the same batch of express freight must remain undivided throughout the transportation process.

(2) The transfer of express freight is limited to a single occurrence at an intermediate node. Concurrently, each node may be included no more than once in the entire route.

(3) The departure and arrival operation times for all batches are identical.

$$\begin{aligned} Z = &\sum_{i,j\in N}\sum_{m\in M}\sum_{k\in K}\sum_{(i,j,t_A,t_S,m,m)\in A} q^k \\ &\cdot(x^k_{i,j,t_A,t_S,m,m}\cdot c_{i,j,t_A,t_S,m,m}\cdot d_{i,j,t_A,t_S,m,m} \\ &+y^k_{j,j,t_S,t_C,m,l}\cdot c_{j,j,t_S,t_C,m,l} \\ &+c_p\cdot\max\left\{\left(T-T_E\right),0\right\}+c_p\cdot\max\left\{\left(T_L-T\right),0\right\}) \end{aligned} \tag{4}$$

The express freight transport scheme optimization model presented in this paper is framed as a 0-1 integer programming model. For model simplification, the objective function focuses on minimizing the generalized transport cost, encompassing generalized transportation costs, transfer operation costs, carbon emission costs, and penalty costs. Without considering the carbon emission policy, the total transportation costs are articulated through equation (4).

The model's constraints are as follows:

TABLE I
SETS AND PARAMETERS

Symbol	Definition
$G(N,A)$	Three-dimensional network of Space-Time-Transportation Mode (STTM)
N	Set of three-dimension nodes in STTM
A	Set of three-dimension arcs in STTM
M	Set of transportation modes, including highway(m_1), general-speed railway(m_2), high-speed railway(m_3), aviation(m_4), $\{m_1,m_2,m_3,m_4\} \in M$; For the convenience of description, M and L are used to indicate different modes of transportation.
t_A, t_S, t_V, t_C	Symbol of time in STTM
N'	Set of nodes in Physical Network, $i,j \in N'$
K	Set of all batches of express goods, $k \in K$
q^k	The volume of the k^{th} batch of express goods
Q	The total volume of express goods of all batches
$[T_e, T_l]$	Time window of expected receiving goods for customer, T_e indicates the expected earliest arrival time, T_l means the expected latest arrival time.
$[T_E, T_L]$	Time window of acceptable receiving goods for customer, T_E indicates the acceptable earliest arrival time, T_L means the acceptable latest arrival time.
θ	The minimum level of customer satisfaction
e^m	Unit carbon emission factors of different transportation modes
E	Total carbon emissions from transportation
c_e	Unit price in market under carbon tax policy
U_e	Carbon emission quota of transportation task under carbon trading policy
γ_e	Unit Price in market under Carbon Trading Policy
c_p	Penalty cost caused by early or late delivery of express freight
$c_{i,j,t_A,t_S,m,m}$	Unit distance cost corresponding to space-time arcs (i,j,t_A,t_S,m,m)
$c_{j,j,t_S,t_C,m,l}$	Unit transit operation cost corresponding to space-time arcs (j,j,t_S,t_C,m,l)
$d_{i,j,t_A,t_S,m,m}$	Distance between nodes i,j using transport m
$\mu_{i,j,t_A,t_S,m,m}$	The capacity corresponding to the space-time arc(j,j,t_S,t_C,m,l), that is, the maximum freight volume that can be transported by m between nodes i,j
T_R、T_Z、T_W、T_X	Receiving time, departure time, waiting time, and arrival time (In this paper, the departure operation and arrival operation time refer to the express freight loading and unloading operation time)
$T_{A(i,t,m)}$	Departure time from i in STTM
$T_{S(j,t,m)}$	Arrive time at j in STTM
$T_{C(j,t,l)}$	Time of complete transit operation at j in STTM
$T_{V(j,t,l)}$	Departure time from j in STTM
$T_{i,j,t_A,t_S,m,m}$	Transportation time of m corresponding to space-time arcs (i,j,t_A,t_S,m,m);
$T_{j,j,t_S,t_C,m,l}$	Transfer time from m to l corresponding to space-time arc (j,j,t_S,t_C,m,l)
$T_{j,j,t_C,t_V,l,l}$	Waiting for departure time after the completion of the transit operation at j corresponding to space-time arc (j,j,t_C,t_V,l,l)

TABLE II
DECISION VARIABLES

Decision variables	Definition
$x^k_{i,j,t_A,t_S,m,m}$	If space-time arcs transport the k^{th} batch of express goods(i,j,t_A,t_S,m,m), its value is 1; otherwise, its value is 0
$y^k_{j,j,t_S,t_C,m,l}$	If the k^{th} batch of express goods selects the space-time arcs (j,j,t_S,t_C,m,l) at the node for transit, its value is 1; otherwise, 0. $m=l$ means transit between the same transportation modes; $m \neq l$ means transit between different transportation modes

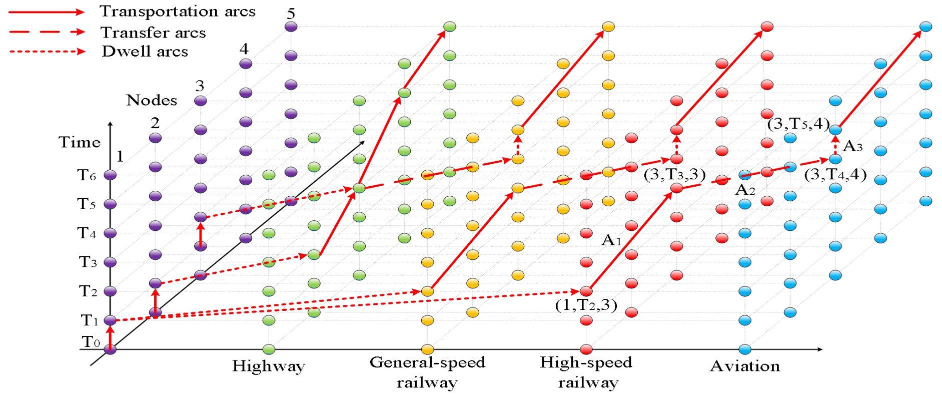


Fig. 4. Space-Time-Transportation mode network

(1) The transportation service selection constraint stipulates that only one transportation arc can be selected between nodes i and j.

$$\sum_{(i,j,t_A,t_S,m,m)\in A} x^k_{i,j,t_A,t_S,m,m} = 1 \tag{5}$$

(2) The constraint pertaining to transfer service selection indicates that, at most, one transfer can occur at node j. In other words, no more than one transfer arc may be selected.

$$\sum_{(j,j,t_S,t_C,m,l)} y^k_{j,j,t_S,t_C,m,l} \le 1 \tag{6}$$

(3) The capacity constraint stipulates that the volume of freight cannot exceed the capacity of the chosen transport service arc.

$$\sum_{k\in K} \sum_{(i,j,t_A,t_S,m,m)\in A} x^k_{i,j,t_A,t_S,m,m} \cdot q^k \le \mu_{i,j,t_A,t_S,m,m} \tag{7}$$

(4) The transportation time limit constraint ensures that the total time does not exceed the maximum acceptable arrival time window, which encompasses departure time, waiting time, transportation time, transit time, and arrival time.

$$\begin{aligned} &\sum_{(i,j,t_A,t_S,m,m)\in A} x^k_{i,j,t_A,t_S,m,m} \cdot T_{i,j,t_A,t_S,m,m} + \\ &\sum_{(j,j,t_S,t_C,m,l)\in A} y^k_{j,j,t_S,t_C,m,l} \cdot T_{j,j,t_S,t_C,m,l} + \\ &\sum_{(j,j,t_C,t_V,l,l)\in A} T_{j,j,t_C,t_V,l,l} + T_W + T_Z + T_X \le T_L \end{aligned} \tag{8}$$

(5) The flow conservation constraint dictates that for an intermediate node i, the outflow must equal the inflow; for a starting node i, a net outflow is generated; and for an ending node i, a net inflow is created.

$$\sum_{\substack{(i,t_A,m),(j,t_S,m)\in N \\ (i,j,t_A,t_S,m,m)\in A}} x^k_{i,j,t_A,t_S,m,m} - \sum_{\substack{(i,t_A,m),(j,t_S,m)\in N \\ (j,i,t_S,t_A,m,m)\in A}} x^k_{j,i,t_S,t_A,m,m} = \begin{cases} 1 \\ 0 \\ -1 \end{cases} \tag{9}$$

(6) The departure time constraints stipulate that the departure time must exceed the completion time of the freight operation.

$$T_R + T_Z \le T_{A(i,t,m)} \tag{10}$$

$$T_{S(j,t,m)} + T_{j,j,t_S,t_C,m,l} \le T_{V(j,t,l)} \tag{11}$$

(7) The customer satisfaction constraint ensures that the satisfaction level for any batch of express freight must not fall below the minimum customer satisfaction level.

$$\varphi(t)^k \ge \theta \tag{12}$$

(8) The constraints pertaining to the values of decision variables are as follows:

$$x^k_{i,j,t_A,t_S,m,m} \in [0,1] \tag{13}$$

$$y^k_{j,j,t_S,t_C,m,l} \in [0,1] \tag{14}$$

In the mathematical model described above, it is essential to compute the waiting time and the total carbon emissions incurred during transportation. The calculation formulas are presented as follows:

(1) Calculation of waiting time: Waiting time refers to the interval between the departure time and the completion time of the transfer.

$$T_{j,j,t_C,t_V,l,l} = T_{V(j,t,l)} - (T_{S(j,t,m)} + T_{j,j,t_S,t_C,m,l}) \tag{15}$$

(2) Calculation of waiting time for shipment.

$$T_W = T_{A(i,t,m)} - (T_R + \mathrm{T}_Z) \tag{16}$$

(3) Total carbon emissions during transportation, including carbon emissions from transportation and transit operations.

$$\begin{aligned} E = &\sum_{i,j\in N} \sum_{m\in M} \sum_{k\in K} \sum_{\substack{(i,j,t_A,t_S,m,m) \\ (j,j,t_S,t_A,m,l)\in A}} q^k \\ &\cdot (x^k_{i,j,t_A,t_S,m,m} \cdot e^{m_1} \cdot d_{i,j,t_A,t_S,m,m} \\ &+ y^k_{j,j,t_S,t_C,m,l} \cdot e^{m,l}) \end{aligned} \tag{17}$$

C. The Models with Different Carbon Emission Policies

(1) Without considering the carbon emission policy

A model of low-carbon transport scheme selection for express freight is constructed using the minimum generalized transportation cost of logistics enterprises as the optimization objective. The model named Model 1 is as follows.

$$\min Z_1 = Z \tag{18}$$

Constraints (5)-(14) are obeyed.

(2) The policy of carbon tax

Carbon tax refers to the tax on carbon dioxide emitted by fossil fuel products after measuring their carbon content. In the research of path optimization, the carbon emission is converted into carbon emission cost by introducing a carbon tax. The carbon tax is levied on carbon dioxide emissions, the product of a fixed tax rate c_e and the total carbon emissions. This part cost needs to be included in the generalized transportation cost of the system. Therefore, we construct the model named Model 2 as follows.

$$\min Z_2 = Z + c_e \cdot E \tag{19}$$

At the same time, constraints (5)-(14) are obeyed.

(3) The policy of carbon cap and trade

The carbon cap and trade policy suggest that the government sets the emission quota for enterprises. If the emission exceeds the emission quota, the enterprise must purchase the emission difference from the market. Carbon cap and trade policy is to ensure that enterprises with their interests pursue the goal of minimizing economic costs while taking the realization of environmental protection goals into account. In contrast, if the emission is lower than the emission quota, it can sell the remaining emission. The costs or benefits represent the total cost. Therefore, we establish Model 3 as follows.

$$\min Z_3 = Z + \gamma_e \cdot (E - U_e) \tag{20}$$

If $E > U_e$, the quota should be purchased, which is the carbon emission cost of transportation enterprise; otherwise $E < U_e$, the quota can be sold out, and it is the revenue of transportation enterprises. Besides, constraints (5)-(14) are obeyed.

D.Analysis of the model

Model 1 contains two decision variables, which determine the selection of the transport scheme. In principle, we selected the optimal solution for each batch of express freight. If the optimal solution is selected for all packs of express shipment, the arc's capacity limit may be exceeded. Therefore, under the premise of meeting the transportation demand and transportation time, some express freight batches will choose the sub-optimal plan. In summary, it is necessary to distribute the freight flow for the transport scheme given that the decision variables, $x^k_{i,j,t_A,t_S,m,m}$ and $y^k_{j,j,t_S,t_C,m,l}$, have been determined. The essence of the above mathematical model is to solve the shortest path problem in a space-time network under constraint conditions. Therefore, according to the characteristics of Model 1, a freight flow distribution model is established to distribute the freight flow of express freight. Model 1 can be transformed into a multi-commodity flow problem.

Set P_k as a collection of alternative transport schemes for the k^{th} batch of express freight is generally k- shortest path of OD pair. $\beta^{kp}_{i,j,t_A,t_S,m,l}$ is a 0-1 variable, if the transportation plan P of the k^{th} batch of express freight contains the space-time arc $(i, j, t_A, t_S m, l)$, the value is 1, otherwise, it is 0; $m = l$ means transport arc, and $m \neq l$ means transfer arc. α^k_p represents the flow of the k^{th} batch of express freight allocated to the transport scheme p. Since the same pack of express cannot be divided during transportation when the k^{th} pack of express freight is on the transport scheme p, $\alpha^k_p = q^k$, otherwise $\alpha^k_p = 0$. c^k_p expresses the generalized transportation cost of unit cargo flow through transport scheme p.

Therefore, given $x^k_{i,j,t_A,t_S,m,m}$ and $y^k_{j,j,t_S,t_C,m,l}$, model 1 can be transformed into the following form named as Model 1'.

The objective function with the minimum total cost of all batches of express goods is as follows.

$$\min Z' = \sum_{k\in K}\sum_{p\in P_k}\alpha^k_p c^k_p \tag{21}$$

Constraints:

(1) Ensure that all packs of express goods are transported.

$$\sum_{p\in P_k}\alpha^k_p = Q \tag{22}$$

(2) The space-time arc capacity constraint is that the total volume of all batches of goods allocated to the transport scheme p cannot exceed the combined arc capacity.

$$\sum_{k\in K}\sum_{p\in P_k}\alpha^k_p \cdot \beta^{kp}_{i,j,t_A,t_S,m,l} \le x^k_{i,j,t_A,t_S,m,l} \cdot \mu_{i,j,t_A,t_S,m,l} \tag{23}$$

(3) Decision variable value constraints are as follows.

$$\alpha^k_p \ge 0 \tag{24}$$

$$\beta^{kp}_{i,j,t_A,t_S,m,l} \in \{0,1\} \tag{25}$$

Model 2 and Model 3 can also be adjusted accordingly as Model 2' and Model 3'.

V. TWO-STAGE SOLUTION ALGORITHM

The selection of the express freight transport scheme being studied in this paper requires the simultaneous transportation mode and route decision, a combined optimization problem. According to the above analysis, the key to solving Model 1' is determining the set P_k of alternative transport schemes for each batch of express freight. Therefore, we designed a two-stage heuristic algorithm to solve the model. In the first stage, we use a double-sweep algorithm to generate the set of alternative transport schemes that meet the transportation time requirements. The simulated annealing algorithm allocates the best transport scheme for each batch of express freight in the second stage.

The specific steps of the first stage are as follows.

Step 1: Taking the cost between space-time nodes as a weight matrix, it is divided into "strict upper triangular matrix L "and "strict lower triangular matrix U ".

Step 2: Determine the initial transportation cost vector value of the shortest path from the initial space-time node to each space-time node d^0_1。

Step 3: Using forward sweep and backward sweep to continually update the value of transportation cost. The forward sweep equation is calculated as $d^{2l+2}_1 = d^{2l+2}_1 L + d^{2l+1}_1$ and the backward sweep equation is calculated as $d^{2l+2}_1 = d^{2l+2}_1 U + d^{2l+1}_1$.

Step 4: When $d^{t-1}_1 = d^t_1$ $(t > 1)$ the shortest path length from the initial node to any node can be obtained.

Step 5: The above processes can only get the k -shortest path length between any space-time nodes. Taking o as the start node, D as the end node, and i as the intermediate node. It can be seen that the k -shortest path between o and D is composed of the q -shortest path between node o and node i, and the arc connecting directly between node i and node D. The equation $d^q_{OD} + h_{ij} = d^k_{OD}$ is got. If the node i is the penultimate node of some q -shortest path from the node o to node D , and the k -shortest path from o to D can be obtained by continuously searching the penultimate node until the node o.

In the second stage, we allocate the best transport scheme for each batch of express freight and the specific steps are as follows.

Step 1: Construction of solution

Define matrix $X = [K, P]$, and it indicates that the p^{th} transport scheme of the k^{th} batch of express freight is selected. Where the vector $K = (1,2, \dots, k)$, $P = (p^k_1, p^k_2, \dots, p^k_n)$, $k \in K$.

Step 2: Generation of the initial solution

Because the final solution obtained by the SA algorithm does not depend on the initial solution, the random method is adopted to generate the initial combined transport scheme. Randomness is reflected in the alternative of randomly selecting a specific batch of freight. Once selected, this alternative's remaining capacity will correspondingly reduce. The total freights in all packs selected by this option will meet the constraint of space-time arc capacity until all batches of freights are chosen to obtain a complete initial solution.

Step 3: Generation of neighborhood solutions

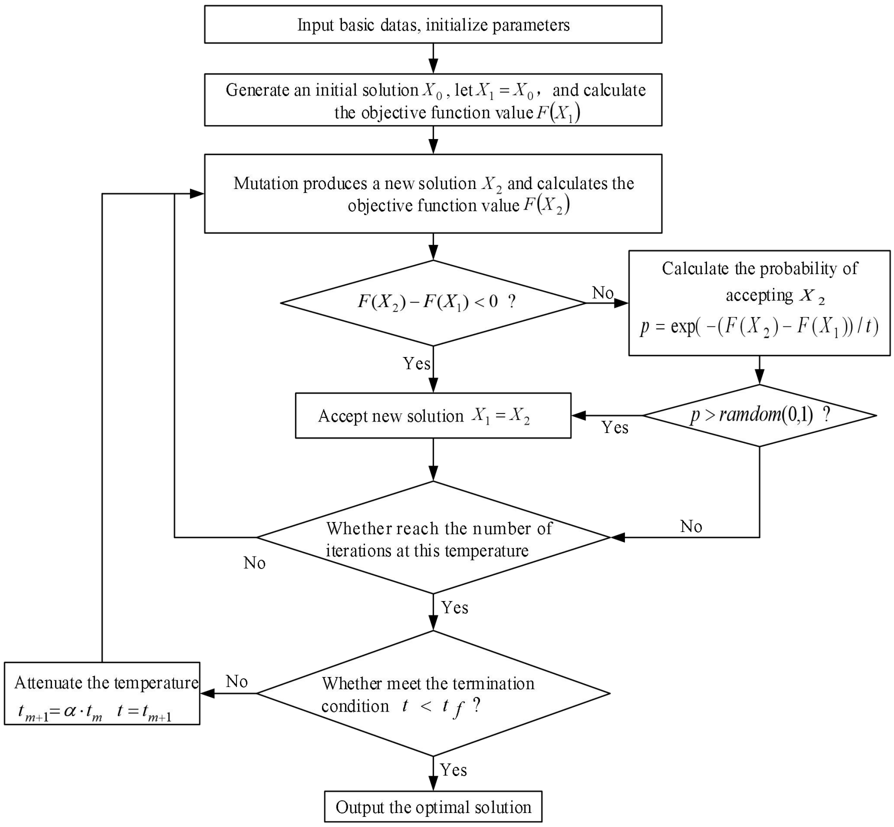


Fig. 5. The flow chart of the SA algorithm

A neighborhood solution is a new group of solutions generated by disturbing the current solution. The random mutation method is suitable to construct it. We randomly select a batch of freight in the current solution as the mutation point, choose other alternatives of the freight pack except for the current transport scheme, and then generate the neighborhood solution.

Step 4: Cooling process

In general, the higher the initial temperature, the better the optimality of the final solution, but the more time it takes. Therefore, the optimization time and efficiency should be considered comprehensively when setting the initial temperature. Based on the calculation experience of previous studies, this paper sets the parameters as follows. We set the initial temperature $t_0 = 100$, final temperature $t_f = 10^{-3}$, temperature decline coefficient $\alpha = 0.95$, $t = t_0$. The algorithm flow is shown in Fig.5.

The solution methods of Model 2' and Model 3' are same to that of Model 1'.Numerical Example.

VI. Two-Stage Solution Algorithm

A. Example design

TABLE III

Service products provided by logistics companies

Service number	Service products	Delivery time
S1	Next day delivery	Before 18: 00 the next day
S2	2-day delivery	Before 18: 00 the day after tomorrow
S3	3-day delivery	Before 18:00 the three days from now

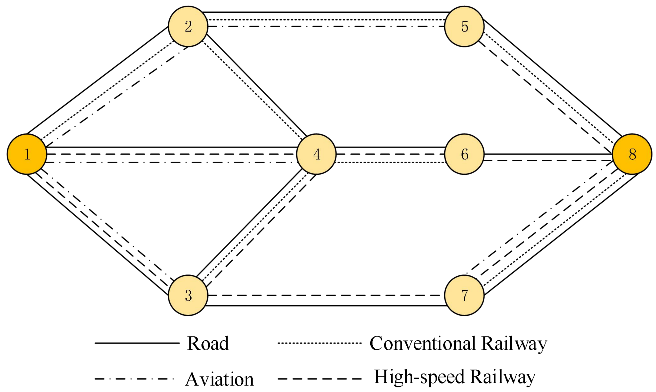


Fig. 6. Integrated transportation network

In an integrated transportation network, various transportation services can be synergized to facilitate commodity movement along designated routes. This network is illustrated in Fig. 6. Four transportation modes exist between adjacent urban nodes: highway (m1), general-speed railway (m2), high-speed railway (m3), and aviation (m4), with the highway offering time-flexible services, free from the constraints of timetables, while the latter three modes provide scheduled-based services, governed by specific schedules. It's posited that multiple batches of express cargo can be transported from Lanzhou to Beijing within a single day. To meet customer requirements and ensure delivery to the intended destination, logistics companies must leverage available transportation services to identify the most suitable transportation method and route. This paper notes that the average speed for highway transportation is set at 90km/h with a capacity of 5000kg. Logistics firms offer three distinct service products to their customers, as indicated in Tab. 3. Tab. 4 details the optional service modes available between each node pair, including information on timetables, capacity, mileage, and other relevant details.

The carbon emission factors were calculated based on the carbon emissions of various transportation modes outlined in the IPCC Guidelines for National Greenhouse Gas Inventories in 2006. Unit transportation costs were obtained by consulting relevant information and referencing the freight rates of railway freight in China as well as individual company freight rates, as displayed in Tab. 5. Operational parameters for different operation modes at the node were obtained by consulting relevant literature, as shown in Tab. 6. Express freight requirements for all batches within a day are presented in Tab. 7.

TABLE IV
TIME, CAPACITY AND MILEAGE OF DIFFERENT SERVICE MODES

No.	OD	Departing time	Arriving time	Capacity (kg)	Mode	Mileage (km)	No.	OD	Departing time	Arriving time	Capacity (kg)	Mode	Mileage (km)
1	(1,8)	10:45	13:00	3500	m4	1201	31	(3,7)	20:17	22:14	3500	m3	519
2	(1,8)	15:30	17:45	3500	m4	1201	32	(3,4)	9:45	13:13	3500	m3	579
3	(1,8)	9:49	18:53	3500	m3	1780	33	(3,4)	12:55	16:37	4500	m3	579
4	(1,8)	16:26	22:42	3500	m3	1780	34	(3,4)	17:23	20:57	4000	m3	579
5	(1,8)	17:30	14:32	6000	m2	1882	35	(3,4)	19:00	5:38	5500	m2	651
6	(1,8)	21:10	13:38	6000	m2	1882	36	(3,6)	10:20	11:50	6000	m4	655
7	(1,7)	14:42	20:41	4500	m3	1087	37	(7,8)	6:42	10:13	3500	m3	693
8	(1,7)	16:21	21:36	3500	m3	1087	38	(7,8)	13:40	16:26	2800	m3	693
9	(1,7)	20:50	22:45	3000	m4	1024	39	(7,8)	22:15	6:31	3500	m2	695
10	(1,3)	14:55	16:10	5000	m4	489	40	(7,8)	17:50	19:30	4000	m4	646
11	(1,3)	9:10	12:19	5500	m3	568	41	(4,8)	21:00	22:35	3000	m4	431
12	(1,3)	11:40	15:08	3000	m3	568	42	(4,8)	8:24	11:22	4500	m3	505
13	(1,3)	15:28	18:42	3500	m3	568	43	(4,8)	11:38	14:36	5000	m3	505
14	(1,3)	19:48	22:59	2500	m3	568	44	(4,8)	19:28	22:32	3500	m3	505
15	(1,6)	10:15	12:05	2500	m4	968	45	(4,6)	6:35	12:30	3000	m2	217
16	(1,6)	15:45	17:40	5000	m4	968	46	(6,8)	7:20	8:53	4000	m3	281
17	(1,4)	8:00	9:35	4500	m4	1087	47	(6,8)	12:24	13:44	4500	m3	281
18	(1,4)	8:42	15:31	5500	m3	1147	48	(6,8)	17:13	18:39	5000	m3	281
19	(1,4)	15:02	21:48	5000	m3	1147	49	(2,8)	14:30	16:25	3000	m4	919
20	(1,2)	12:00	12:55	4000	m4	333	50	(2,8)	20:52	8:34	4500	m2	1216
21	(1,5)	12:45	14:25	4500	m4	844	51	(2,8)	9:20	11:15	3000	m4	919
22	(1,5)	11:10	6:18	5500	m2	1152	52	(2,5)	15:10	16:15	2500	m4	837
23	(3,8)	7:50	13:27	3500	m3	1212	53	(2,5)	6:45	15:57	2500	m2	684
24	(3,8)	9:18	13:50	3000	m3	1212	54	(5,8)	12:22	15:08	3000	m3	460
25	(3,8)	12:43	18:26	2500	m3	1212	55	(5,8)	16:20	18:32	3500	m3	460
26	(3,8)	17:38	6:08	2000	m2	1206	56	(5,8)	20:33	23:12	4000	m3	460
27	(3,8)	19:27	8:22	2000	m2	1206	57	(5,8)	21:42	7:30	5000	m2	532
28	(3,8)	3:00	5:15	3500	m4	942	58	(2,4)	23:30	9:25	3000	m2	710
29	(3,8)	8:30	10:45	4000	m4	942	59	(2,6)	11:20	12:55	2500	m4	729
30	(3,7)	8:10	10:29	5000	m3	519	60	(2,6)	18:20	19:50	2500	m4	729

TABLE V
TRANSPORTATION COST AND CARBON EMISSION FACTORS OF DIFFERENT TRANSPORTATION MODES

	Highway	General-speed railway	High-speed railway	Aviation
Transportation cost（$yuan/kg \cdot km$）	1.92	0.85	3.16	4.21
carbon emission factor （$kg/t \cdot km$）	0.0479	0.0084	0.0199	0.564

TABLE VI
TRANSIT COST (YUAN /KG)/ TRANSIT TIME (H)/ TRANSIT CARBON EMISSION FACTOR (KG/T) BETWEEN DIFFERENT MODES OF TRANSPORTATION

Transfer method	Transfer parameters	Transfer method	Transfer parameters	Transfer method	Transfer parameters	Transfer method	Transfer parameters
m1-m2	0.35/2.5/150	m3-m1	0.35/2.5/200	m2-m1	0.35/2.5/150	m4-m1	0.35/2.5/250
m1-m3	0.35/2.5/200	m3-m2	0.35/3/100	m2-m3	0.35/3/100	m4-m2	0.35/3.5/220
m1-m4	0.35/2.5/250	m3-m4	0.35/3.5/240	m2-m4	0.35/3.5/220	m4-m3	0.35/3.5/240

TABLE VII
TRANSPORTATION DEMANDS OF SHIPPERS

Demand	Receiving time	Freight volume	service	Expected time window	Demand	Receiving time	Freight volume	service	Expected time window
1	7:30	500	S1	[12:00-16:00]	11	7:50	675	S1	[13:30-15:30]
2	8:10	450	S1	[10:00-16:00]	12	9:20	1800	S2	[15:00-16:00]
3	9:30	1500	S2	[10:00-14:00]	13	8:30	285	S3	[12:00-16:00]
4	10:40	625	S2	[14:00-16:00]	14	8:45	775	S3	[8:00-9:30]
5	11:30	355	S3	[10:00-15:00]	15	10:40	480	S2	[10:00-12:00]
6	13:40	1200	S2	[8:00-12:00]	16	11:50	1250	S2	[16:00-17:00]
7	15:45	560	S2	[14:00-16:00]	17	13:20	695	S3	[15:00-16:00]
8	18:40	175	S2	[9:30-12:30]	18	14:15	1780	S3	[8:00-10:00]
9	19:30	800	S3	[8:00-10:00]	19	17:45	370	S2	[13:30-15:00]
10	20:45	550	S3	[11:00-14:00]	20	19:00	880	S2	[9:00-11:00]

TABLE VIII
TRANSPORT SCHEME OF EXPRESS FREIGHT WITHOUT CONSIDERING CARBON EMISSION

Number	Transportation route	transportation mode	Demand	Departure time	Transit departure time	Arrival time	Terminal operation completion time
1	1-2-8	m4-m1	1	16:30	23:05	4:28	14:28
2	1-3-8	m3-m4	2,11	17:03	3:00	5:15	15:15
3	1-8	m2	3,4,12,15,16	21:10		13:38	23:18
4	1-8	m2	5,9,10,17,18	17:30		14:32	0:32
5	1-2-4-6-8	m1-m1-m1-m1	6	22:10		1:38	11:38
6	1-3-8	m3-m2	7	8:24	17:38	6:08	16:08
7	1-4-6-8	m1-m1-m1	8,19,20	3:30		2:54	12:54
8	1-2-8	m2-m1	13,14	11:10	11:18	16:41	2:41

TABLE IX
THE CHANGES IN TRANSPORT SCHEME UNDER CONSIDERATION OF CARBON EMISSIONS

Number	Transportation route	Transportation mode	Demand	Departure time	Transit departure time	Arrival time	Terminal operation completion time
1	1-8	m3	1	16:26		22:42	8:42
2	1-2-4-6-8	m1-m1-m1-m1	7	0:15		3:43	13:43
3	1-3-8	m3-m2	13	11:40	17:38	6:08	16:08

B. Result analysis

1) Analysis of optimal transport scheme

The customer satisfaction level θ=0.7 is set in the calculation process. The model is computed without taking carbon emissions into account, and the transportation scheme (Scheme 1) is presented in Tab. 8. All shipments meet the time requirements, with a total transportation cost of 50243.73 yuan, carbon emissions of 1824.79 kg, and an average customer satisfaction of 0.968. Under the carbon tax policy, the total transportation cost amounts to 53503.01 yuan, resulting in carbon emissions of 1444.52 kg, with an average customer satisfaction of 0.983. Under the carbon cap and trade policy, the total transportation cost is 48502.76 yuan, producing carbon emissions of 1444.52 kg, with an average customer satisfaction of 0.983. Considering carbon emissions, the transportation schemes for the 1st, 7th, and 13th batches of freight have changed, as illustrated in Tab. 9. The express freight transport scheme remains the same under both carbon emission policies.

2) The influence of operation time on the selection of transport scheme

Section 4 stipulates that the total time must not exceed the upper limit of the arrival time window. However, reducing operational time can ensure the timeliness of express freight transportation and decrease transportation costs for logistics enterprises.

Based on the 2020 express service satisfaction survey and punctuality test results, the average processing time limit at the departure point is 7.42 hours, while at the arrival point it is 9.78 hours. For analytical convenience, rounded values of 8.5 hours and 10 hours are adopted, respectively.

(1) Departure operation time

Reducing the departure time by one hour resulted in the fast cargo transport scheme outlined in Tab. 10. Compared with Scheme 1, the transportation cost decreased by 3305.91 yuan. The transportation costs, carbon emissions, and customer satisfaction in the three cases are presented in Tab.11. Furthermore, the changing trend of transportation costs with departure operation time under different conditions was obtained, as depicted in Fig. 7 (a), (b), and (c). It is evident from figures (a), (b), and (c) that under conditions where the arrival operation remains unchanged, reducing the departure operation time can effectively decrease the enterprise's transportation costs to a certain extent. This is due to the increased flexibility in goods transportation resulting from a shortened departure time.

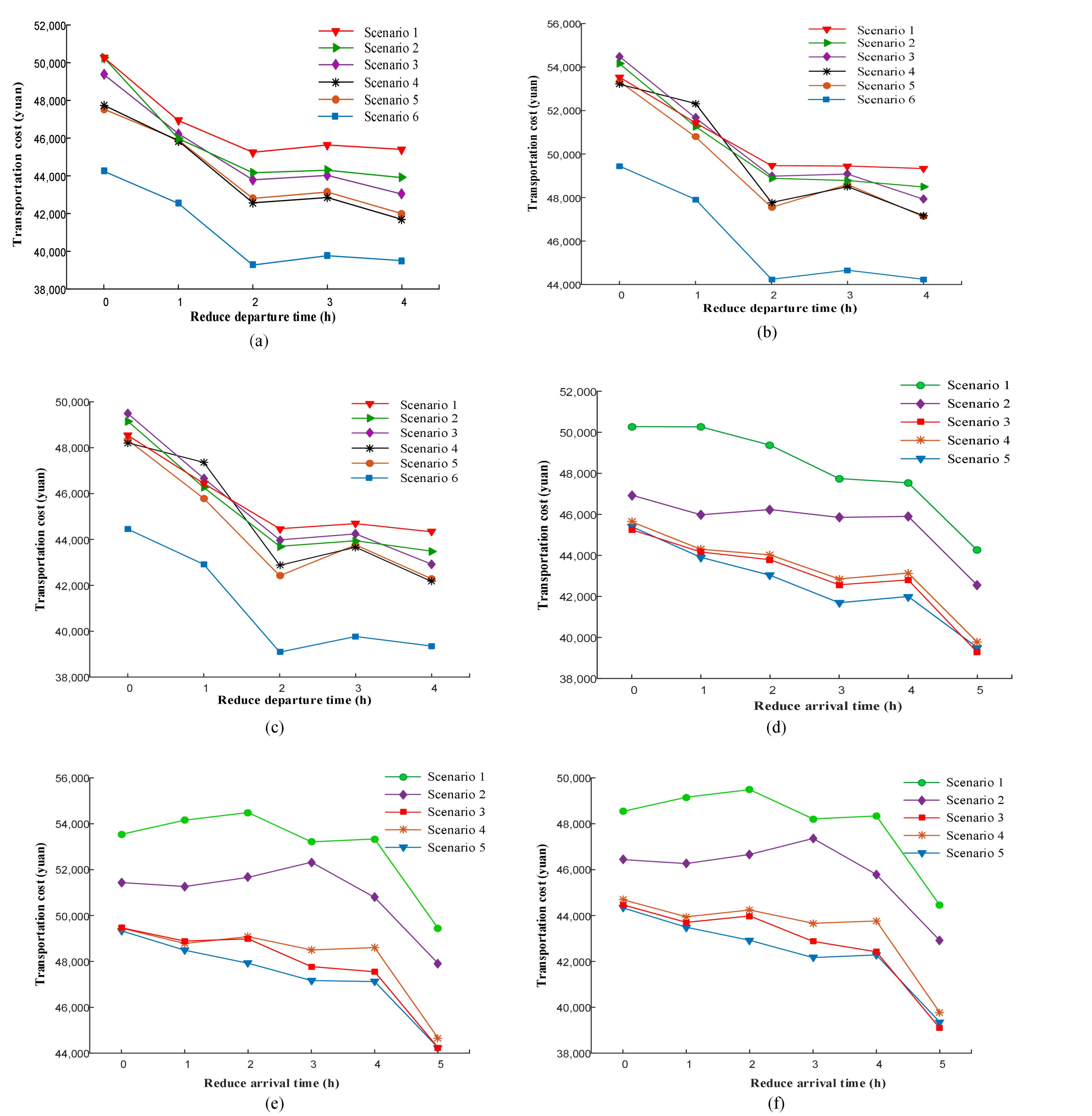
TABLE X
THE CHANGES IN TRANSPORT SCHEME UNDER CONSIDERATION OF CARBON EMISSIONS

Number	Transportation route	Transportation mode	Demand	Departure time	Transit departure time	Arrival time	Terminal operation completion time
1	1-6-8	m4-m1	1,2,11	15:45	22:40	1:56	11:56
2	1-8	m2	3	17:30			14:32
3	1-3-8	m1-m2	4,12,16	19:20	17:38	6:08	16:08
4	1-8	m2	6,15	21:10		13:38	23:38
5	1-3-8	m3-m2	7	8:24	17:38	6:08	16:08
6	1-4-6-8	m1-m1-m1	8,19,20	2:30		1:54	11:54
7	1-8	m2	5,9,10,17,18	17:30		14:32	0:32
8	1-3-8	m3-m2	13	11:40	17:38	6:08	16:08
9	1-2-8	m2-m1	14	11:10	11:18	16:41	2:41

(2) Arrival operation time

Subsequently, when the arrival time is reduced by one hour, we obtain the express freight transport scheme in Tab. 12. The transportation cost, carbon emissions, and customer satisfaction are displayed in Tab. 11. Compared with Scheme 1, there is a slight change in the total cost. This is because, in comparison with Scheme 1, the transport scheme for most freights remains unchanged, leading to an increase in storage costs (penalty costs) following the early completion of the arrival operation. After further investigation, the changing trend of total cost with arrival time under different conditions is depicted in Fig. 7 (d), (e), and (f). It is evident that the transportation cost does not decrease linearly with the arrival operation time; only by properly planning the arrival operation time can the total cost be reduced to a certain extent.

In the scenario of varying arrival times, the fluctuations in transportation cost concerning departure operation time are illustrated in Fig. 7 (a), (b), and (c). As depicted in the figure, a reduction in departure operation time corresponds to a gradual decrease in transportation cost.



Scenario 1~ scenario 6 in figure (a), (b) and (c) correspond to different arrival operation times, which are 10h, 9h, 8h, 7h, 6h and 5h, respectively. In Figure (d), (e) and (f), Scenario 1- Scenario 5 correspond to different departure operation times, which are 8.5h, 7.5h, 6.5h, 5.5h, 4.5h, respectively.

Fig. 7. Diagram of transportation cost changing with operation time

TABLE XI
THE CHANGES IN TRANSPORT SCHEME UNDER CONSIDERATION OF CARBON EMISSIONS

conditions	Polices	transportation cost	carbon emissions	customer satisfaction
The departure time is reduced by one hour	Regardless of carbon emissions	46937.82	2489.00	0.97
	The policy of carbon tax	51438.26	1756.54	0.98
	The policy of carbon cap and trade	46438.26	1756.54	0.98
The arrival time is reduced by one hour	Regardless of carbon emissions	50248.42	2306.04	0.97
	The policy of carbon tax	54140.33	1861.98	0.98
	The policy of carbon cap and trade	49140.33	1861.98	0.98

TABLE XII
THE CHANGES IN TRANSPORT SCHEME UNDER CONSIDERATION OF CARBON EMISSIONS

Number	Transportation route	Transportation mode	Demand	Departure time	Transit departure time	Arrival time	Terminal operation completion time
1	1-2-8	m4-m1	1	16:30	23:05	4:28	13:28
2	1-3-8	m3-m4	2,11	17:03	3:00	5:15	14:15
3	1-8	m2	3,4,15	21:10		13:38	22:18
4	1-8	m2	5,9,10,17,18	17:30		14:32	23:32
5	1-2-4-6-8	m1-m1-m1-m1	6	22:10		1:38	10:38
6	1-3-8	m3-m2	7,12,19	8:24	17:38	6:08	15:08
7	1-4-6-8	m1-m1-m1	8,20	3:30		2:54	11:54
8	1-2-8	m2-m1	14	11:10	11:18	16:41	1:41
9	1-3-8	m3-m2	13	11:40	17:38	6:08	15:08
10	1-3-8	m1-m2	16	20:20	17:38	6:08	15:08

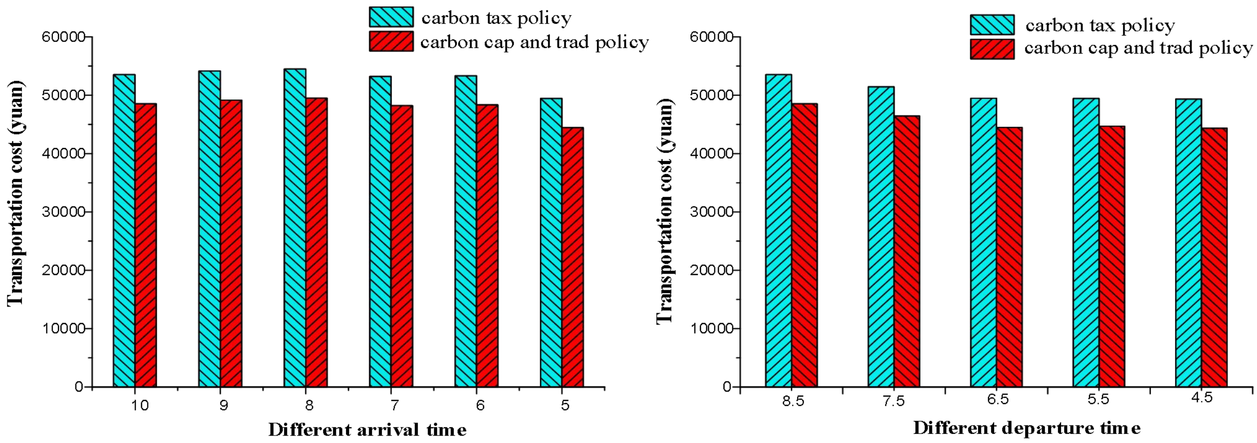


Fig. 8. Comparison of transportation costs under two carbon emission policies

3) Analysis of the impact of different carbon emission policies

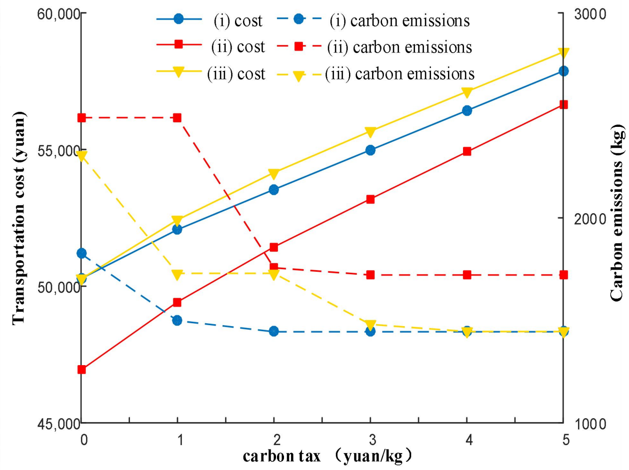


Fig. 9. Changes in transportation cost and carbon emission with the carbon tax value

When the carbon-trading price and the carbon tax rate are both set at 2 yuan/kg, the two carbon emission policies yield the same transportation scheme under various conditions. Consequently, the resultant carbon emissions are identical, as depicted in Tab. 11. The cost comparison is presented in Fig. 8. With equivalent levels of carbon emission control, the transportation costs under the carbon cap and trade policy are lower than those under the carbon tax policy. Under the carbon cap and trade policy, logistics enterprises can capitalize on the surplus carbon emission quotas by selling them to generate profits and reduce costs, particularly when the total carbon emissions fall below the carbon quota.(1) The policy of carbon tax

Under the carbon tax policy, the variations in transportation costs and carbon emissions with respect to the carbon tax rate are illustrated in Fig. 9. Without loss of generality, we examine three scenarios for analysis: (i) unchanged operation time; (ii) departure operation time reduced by one hour; (iii) arrival operation time reduced by one hour. With the escalation of the carbon tax rate, the total cost consistently rises, while the reduction in carbon emissions remains relatively unchanged. In such cases, the transportation scheme for all batches of freights exhibits the minimal carbon emissions.

(2) The policy of carbon cap and trade

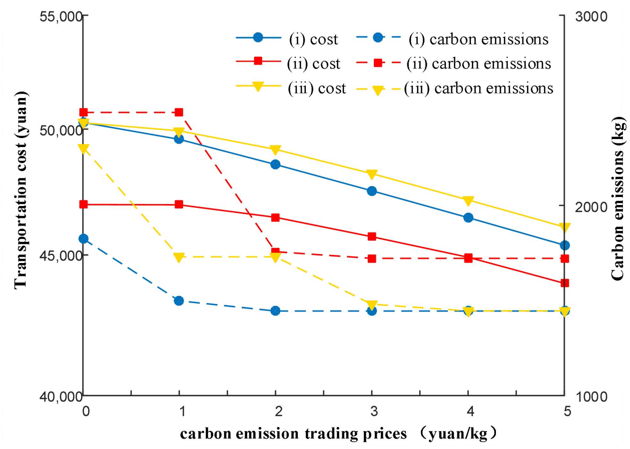


Fig. 10. Changes in transportation cost and carbon emission with carbon trading prices

Under the carbon cap and trade policy, the fluctuations in transportation costs and carbon emissions with respect to the carbon trading price are depicted in Fig. 10, with the aforementioned three scenarios (i), (ii), and (iii) also selected for analysis. The authors observed that as the carbon trading price increases, the total cost decreases, and carbon emissions decrease to a certain extent, after which they plateau. The variations in transportation costs and carbon emissions under different carbon quotas are illustrated in Fig. 11. It was noted that carbon emissions remained constant under varying carbon quotas, while the total cost gradually decreased with increasing carbon quotas. This can be attributed to the fact that at the optimal transportation scheme, logistics enterprises can sell more carbon emissions as the carbon emission quota increases.

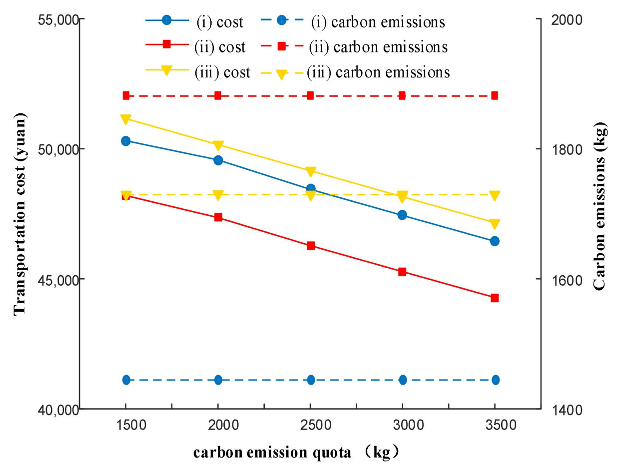


Fig. 11. Changes in transportation cost and carbon emission with carbon emission quota

4) Impact of Customer satisfaction

The impact of varying levels of customer satisfaction on transportation costs is depicted in Fig. 12. As customer satisfaction improves, transportation costs gradually rise. Consequently, enterprises are required to allocate specific funds to sustain high levels of customer satisfaction.

Numerical experiments conducted from Lanzhou to Beijing validate the efficacy of the model and algorithm. The low-carbon transport scheme selection model for express freight proposed in this paper can be further applied to various regions or OD pairs. It is imperative to adjust relevant parameters (timetable, cost, distance, etc.) according to the actual fast freight transportation scenarios and subsequently select the low-carbon transport scheme to facilitate better decision-making for enterprises.

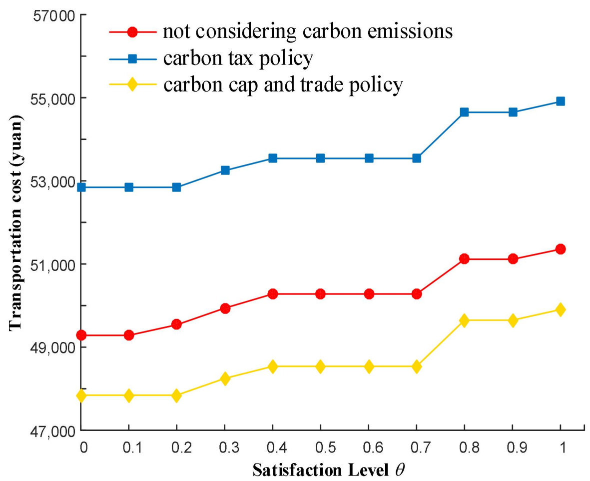


Fig. 12. Transportation costs under different satisfaction levels

VII. Conclusion

This paper introduces a formulation for selecting the optimal transport scheme for express freight, considering carbon emissions and the impact of fixed arrival-departure times for railways and aviation within the integrated transportation system. We establish a three-layer service network for time-space transportation modes to reflect actual transportation schedules. The space-time shortest path problem with minimum generalized transportation cost under multi-mode and multi-commodity flow is defined, and a 0-1 integer programming model is developed. A two-stage heuristic algorithm is designed to solve the model, tailored to its characteristics. An example of express freight transport demands from Lanzhou to Beijing verifies the effectiveness of the model and algorithm. Based on the results, several conclusions are drawn:

(1) The proposed model and algorithm are applicable for selecting transport schemes for express freight, considering the influence of fixed arrival-departure time and carbon emissions.

(2) Under the condition of meeting shipper demands, logistics enterprises can reduce their costs and carbon emissions by designing reasonable transport schemes.

(3) The reduction of arrival operation time does not influence the choice of transport scheme, whereas planning the departure operation time can lead to a reduction in transportation costs to some extent.

(4) A carbon trading policy is more effective than a carbon tax policy in controlling carbon emissions, making it more suitable for managing the carbon emissions of logistics enterprises. When the carbon emission quota is substantial, it can decrease carbon emissions and mitigate enterprises' transportation costs to a certain extent.

In our future research endeavors, we will concentrate on the decision-making process regarding express freight transport schemes among multiple OD pairs while considering the influence of various uncertain factors. Additionally, we will focus on developing algorithms suitable for large-scale networks and validate our methodology by utilizing real-world data.

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