Route Optimization of Multimodal Transportation Considering Customer Satisfaction

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Abstract. With economic advancement, cargo transportation faces increased demands for efficiency, cost-effectiveness, and carbon footprint reduction. A multi-objective mathematical model prioritizes minimizing costs and maximizing customer satisfaction, considering factors like route expenditure, transfer fees, and carbon emission fees. Non-dominated sorting genetic algorithms are applied, validated with a case study from Lanzhou to Shanghai. Findings show that: Higher levels of customer satisfaction often come with higher transportation costs; Carbon emission costs under the trading mechanism are relatively minor. Research on route optimization offers insights for strategic planning by multimodal transport operators.

Keywords: Route Optimization, Multimodal Transportation, Customer Satisfaction.

1 Introduction

The rapid pace of globalization and the development of international trade have created a huge demand for freight transport, especially for countries with a strong manufacturing sector. Consequently, there is an inevitable increase in emissions from transport, which exacerbates the environmental situation. Transport emissions account for 39% of global carbon emissions, ranking first in electricity, industry, housing and commerce [1]. There are fruitful researches on route optimization of multimodal transport from around the world. Wen studied how to plan transport at each node of the rail to improve transport efficiency and meet customers' transport needs [2]. Yang established a multimodal transport model to minimize transport distance, transport time, carbon emission [3]. Jiang took into account the interests of multimodal transport stakeholders and studied how to guide enterprises to adopt rail transport to achieve the goal of minimal carbon emissions [4]. Fazayeli considered to minimize the total cost of the entire multimodal transport service process under the time-window constraints [5]. Sun constructed a multi-objective model with the minimum transport cost and the highest service level to explored the effects of fuzzy soft time windows and time uncertainty on path optimization [6]. Marco studied the intermodal supply chain problem

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by establishing a multi-objective model for overall operating costs, carbon emissions, arrival time [7]. Chen constructed a multi-objective model of costs and service levels [8]. Liu constructed a multi-objective model to minimize the cost and carbon emission under time window constraints [9]. Intermodal transport under uncertainty was considered in [10], and provided a general way of the different optimization paradigms and approaches used to support decision-making in the face of uncertainty.

Most multimodal transport modes emphasize road, rail, and waterway, overlooking air as an alternative. Customer satisfaction often hinges on arrival time, though various factors impact it. Few studies compare departure schedules of different modes. Rail and air frequency can alter transport plans. Thus, road, rail, and air form alternative transport sets, integrating speed, cost, emissions, and departure constraints. Transport services are categorized into route and hub services, considering factors like cost, emissions, time, and damage. Carbon emissions are translated into costs, aligning with operators' goals of minimizing costs and maximizing satisfaction. The proportion of carbon costs and departure frequencies' effects are analyzed to aid multimodal operators' route decisions. The study aims for cost reduction, efficiency enhancement, and promoting low-carbon, high-quality cargo transport.

2 Model Building

2.1 Problem Description

A cargo carrier undertakes a batch of cargos that should be transported from the origin city O to the destination city D, passing through several hub cities. Road, rail and air are alternative modes of transport among the hub cities. The network of transport services is shown in Fig.1, which is divided into path transport service and hub node service according to different places of operation.

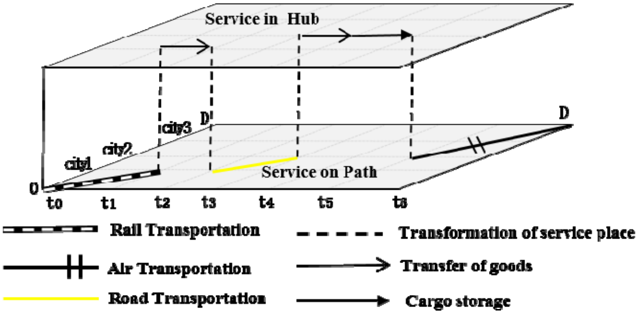

Fig. 1. Diagram of transportation services

2.2 Problem Assumptions and Variable Definitions

In order to reduce the complexity of the problem, the assumptions are as follows: The cargo cannot be divided up、Considering only the cost and time difference of transfer between different modes of transport、Road transport is not restricted by the departure time、Regardless of the limitation of transportation capacity.

The parameters in this paper are defined as follows: T_o respects departure time of the cargos from the origin city; TD_j respects arrival time of cargos at the hub j; TC_i respects departure time of cargos from the hub i; TW_i respects completion time of transfer at the hub i; $T_{\mathrm{ijf}}^{departure}$ respects departure schedules from hub i to j for transport mode f; T_{end} respects delivery time of the cargos. Q respects transport requirements; $L_{\mathrm{ij}}^{\mathrm{f}}$ respects departure time of cargos from the hub i; V^f respects speed of transport mode f; t_{j}^{kf} respects time required to transfer cargo from k to f at hub j; C is unit price of cargos; C_f is unit tariff for transport mode f; C_g is unit price for storage of cargos; C_h is unit price of cargos transfer; C_e is unit cost of carbon emissions; ω_{f} is cargo damage rate for transport mode; ω_h^{kf} is unit rate of cargo damage when cargos are transferred from mode k to f; e^f is unit carbon emissions of transport mode f; x_{ij}^f is the decision variable one, takes a value of 1 when mode of transport between hub i to j is f, and 0 otherwise; y_j^{kf} is the decision variable two, takes a value of 1 when mode of transport between hub i to j is f, and 0 otherwise.

2.3 Model Establishment

Time Succession under Schedule Constraints

Formula (1) represents arrival time of cargos at the hub j. Formula (2) represents the moment when the cargos finish the process of transfer in hub i. Formula (3) represents the moment when the cargos depart from the hub i, it is necessary to wait the departure schedule except the transport mode is road on next path.

$$TD_j = TC_i + \frac{L_{ij}^f}{V^f} \tag{1}$$

$$TW_i = TD_i + y_i^{kf} t_i^{kf} \tag{2}$$

$$TC_i = \begin{cases} TW_i, \text{Next path transport mode is road} \\ T_{ijf}^{depature}, \text{Otherwise} \end{cases} \tag{3}$$

Calculation of Cargo Damage Rate

Cargo transport damage rate is shown in formula (4), including the cargo damage caused by transport on the route and caused by transfer in the hubs.

$$\delta = \sum_{i \neq j} \sum_{f} L_{ij}^f x_{ij}^f \omega_f + \sum_{k \neq f} \sum_{j} y_j^{kf} \omega_h \tag{4}$$

Calculation of Carbon Emissions

Carbon emissions mainly include carbon emissions generated on the transport route and caused by transfer, which is shown in formula (5).

$$e_c = \sum_{i \neq j} \sum_{f} x_{ij}^{f} L_{ij}^{f} Q e_{ij}^{f} + \sum_{k \neq f} \sum_{j} y_{j}^{kf} Q e_{h}^{kf} \tag{5}$$

Customer Satisfaction.

Time satisfaction is shown in formula (6). Cargo security is portrayed by the damage rate of cargos, which is shown in Formula (7).

$$R_T = \begin{cases} \dfrac{T_{end} - T_E}{T_E - T_e} \text{,} & T_E < T_{end} < T_e \\ 1\text{,} \ T_e < T_{end} < T_l & \\ \dfrac{T_L - T_{end}}{T_L - T_l}\text{,} & T_l < T_{end} < T_L \\ 0\text{,} \ others & \end{cases} \tag{6}$$

$$R_W = \begin{cases} 1, 0 < \delta < \delta_u & \\ \dfrac{\delta_v - \delta}{\delta_v - \delta_u}\text{,} & \delta_u < \delta < \delta_v \\ 0\text{,} \ others & \end{cases} \tag{7}$$

Objective Function

Considering all the assumption, the mathematical function is constructed with the minimum transportation cost and the highest customer satisfaction. the objective function is shown in Formulas (8) and (9).

$$\min Z_1 = \sum_{i \neq j} \sum_{k} L_{ij}^{f} Q x_{ij}^{f} C_f + \sum_{k \neq f} \sum_{j} Q y_{j}^{kf} C_h + \sum_{k \neq f} \sum_{i} Q(TC_i - TD_i) C_g + \delta Q C + C_e e_c \tag{8}$$

$$\max Z_2 = \theta_1 R_T + \theta_2 R_W \tag{9}$$

Formula (8) is the total cost, which consists of the route transportation cost, transfer cost in the hubs, storage cost, compensation for damage, carbon emission cost. Formula (9) is to maximize the customer satisfaction, which consists of time satisfaction and cargo damage satisfaction.

Other constraints

$$\sum_{f} \sum_{i \neq j} x_{ij}^{f} - \sum_{f} \sum_{j \neq i} x_{ji}^{f} = \begin{cases} 1, j = d \\ 0 \\ -1\text{,} \ j = o \end{cases} \qquad \forall i, j \in N\text{,} \ f \in F \tag{10}$$

$$\sum_{f} x_{ij}^{f} \leq 1, \ \forall i, \ j \in N, \ f \in F \tag{11}$$

$$\sum_{f} y_{j}^{kf} \leq 1, \ j \in N, \ f,k \in F \tag{12}$$

$$\sum_{j} \sum_{f} y_{j}^{kf} \leq m, \ j \in N, \ f,k \in F \tag{13}$$

Formula (10) is a flow balance constraint, where the inflow of cargos is equal to the outflow of cargos at each hub, except for the origin and destination cities. Formula (11) ensures that only one mode of transport can undertake the transport service on each transport arc. Formula (12) ensures that only one operation of transfer is performed at each hub. Formula (13) indicates the transfer does not exceed m during the entire transport process.

3 Case Analysis

3.1 Case Design

Assuming that a batch of cargos is being transported from hub one to hub eleven. To make the virtual transport network closer to the actual transport operation, the transport network is an undirected network with no limitation on the direction of departure from each hub and air transport. Alternative modes of transport between hubs are shown in Fig.2. The values on each arc segment correspond to the travel distance. Customer satisfaction with cargo damage and time have equal weights of 0.5 each. The unit price of the cargos is 25,000 yuan/t. 1 to 12 hours is the early arrivals time window that the customer can accept, 12 to 24 hours is the optimal time window, 24 to 60 hours is delayed arrivals time window that the customer can accept. The highest level of satisfaction occurs when there is less than 1% of cargo damage, and the maximum rate of cargo damage the customer can accept is 3%. In accordance with carbon trading regulations, The unit price of carbon emissions is 50 yuan per ton. The departure frequency of flights is 6h per flight and the train departure frequency is 6h per train.

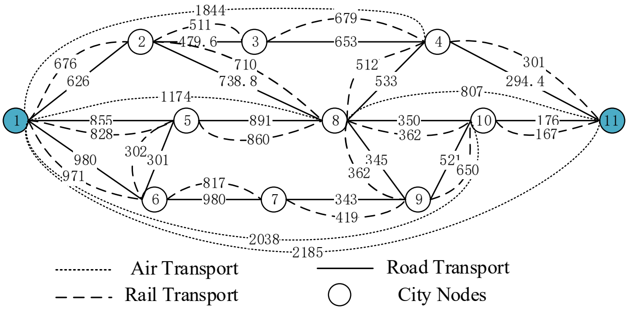

Fig. 2. The path and distance transportation network

The price of transport, carbon emissions, cargo damage rate, and transport speeds of various modes of transportation are displayed in Table. 1. The basic data is obtained by inquiring the “benchmark tariff rate table of China's railway transport” and consulting the statistical data of the "2022 Statistical Bulletin on the Development of the Civil Aviation Industry." The price of transport, cargo damage rate, and transport speeds were calculated according to the basic data. The unit carbon emissions are estimated based on the carbon emission factors in the “IPCC 2006 Guidelines for National Greenhouse Gas Inventories 2019 Revision.” Parameters such as energy consumption of carriers, nuclear loads, and full freight load are considered.

Table 1. Per Freight Rate, Carbon Emission, Cargo Damage Rate, Speed of Different Modes of Transportation

Mode of transport	Price of transport (yuan/t.km)	Carbon emissions, (kg/t.km)	Unit damage rate (%/km)	Speed(km/h)
Road	0.467	0.0556	0.00015	70
Rail	0.211	0.0165	0.00007	50
Air	3.31	0.679	0.00003	800

The average cost of transfer, carbon emission, cargo damage rate, and transfer time of different modes of transport are shown in Table. 2. These data based on the survey information of logistics parks and logistics enterprises and reviewing the pertinent statistical data in documents such as "2022 Statistical Bulletin on the Development of Civil Aviation Industry," "China Logistics Yearbook," "China Transportation Yearbook," "Statistical Bulletin on the Development of the Transportation Industry," and so on.

Table 2. Per Cost, Carbon Emission, Cargo Damage Rate and Time of Different Ways of Transfer

Type of transfer	Unit cost (Yuan)	Carbon emissions (kg)	Transfer damage rate (%/time)	Transfer time (h)
Way-Rail	250	18	0.03	0.5
Way-Air	350	22	0.05	0.5
Air-Rail	400	30	0.07	0.5

3.2 Result Analysis

A fast non-dominated genetic algorithm is used to solve the problem in this paper. The Pareto solution sets are depicted in Table. 3 when the departure frequency for flights is every 3 hours and for trains is also every 6 hours.

Table 3. Sets of Pareto solutions

Transport option	Transport route	mode of transport
1	1-2-3-4-11	rail-rail-rail-rail

2	1-2-3-4-11	rail-rail-rail-road
3	1-2-3-4-11	road-road-road-road
4	1-8-10-11	Air-rail-rail

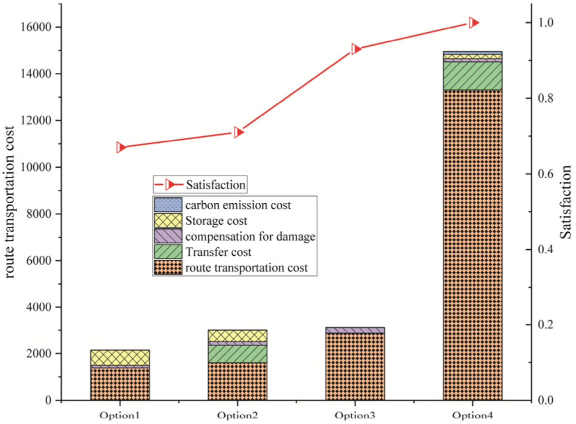

Fig. 3. Comparison of component of total cost under different options

The composition of total costs under different options is illustrated in Fig. 3. Options one, two, and three all pass through the same hub, but employ different transportation modes. As the proportion of railway transportation decreases, transportation costs continue to rise, but customer satisfaction increases accordingly. The inclusion of air transportation in option four results in a significant increase in costs, but concurrently leads to the highest level of customer satisfaction.

From the perspective of cost composition, route transportation expenses represent the largest proportion of total costs. Therefore, reducing transportation expenses is a crucial means to decrease cost. Transfer charges and management fees are also relatively high in options one, two, and four, so, It is necessary to reduce the transfer and decrease the time spent on cargo management. Carbon emission costs represent a negligible fraction of total costs under the carbon trading mechanism, regardless of the chosen mode of transportation. This observation suggests that incentivizing carriers to adopt low-carbon transportation modes independently within the carbon trading system remains challenging.

4 Conclusion

After analyzing various scenarios, the primary conclusions can be summarized as follows:

Higher levels of customer satisfaction often come with higher transportation costs. Therefore, it is crucial to select transportation options based on customer needs reasonably.

Carbon costs represent a negligible fraction of the total expenditure at current carbon trading prices. Consequently, it is challenging to incentivize multimodal transportation operators to actively adopt low-carbon transportation modes. Thus, there is significant value in further research aimed at guiding companies to autonomously reduce carbon emissions.

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References

1. Palmer, P. Doherty, S. Allen, G. Bower, K.elt. (2018) A measurement-based verification framework for UK greenhouse gas emissions: an overview of the Greenhouse gAs Uk and Global Emissions (GAUGE) project. Atmospheric Chemistry and Physics, 19: 1-52. http://doi.org/10.5194/acp-2018-135.
2. Wen, X. Mei, R. (2021) Research on optimization of expressway logistics path based on the advantages of multimodal transport in the environment of internet of things. Wireless Personal Communications, 126: 1981-1997. http://doi.org/10.1007/s11277-021-08755-y.
3. Yang, L. Zhang, C. Wu, X. (2023) Multi-Objective Path Optimization of Highway-Railway Multimodal Transport Considering Carbon Emissions. Applied Sciences, 13: 4731. http://doi.org/10.3390/app13084731.
4. Jiang, JH. Zhang, DZ. Meng, Q. (2020) Regional multimodal logistics network design considering demand uncertainty and CO2 emission reduction target: A system-optimization approach. Journal of Cleaner Production, 248: 119304. http://doi.org/10.1016/j.jclepro.2019.119304.
5. Fazayeli, S. Eydi, A. Kamalabadi, I. (2018) Location routing problem in multimodal transportation network with time windows and fuzzy demands: presenting a two-part genetic algorithm. Computers & Industrial Engineering. 119: 233-246. http://doi.org/10.1016/j.cie.2018.03.041.
6. Sun, Y. Li, X. (2019) Fuzzy programming approaches for modeling a customer-centred freight routing problem in the road-rail intermodal hub-and-spoke network with fuzzy soft time windows and multiple sources of time uncertainty. Mathematics. 7: 739. http://doi.org/10.3390/math7080739.
7. Marco, B. Maurizio, F. Mauro, G. (2016) Multi-objective design of multi-modal fresh food distribution networks. International Journal of Logistics Systems and Management. 24: 155-177. http://doi.org/10.1504/IJLSM.2016.076470.
8. Chen, WY. Gong, H. Fang, XP (2022) Multimodal transportation route optimization considering transportation carbon tax and quality commitment. Journal of Rail Way Science and Engineering. 19: 34-41. http://doi.org/10.1504/IJLSM.2016.076470.
9. Liu, SC. (2023) Multimodal Transportation Route Optimization of Cold Chain Container in Time-Varying Network Considering Carbon Emissions. Sustainability. 15:4435. http://doi.org/10.3390/su15054435.
10. Rouky, N. Boukachou,r J. Boudebous, D. (2023) Optimization under uncertainty: generality and application to multimodal transport. International Journal of Supply & Operations Management. 10: 223-244. http://doi.org/10.22034/IJSOM.2022.109357.2378.