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Abstract: In recent years, RFT has gradually transformed into a service-oriented business, and door-to-door transport has become an important advancement direction of RFT transport. To improve the carriage quality and efficiency of railway carriage enterprises, the majorisation pattern of RFTD2DT route design is studied by IMOQPSO algorithm. The astringency performance is enhanced by improving the operation of parameter setting and location updating. The research results indicate that the average GD value of IMOQPSO is 0.04 and 0.01, and the average IGD value is 0.81 and 0.01, which is obviously superior to IMOMPPSO, IMOQPSO has good Pareto front astringency. The research introduces multi-objective optimisation algorithm into the design of RFTD2DT route. The IMOQPSO algorithm is used to determine the best transportation route in the transportation process of the door-to-door, which can effectively provide decision-making reference for the route design of railway transportation enterprises, reduce the transportation time and cost of railway freight and improve the operation efficiency. It has important value for promoting the upgrading of railway freight door-to-door service.

Keywords: railway; carriage; IMOMPPSO; multi-objective majorisation; by route.

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1   Introduction

The railway carriage is a common way of long-distance carriage of cargo. Railway Freight Transportation (RFT) has the distinctions of high dependability, and has a good effect on the green advancement of carriage of cargo. The advancement of RFT is of great value in reducing the consumption of non-renewable energy in the carriage industry, and has practical significance in promoting global energy conservation and emission reduction actions (Adi et al., 2020; Sun et al., 2019). Although railway carriage has obvious advantages of safety and economy, there are many problems such as long delivery periods, inconvenient query of cargo status, disorder of carriage organisation and there is a gap between railway carriage and other carriage modes in timeliness and convenience (Butko et al., 2019; Stoilova, 2020). In recent years, the reform of railway transportation organisation has been continuously promoted. The new situation of the reform of railway company system and the structural reform of railway transportation supply-side has put forward higher requirements for the supply quality and efficiency of railway transportation. It is emphasised to deeply grasp the changing characteristics of market demand, understand the actual and potential needs of railway transportation development and optimise the supply chain of the existing railway transportation industry. In the context of supply-side reform, the railway freight service has gradually changed from production-oriented to market-oriented and service-oriented. It is required to improve the organisation and planning of railway freight and improve the efficiency of traditional railway transportation to meet the needs of the market and customers. On the other hand, the traditional depot-to-depot freight transport mode has lagged behind the market orientation, while the door-to-door transport mode has begun to become the advancement direction of RFT transport. It is required to realise the extension service of traditional RFT transport and further enhance the customer's RFT transport experience (Baykasoğlu et al., 2019; Noureddine and Ristic, 2019). The door-to-door transportation of railway goods includes the entire transportation service of goods from the origin to the destination, which expands the service scope of traditional RFT. On the basis of traditional RFT, the door-to-door transportation service of goods at both ends of railway transportation is added. When the railway transport department accepts the consignor's entrustment, the railway transport enterprise will pick up the goods on the doorstep by road and other means of transportation and transport the goods to the origin station of the railway transport. When the goods are transported to the destination station by railway, the railway transport enterprise will directly deliver the goods to the designated place of the consignee by other means of transportation. The door-to-door transportation of railway goods reduces the transportation docking process of the transportation consignor, and the entire transportation process of goods from the origin to the destination is directly undertaken by the railway transportation enterprise. Therefore, in order to improve the

comprehensive utilisation rate of resources for railway goods door-to-door transportation and improve the efficiency of it, the route design optimisation model for door-to-door transportation of railway goods is studied by using multi-objective cluster intelligent algorithm, which is expected to provide help for improving the quality and efficiency of railway freight.

The main contribution of the research is to introduce the multi-objective continuous cluster intelligent algorithm into the railway Freight Door-to-Door Transportation (RFTD2DT) route planning, improve the classical particle swarm optimisation algorithm, and use the multi-objective quantum behaviour particle swarm optimisation algorithm to solve the real route planning problem in the RFTD2DT process. The research improves the global search ability of the algorithm through parameter optimisation and location update, and effectively improves the operation efficiency of the algorithm. The research uses multi-objective intelligent algorithm to determine the optimal route planning of RFTD2DT, which can effectively provide decision-making support for the door-to-door transportation services of railway transportation enterprises. It improves the transportation efficiency of railway transportation enterprises by using intelligent optimisation technology. It fully utilises the existing resources of railway transportation, reduces the transportation time and transportation costs of railway transportation enterprises and improves the market competitiveness of RFT.

The research is mainly divided into four parts. The first part analyses the relevant research status of railway transport route planning and door-to-door transport services. The second part describes the railway transport route design model based on the improved multiple target quantum behaved particle swarm majorisation (IMOQPSO) algorithm in depth. First, it models the door-to-door transport of railway goods, and analyses the specific content of the IMOQPSO algorithm. In the third part, the feasibility and application effect of the model based on IMOQPSO algorithm are verified by the way of numerical examples and experiments. The last part is a summary of the main contents and contributions of the article.

2   Related works

Carriage route planning has always been a hot issue in research, and many scholars have carried out research on carriage route design. Zhang et al. (2019) put forward an RFT planning majorisation pattern considering the railway operating profit and customer waiting problems for the RFT system. The majorisation pattern solves the balance between user waiting and profit by optimising pricing and controlling the backlog, and seeks the best balance between the interests of RFT forwarders and customers. Yin et al. (2020) put forwarded a railway container freight planning pattern based on a simulated annealing algorithm, fully considering the three aspects of carriage time cost and environmental protection. Based on the simulated return algorithm, they established a mixed integer planning majorisation pattern for freight carriage. The research indicated that the planning majorisation pattern could reduce the cost and time of freight carriage, and the carbon emissions in the process of shipment carriage. Sun (2020) put forwarded a route majorisation pattern for highway and railway dual transport systems in view of the impact of uncertain factors such as delivery time and transport capacity on the actual cost and time of freight transport. The majorisation pattern combines nonlinear programming with fuzzy-constrained programming to solve the intermodal carriage route planning

problem. Sun and Li (2019) put forward an equivalent mixed integer linear programming pattern for railway intermodal transport route planning, fully considering the impact of uncertain time factors such as loading and unloading and travel time on operation economy and reliability. The pattern was combined with the fuzzy expected value pattern to solve the fuzzy target, so as to provide a better transport scheme for the decision-making of intermodal transport route. Gasparik et al. (2020) analysed the relationship between the regional population, the length of the transport line and the stops and proposed a public transport pattern for railway transport, which provides help for the advancement of an integrated transport system. The research indicated that the transport pattern can improve the quality of railway transport, and explore the transport potential of railway transport.

Multi-modal door-to-door transport service has become an important development direction of freight transport. Many researchers have carried out research on multimodal transport route planning. Sun (2020) proposed a route planning model for the transportation of dangerous goods in the process of door-to-door transportation of road and railway multimodal transport. The fuzzy time window is used to realise the terminal distribution decision of dangerous goods door-to-door transportation. The fuzzy expected value method is used to solve the optimisation problem, and the door-to-door multimodal transport of dangerous goods is realised by comprehensively considering the risk, economy, timeliness and other factors (Sun, 2020). Kravets et al. (2021) put forward a multi-criteria decision-making method considering the time index for the distribution of cargo flow in the multimodal freight transport system. Based on various factors in the railway transport and cargo accumulation process, the mathematical model of the transport process was constructed and the optimal distribution mode of cargo logistics in the multimodal transport process is obtained by solving the objective function (Kravets et al. 2021). Anoop and Panicker (2022) proposed a transportation planning model considering freight discount for the problem of door-to-door multimodal freight transport based on railway and highway. He carried out constraint planning for the door-to-door multimodal freight transport of railway goods under the conditions of small quantity of shipments and large-scale continuous freight to obtain the best route of door-to-door multimodal transport under different conditions (Anoop and Panicker, 2022). In order to improve the competitiveness of railway transport in the door-to-door multimodal freight transport system, Yin et al. (2021) proposed a freight subsidy solution model for railway transport, which comprehensively considered the operating costs, transfer costs and other factors in the door-to-door multimodal transport process and solved the optimal solution of railway transport subsidies in the door-to-door multimodal transport process through the double-layer editing model. Kaewfak et al. (2021) proposed a comprehensive risk assessment model under the influence of multiple factors for the problem of path planning in multimodal transport system, and used the zero objective planning method to assist in the route decision of multimodal transport. The analytic hierarchy process was introduced to determine the weight.

To sum up, many researchers have worked on the transportation route planning problem from a variety of perspectives, but the optimisation and feasibility of railway transportation route planning still need to be improved. Many studies have problems of complex operation and poor convergence performance. Therefore, the research is based on the multi-objective cluster intelligent optimisation algorithm to build an optimisation model for railway freight route design. It is expected to use the advantages of IMOQPSO

algorithm in global search and operational efficiency to provide route planning optimisation design for RFTD2DT problems, and provide reference for improving the quality of RFTD2DT.

3 Research on railway carriage routing design based on IMOQPSO

3.1 Patterning of railway carriage via design

Railway Door-to-Door Transportation (D2DT) is a one-stop carriage service provided by railway enterprises. It is simple and efficient and has significant advantages in long-distance freight carriage. It can optimise the carriage process through integrated management of the carriage supply chain, and improve high-quality long-distance freight carriage services (Kelle et al., 2019; Uddin and Huynh, 2019). After receiving the carriage order, the railway carriage enterprise will carry out the route planning according to the weight, volume, distance and other information of the cargoes. An enterprise comprehensively optimises the design based on the carriage route occupation, loading and unloading capacity of intermediate transit depots, unit carriage cost and other carriage route information. It must make full use of existing carriage resources to provide customers with high-quality D2DT services for railway cargoes, improve carriage level and reduce carriage time and cost (Demir et al., 2019; Zhang and Li, 2019). The service process pattern of railway cargo D2DT is indicated in Figure 1.

Figure 1 The service process pattern of railway cargo D2DT
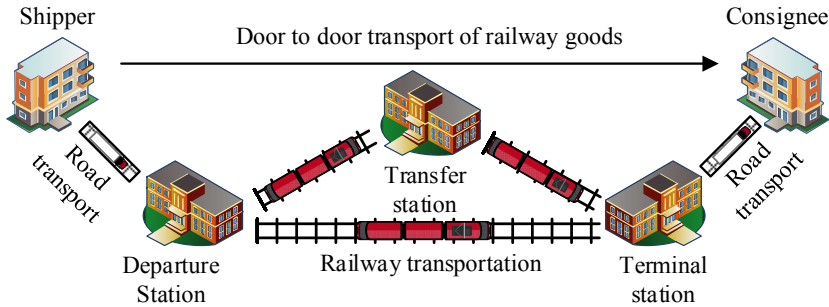
According to the activity-based costing method, the production process of RFT can be divided into two parts: door-to-door service at both ends and intermediate railway transportation. Railway freight transport is mostly inland transport, and door-to-door services at both ends are generally undertaken by road transport. The study takes the door-to-door transport of inland railway freight as the analysis object, and only considers the situation that the door-to-door transport services at both ends are undertaken by road transport, without discussing other transport service modes such as sea transport. The door-to-door service at both ends transports goods to the railway departure station and the customer's receiving location through road transportation, while the railway transportation can be divided into four links: departure, transportation, transfer and arrival (Petrović et al., 2019). Factors such as railway operation conditions, carriage time, carriage distance, carriage cost and service capacity will affect the quality of carriage

services in the process of D2DT of railway cargoes. Among them, carriage cost and time are the critical influencing elements. Therefore, the research focuses on the design and patterning of carriage routes based on carriage cost and time, and the construction of the majorisation design pattern of RFT routes. The railway carriage starting link requires the linkage between the depot and the train sections. The workload of the starting depot is expressed by the quantity of departure trains, and the workload of the train is expressed by the occupied time of freight trains. The carriage workload function of the starting link is indicated in equation (1).

$$\begin{cases} H_{11} = \varpi = \left[\dfrac{W}{\gamma(1+\lambda)} \right] \\ H_{12} = \dfrac{\tau_1 \varpi (1+\varepsilon)}{24} \end{cases} \tag{1}$$

In equation (1), H_{11}, H_{12} represents the workload of the departure depot and the train workload, W represents the weight of the transported cargoes. γ, λ represent the static load and the allowable loading rate, respectively, $[.]$ represents the rounding up, τ_1 represents the dwell time, and ε represents the vacancy rate. The carriage link includes the joint operation of the power supply, locomotive, train and other sections. The locomotive running workload H_{21} and traction workload H_{22} are used to represent the workload of the locomotive and power supply sections. The workload of track and communication sections and train sections is expressed as the total tonnage H_{23}, train travel length H_{24}, train running workload H_{25} and train occupation time H_{26}. The carriage workload function of the carriage link is indicated in equation (2).

$$\begin{cases} H_{21} = \dfrac{L(W + \varpi \omega_1)}{\sigma} (1 + \delta_1 + \delta_2 + \delta_3)(1 + \delta_4) \\ H_{22} = L(W + \varpi \omega_1) \\ H_{23} = \dfrac{W \omega_2 L}{\sigma} + L(W + \varpi \omega_1) \\ H_{24} = \dfrac{L(W + \varpi \omega_1)}{\sigma} \\ H_{25} = \varpi L(1 + \varepsilon) \\ H_{26} = \dfrac{\varpi L(1 + \varepsilon)}{24v} \end{cases} \tag{2}$$

In equation (2), L represents the carriage distance, σ represents the average traction weight of the locomotive, σ represents the dead weight of the train. $\delta_1, \delta_2, \delta_3$ represent the single machine rate, reconnection rate and repair rate. δ_4 represents the converted running rate. ω_2 represents the dead weight of the locomotive, and v represents the traveling speed. The transit link is jointly operated by the train section and the transit depot, which are respectively expressed as the transit truck occupation time H_{31} and the quantity of transit trains H_{32}. The transport workload function of the transit link is indicated in equation (3).

$$\begin{cases} H_{31} = \dfrac{\pi\tau_2\varpi(1+\varepsilon)}{24} \\ H_{32} = \pi\varpi \end{cases} \tag{3}$$

In equation (3), π represents the number of transfers, and τ_2 represents the average transfer dwell time. The arrival link includes two sections: the terminal depot and the train section. The workload of the terminal depot is expressed as the quantity of arriving trains, which is consistent with the workload of the departure depot in numerical value. The occupation time of arriving trucks is used to express the workload of the train section. The carriage cost of the arrival link is indicated in equation (4).

$$\begin{cases} H_{41} = \varpi \\ H_{42} = \dfrac{\tau_3\varpi(1+\varepsilon)}{24} \end{cases} \tag{4}$$

In equation (4), τ_3 represents the arrival time of the operation. The door-to-door service link at both ends only considers the road carriage cost, which is expressed as the ton kilometres of receiving and delivering cargoes, so the workload function of door-to-door service at both ends is indicated in equation (5).

$$\begin{cases} H_{51} = WL_1 \\ H_{42} = WL_2 \end{cases} \tag{5}$$

In equation (5), L_1, L_2 is the carriage distance from door to depot and from depot to door, respectively. The freight carriage cost is multiplied by the workload by the unit activity cost, and there is a certain variation relationship between the activity volume and the cost. The rail freight D2DT cost can be divided into fixed cost $FC(W,E)$, variable cost $VC(W,E,L)$, etc. The rail freight D2DT cost function TC is indicated in equation (6).

$$\begin{cases} TC = FC(W,E) + VC(W,E,L) \\ FC(W,E) = (C_{11}H_{11} + C_{12}H_{12}) + (C_{31}H_{31} + C_{31}H_{31}) + (C_{41}H_{41} + C_{42}H_{42}) \\ VC(W,E,L) = (C_{21}H_{21} + C_{22}H_{22} + C_{23}H_{23} + C_{24}H_{24} + C_{25}H_{25} + C_{26}H_{26}) \\ \qquad\qquad + (C_{51}H_{51} + C_{52}H_{52}) \end{cases} \tag{6}$$

In equation (6), E is the activity efficiency parameter, H_{ij} is the workload indicator j of phase i, and C_{ij} is the unit activity cost of H_{ij}. The door-to-door transport time of railway cargoes is patterned. Owing the loading capacity of the departure depot itself and the interaction between cargoes at the same depot, the parallel loading capacity of the depot needs to be considered. Therefore, the time function of the departure link is indicated in equation (7).

$$t_1 = \dfrac{W}{v_1}\left(1 + \alpha\left(\dfrac{K_1}{\psi_1}\right)^\beta\right) \tag{7}$$

In equation (7), v_1 refers to the loading speed of the departure depot, K_1 refers to the quantity of concurrent processing of the depot's clients, ψ_1 refers to the current total

quantity of delegates, and α, β refer to the undetermined parameters. The carriage and transit links only consider the carriage and operation time, and do not consider the impact of other trains. The time function of the carriage and transit links is indicated in equation (8).

$$\begin{cases} t_2 = \dfrac{L}{v} \\ t_3 = \pi\tau_2 \end{cases} \tag{8}$$

In equation (8), t_2, t_3 represent the time of carriage and transit. The arrival link is similar to the departure link, so the parallel processing capacity of the depot should be considered. The time function of the arrival link is indicated in equation (9).

$$t_4 = \frac{W}{v_2}\left(1 + \alpha\left(\frac{K_2}{\psi_2}\right)^{\beta}\right) \tag{9}$$

In equation (9), v_2 refers to the loading speed of the depot, K_2 refers to the quantity of concurrent processing of the clients arriving at the depot, and ψ_2 refers to the current total quantity of clients. Since the cargo handling time of door-to-door service at both ends is not affected by the route, the cargo handling time of the starting and ending points at both ends is not considered in the carriage time patterning, and the time function of door-to-door service at both ends is indicated in equation (10).

$$\begin{cases} t_5 = \dfrac{L_1}{v_3} \\ t_6 = \dfrac{L_2}{v_3} \end{cases} \tag{10}$$

In equation (10), t_2, t_3 represent the receiving time and delivery time. L_1, L_2 represent the receiving distance and delivery distance, and v_3 represent the highway carriage speed. The total time of RFTD2DT is the sum of time of each link. The selection of the departure depot and arrival depot of freight railway carriage determines the main route of carriage, and directly affects the distance between highway carriage at both ends and railway carriage in the middle, which plays a critical role in the allocation of carriage resources. The current entrusted saturation and parallel processing capacity of the departure and arrival depots will also directly affect the time and cost of freight carriage. Therefore, the research focuses on the selection and planning of the departure and arrival depots to build a majorisation pattern for the design of RFTD2DT. The consignor is set as i, the total quantity of consignors accepted by the carriage enterprise is N_C, the departure depot and arrival depot are j and k, respectively. There are N_O available departure depots at the consignor's carriage starting point A, and N_D available arrival depots at the carriage terminal B. Taking the minimisation of transport time and transport cost as the design majorisation objective, the door-to-door transport pattern of railway cargoes is indicated in equation (11).

$$
\begin{cases}
\min_x f(x) = \begin{cases} TC(x) \\ T(x) \end{cases} \\
TC(x) = \sum_{i=1}^{N_C} \sum_{j=1}^{N_O} X'_{ij} \left(TC'_{ij} + TCO_{ij} \right) + \sum_{i=1}^{N_C} \sum_{j=1}^{N_O} \sum_{k=1}^{N_D} X'_{ij} X'_{ik} TC_{ijk} \\
\qquad\quad + \sum_{i=1}^{N_C} TC_i + \sum_{i=1}^{N_C} \sum_{k=1}^{N_D} X'_{ik} \left(TCD_{ik} + TC'_{ik} \right) \\
TC(x) = \sum_{i=1}^{N_C} \sum_{j=1}^{N_O} X'_{ij} + \sum_{i=1}^{N_C} \sum_{j=1}^{N_O} \sum_{k=1}^{N_D} X'_{ij} X'_{ik} T_{ijk} \\
\qquad\quad + \sum_{i=1}^{N_C} T_i + \sum_{i=1}^{N_C} \sum_{k=1}^{N_D} X'_{ik} \left(TD_{ik} + T'_{ik} \right) \\
\varpi = \left[\dfrac{W_i}{\gamma(1+\lambda)} \right]
\end{cases}
\tag{11}
$$

In equation (11), TC'_{ij} represents the highway carriage cost between the place of shipment and the departure depot. T'_{ij} represents the highway carriage time between the place of shipment and the departure depot. TCO_{ij}, TO_{ij} represents the carriage cost and time of cargoes at the departure depot. TC_{ijk}, T_{ijk} represent the railway carriage cost and time between the departure depot and the arrival depot. TC_i, T_i represent the carriage cost and time. TCD_{ik}, TD_{ik} represent the carriage cost and time of cargoes at the arrival depot. TC'_{ik}, T'_{ik} refer to the cost and time of road carriage from the depot to the receiving place.

3.2 Transport routing design planning pattern based on IMOQPSO

Considering the parallel processing of cargo carriage orders of multiple consignors, the design of the railway cargo D2DT route is optimised and the carriage resources of departure depot and arrival depot are allocated to multiple consignors to reduce the cost and time consumption of cargo carriage and improve service quality and efficiency. The carriage route design majorisation considering parallel delegation processing is essentially a multiple target combination majorisation solution, and the goal of a multiple target majorisation solution is to find the Pareto front (Wu et al., 2019). Traditional Particle Swarm Majorisation (PSO) searches for the first-best solution, but it is easy to sink into the local best solution problem. Based on classical particle swarm majorisation, IMOQPSO is proposed to improve the global search ability while reducing the number of control parameters, which improves the solving ability for multiple target majorisation problems. The IMOQPSO first sets parameters and initialises the population, determines the initial location of particles by means of chaotic mapping, calculates the fitness of initial particles, obtains the first-best individual location of initial particles and the first-best particle fitness value and obtains the uncontrolled solution aggregation. The next step is to determine the location of the initialisation particles to renew the mutation parameters and chaos parameters, and to find the Pareto front of multiple target majorisations through iterative search. In the iteration process, the average first-best location and the coefficient of contraction and expansion are first determined and then the particle evolution is carried out. The chaotic mapping method is used to obtain the location renew random quantity, and then the global derivative solution and local attraction point of the particle are obtained. The particle location renew operation is realised, and the global uncontrolled solution aggregation is renewed and trimmed. The running process of the IMOQPSO is displayed in Figure 2.

Figure 2   Operation process of IMOQPSO
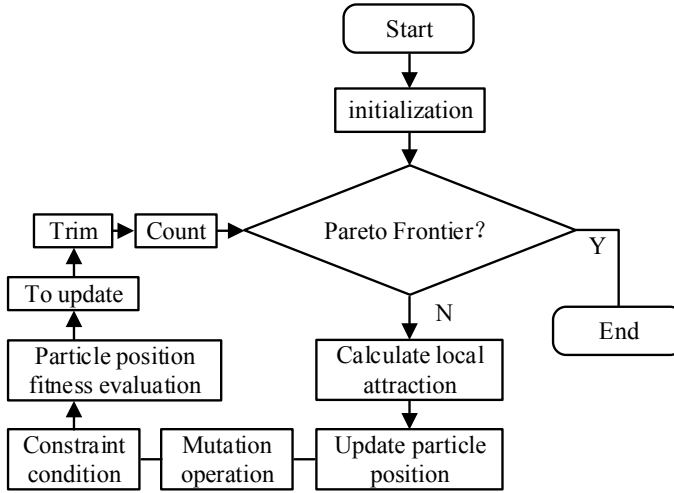
In the initialisation phase, the IMOQPSO uses the logistic chaotic map to initialise the particle location and determines the initial location of the particle. The IMOQPSO uses an aggregation of uncontrolled solutions with a volume limit to save the uncontrolled solutions obtained from the search, and initialises them together after the population initialisation to generate a logistic chaotic map of the uncontrolled frontier. The IMOQPSO relies on the uncontrolled solution aggregation storage algorithm with an upper capacity limit to achieve global majorisation. During the majorisation process, the uncontrolled solution aggregation is renewed and a first-best location is selected to guide the particle search. The mainstream idea has an important impact on the creativity and scope of particle search. The IMOQPSO takes the average first-best location as the mainstream idea, and introduces the Fast Uncontrolled Sorting Approach (FNSA) to consider the role of elites based on the average first-best location idea. FNSA arranges the population by fast uncontrolled sorting, and the particles in the community are distributed on many different uncontrolled fronts. The average first-best location of each uncontrolled frontier is consistent. The average first-best location of the uncontrolled front is displayed in equation (12).

$$\begin{cases} Mbests_i = Mbests\left(fns.frontIndex\left(i\right)\right) \\ Mbests_g = mean\left(Pbx_g\right) \\ Pbx_g = Pbx\left(fns.frontIndex <= g,:\right), g \in \left[1, fns.Nf\right] \\ \left[fns\right] = fastNondominatedSort\left(x, f\right) \end{cases} \tag{12}$$

In equation (12), *astNondominatedSort* is a fast uncontrolled sequencing function that returns the sorted output structure, including the frontier *frontIndex* where the particles are located and the quantity of frontier *Nf*. *mean*(.) is a calculation function of the average value of the parameters. The IMOQPSO uses the quantum behaviour of particles to achieve particle location renewal. First, the logistic chaotic map is used to obtain the location renew parameters, and the global first-best location and the average first-best

location are combined to calculate the local attraction points of particles and complete the particle renew operation. To further improve the astringency performance, the particle renews behaviour of the IMOQPSO has a 25% probability based on the individual first-best corresponding dimension, and a 25% probability based on the corresponding dimension value of the global first-best location. The particle renews function of IMOQPSO is displayed in equation (13).

$$x(i,j) = \begin{cases} Pi(i,j) - \beta(Mbests_i(j) - x(i,j))\ln(1/u), m \le 0.25 \\ Pi(i,j) + \beta(Mbests_i(j) - x(i,j))\ln(1/u), 0.25 < m \le 0.5 \\ Pb(i,j), 0.5 < m \le 0.75 \\ Gbx(j), m > 0.75 \end{cases} \quad (13)$$

To meet the continuous majorisation needs in solving combinatorial majorisation problems, particles need to be renewed using the current location and cannot be affected by the historical first-best location. The renew function of the particle's first-best location can be displayed in equation (14).

$$Pbx_i(t) = \begin{cases} Pbx_i(t-1), & \text{if } fb_i(t-1) \prec f_i \\ x_i(t), & \text{otherwise} \end{cases} \quad (14)$$

When solving the practical combinatorial majorisation problem, the IMOQPSO considers the problem of actual resource constraints, and uses the method of restricting the feasible area of individual flight to constrain conditions. When the individual flies out of the feasible area, the algorithm replaces the dimension value of particles flying out of the feasible area by randomly generating. It sets the global optimum, the individual optimum and the corresponding dimension boundary value in the feasible area. The constraint processing function is displayed in equation (15).

$$x_{i,j}(r) = \begin{cases} lu(1,j) + (lu(2,j) - lu(1,j)).*r\text{and}, r \le 0.25 \\ Pbx_{i,j}, 0.25 < r \le 0.5 \\ Gbx_{i,j}, 0.5 < r \le 0.75 \\ bv_{i,j}, \text{otherwise} \end{cases} \quad (15)$$

When the capacity of the solution set exceeds the maximum limit, the uncontrolled solution aggregation needs to be trimmed. To ensure the global first-best orientation in the evolutionary majorisation process, and improve the efficiency of algorithm updating and majorisation, the IMOQPSO chooses to delete the solution with the least feasibility of being checked when pruning the uncontrolled solution aggregation and guide it to meet the volume limit.

4 Effect analysis of design majorisation pattern

4.1 Astringency performance analysis

To verify the performance of the IMOQPSO proposed in the research for solving multiple target combinatorial majorisation problems, the astringency of the IMOQPSO was studied. The benchmark case verification based on the classic flexible job shop
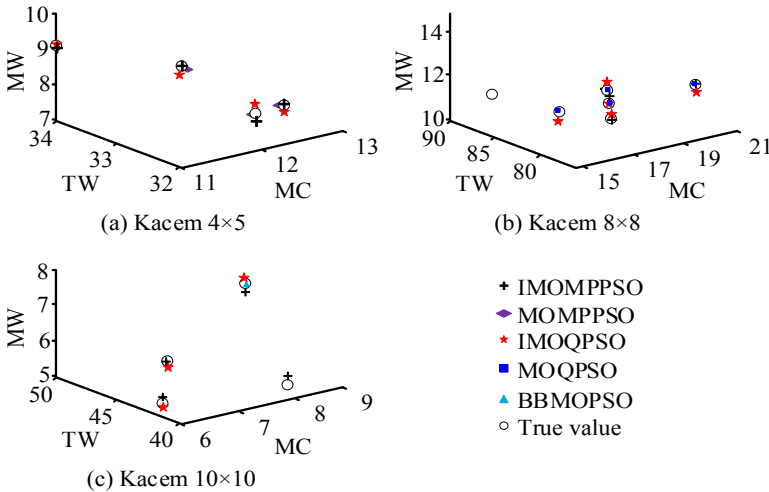
scheduling combinatorial majorisation problem was researched. The argument settings of the IMOQPSO are displayed in Figure 1.

Table 1   Algorithm parameter setting

| Serial number	Index	Numerical value
1	α	0.863
2	β_{max}	0.871
3	β_{min}	0.896
4	Max-ite	3000
5	Min-ite	1000

The benchmark cases of three dimensions in the workshop scheduling combinatorial majorisation problem are selected for experimental analysis. The IMOQPSO, the improved multiple target multi-phase particle swarm majorisation (IMOPPSO), the multiple target multi-phase particle swarm majorisation (MOMPPSO), the Multi-Objective Quantum shared Particle Swarm Majorisation (MOQPSO) and basic Multiple target particle swarm majorisation algorithm (BBMOPSO) were compared and verified. Combined with Maximum Workload (MW), the Maximum Completion (MC) and Total Workload (TW) indicators were studied. The comparison results of the Pareto front astringency of the five algorithms in the benchmark example are displayed in Figure 3.

Figure 3   Comparison results of pareto frontier astringency of five algorithms in benchmark example

(a) Kacem 4×5

(b) Kacem 8×8

(c) Kacem 10×10

From Figure 3, the Pareto front astringency of the five algorithms was within the acceptable range when solving the job shop scheduling combinatorial majorisation problem. The IMOQPSO had the best frontier astringency, slightly better than the other four algorithms. The population diversity characteristics of the five algorithms were analysed, and 50 independent experiments were conducted in the benchmark cases of three dimensions. The population diversity comparison results of the five techniques are displayed in Figure 4.

Figure 4 Comparison results of population diversity of five algorithms

(a) Kacem 4×5

(b) Kacem 8×8

(c) Kacem 10×10
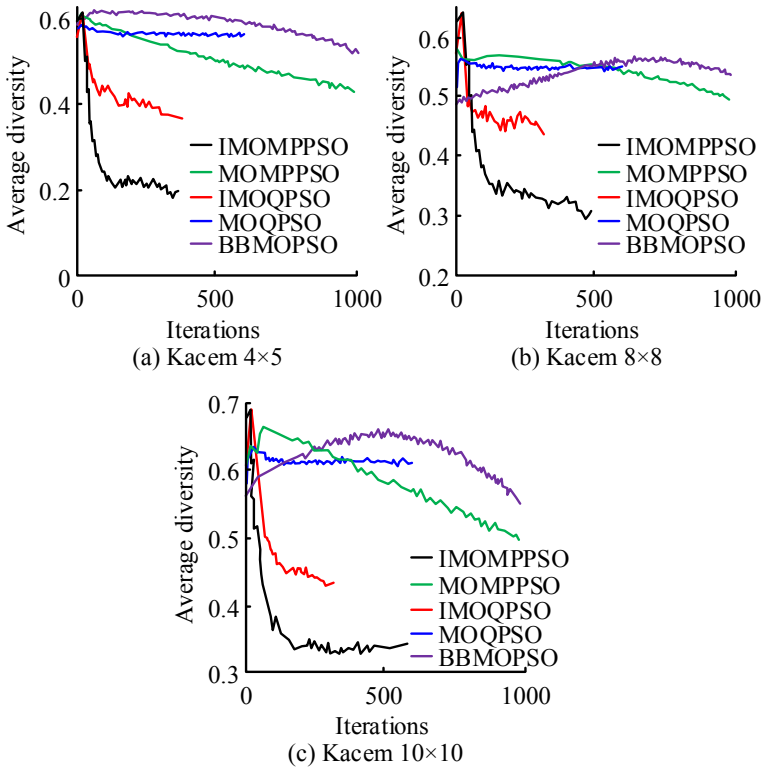
From Figure 4, with the increment of iteration times, the population diversity of the IMOQPSO decreases rapidly. Compared with the traditional MOQPSO algorithm, the decline of the IMOQPSO is greatly improved, which proves that the IMOQPSO effectively improves the astringency performance.

4.2 *Example validation analysis*

To verify the effectiveness of the RFT route planning majorisation pattern based on IMOQPSO, the RFT Routing Design (RFTRD) example is used for verification and analysis. The real coding system is used to code the problem, and the actual application of five algorithms in the RFTRD problem is analysed. The example includes three departure stations and three terminal stations. There are six consignors in the experiment, and the delivery and receipt addresses of each consignor are randomly generated. The comparison results of Pareto front astringency and population diversity of the five algorithms are displayed in Figure 5.

Figure 5   Comparison results of Pareto front astringency and population diversity of five algorithms

(a) Pareto front   (b) Population diversity
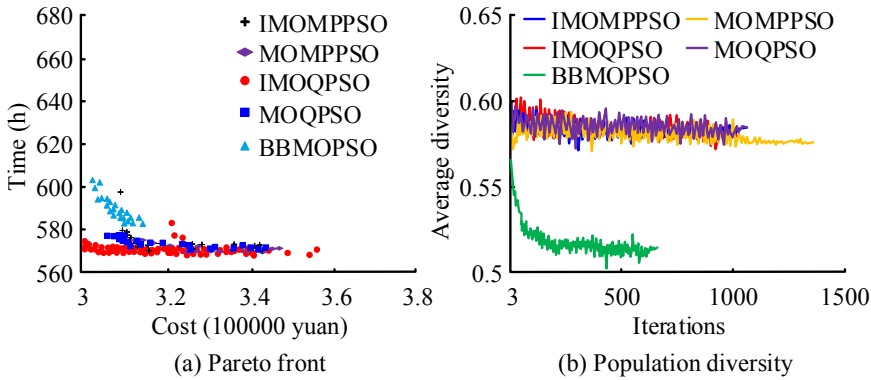
From Figure 5 that the Pareto front astringency effect of IMOQPSO was the best, which was obviously better than IMO PPSO and other algorithms. From the perspective of population diversity, the BBMOPSO algorithm indicated strong astringency, but the Pareto front astringency of the BBMOPSO algorithm was poor. According to the comprehensive analysis, the IMOQPSO had the best comprehensive performance in pattern astringency. The compromise solution of the RFT route planning majorisation pattern based on IMOQPSO in the solution of the RFTRD example is displayed in Figure 6. The selected compromise solution is the first-best solution.

Figure 6   Operation process of IMOQPSO

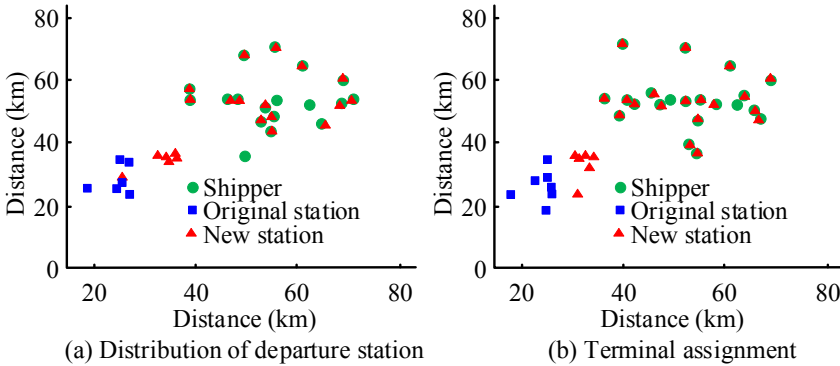(a) Distribution of departure station   (b) Terminal assignment

Figure 6 shows that the closer the departure and arrival depots were to the Client's location, the shorter the road carriage distance, and the lower the time and cost of D2DT at both ends. This was to reduce the overall time and cost of the carriage while improving the carriage efficiency. The General Distance (GD) index was used to evaluate the astringency of the planning majorisation pattern. All algorithms have been tested 50 times independently. The GD index comparison results of five algorithms when solving two RFTRD examples are displayed in Table 2.

Table 2 GD index comparison results of five patterns in solving two RFTRD examples

Example question number	Serial number	Algorithm	Max	Min	Mean	Std.
A	1	IMOQPSO	0.44	0	0.04	0.12
	2	IMOMPPSO	0.71	0	0.10	0.17
	3	MOQPSO	0.46	0	0.11	0.19
	4	MOMPPSO	0.75	0	0.22	0.54
	5	BBMOPSO	0.39	0	0.13	0.15
B	1	IMOQPSO	0.37	0	0.01	0.14
	2	IMOMPPSO	0.58	0	0.04	0.24
	3	MOQPSO	1.12	0	0.07	0.17
	4	MOMPPSO	0.76	0	0.52	0.29
	5	BBMOPSO	1.37	0	0.54	0.21

Table 2 shows that the evaluation result of the GD index of the IMOQPSO is the best, with an average GD of 0.04 and 0.01, and a standard deviation of 0.12 and 0.14, which is significantly better than the other four algorithms. This data proves that the IMOQPSO has the best astringency in solving the freight route planning problem. The Inverted Generation Distance (IGD) index is introduced to analyse the comprehensive solution performance of the five algorithms. The IGD index comparison results of the five algorithms are displayed in Table 3.

Table 3 IGD index comparison results of five patterns in solving two RFTRD examples

Example question number	Serial number	Algorithm	Max	Min	Mean	Std.
A	1	IMOQPSO	0.87	0.47	0.81	0.07
	2	IMOMPPSO	1.37	0.53	0.87	0.14
	3	MOQPSO	0.89	0.48	0.84	0.11
	4	MOMPPSO	1.39	0.66	0.89	0.15
	5	BBMOPSO	1.39	0.66	1.00	0.24
B	1	IMOQPSO	0.34	0	0.01	0.06
	2	IMOMPPSO	0.58	0	0.09	0.18
	3	MOQPSO	0.56	0	0.11	0.15
	4	MOMPPSO	0.67	0	0.14	0.24
	5	BBMOPSO	0.68	0.31	0.61	0.12

Table 3 shows that the average IGD of IMOQPSO is 0.81 and 0.01, and the standard deviation is 0.07 and 0.06. The comprehensive performance of IMOQPSO in solving RFT route planning problems is better than that of IMO PPSO and the other four algorithms. IMOQPSO can effectively provide decision-making reference for freight route planning, achieve rapid astringency in planning majorisation and has good pattern astringency and population diversity decline performance. Further introduce the Multiple target particle swarm majorisation algorithm (MOPSO) for comparative experiments.

The comparison results of the elapsed time and iteration frequency of the six algorithms in the process of freight route optimisation are displayed in Figure 7.

Figure 7   Comparison results of running time and iteration times of six algorithms in the process of freight route majorisation

(a) Running time   (b) Iterations
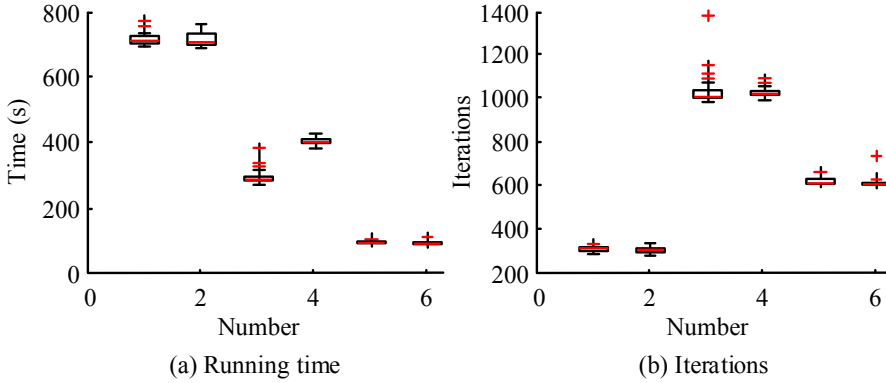
It can be seen from Figure 7 that the No. 1 algorithm BBMOPSO and No. 2 algorithm MOPSO have the longest running time, and their Pareto front convergence effect is not obvious. No. 3 algorithm IMOMPPSO and No. 4 algorithm MOMPPSO have short running times but poor convergence. No. 5 algorithm IMOQPSO and No. 6 algorithm MOQPSO have the best performance in terms of running time and Pareto front convergence, but the convergence of MOQPSO fluctuates slightly, and the comprehensive performance of IMOQPSO is superior to other algorithms.

5   Conclusion

Railway freight transport is one of the important ways of long-distance transportation of bulk goods. To reduce the transportation cost and consumption of railway transport enterprises, this paper studies the use of IMOQPSO to build a majorisation model for the design of RFTD2DT routes. The particle location updates and parameter settings are improved and optimised to solve the transport route design problem of railway transport enterprises. The outcomes displayed that the IMOQPSO had good convergence in solving the classical job shop scheduling combinatorial majorisation problem. When solving the problem of railway freight transport route planning, the GD index evaluation result of IMOQPSO was the best, with an average GD of 0.04 and 0.01, standard deviation of 0.12 and 0.14, an average IGD of 0.81 and 0.01 and the standard deviation of 0.07 and 0.06, which was obviously superior to IMOPPSO and other algorithms. The research results show that the use of IMOQPSO algorithm to solve the optimisation problem of door-to-door transportation route design of railway goods can effectively reduce the transportation time and cost of door-to-door transportation of railway goods, improve the comprehensive utilisation rate of transportation resources in the process of door-to-door transportation of railway goods and provide a reference for railway transportation route planning and decision-making. RFTD2DT is a complex transportation system involving the deployment of multiple transportation resources. The

research simplifies the door-to-door transportation process in the modelling process, mainly considering the impact of the departure and arrival stations on the route design. The next step is to refine the time estimation of each link, and comprehensively consider various transportation situations and transportation resources to improve the practicability of the route planning model.

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