

Original Paper

Synchronous Scheduling and Vehicle Optimization of In-Plant Parts Transport Under Bidirectional Loading-Unloading

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Abstract

Aiming at the bidirectional closed-loop transport scenario between the auto parts logistics center and the complete vehicle factory in the in-plant logistics of automobile original equipment manufacturers (OEMs), this paper constructs a synchronous scheduling optimization model for tractors and trailers with hard time windows, to address the problems of long vehicle waiting time, low utilization rate and high operating cost in the traditional integrated transport mode. The model takes the completion of daily transport tasks as the hard constraint, takes the minimization of the total daily operating cost of tractors and trailers as the optimization objective, and fully considers the decoupling operation characteristics of tractors and trailers in bidirectional loading and unloading operations. Aiming at the NP-hard property of the model, a Tabu Search algorithm adapted to the two-point bidirectional scenario is designed. The feasibility verification of the solution is implemented through event-driven simulation based on greedy strategy, and global optimization is realized by combining neighborhood search rules, tabu list and aspiration criterion. Finally, a numerical example analysis is carried out with the actual operation data of an automobile OEM. The results show that, under the scenario with a daily transport demand of 50 vehicle trips and an effective working time of 480 minutes, the model and algorithm proposed in this paper can quickly obtain the optimal vehicle configuration scheme. Compared with the traditional integrated truck transport mode, the proposed method reduces the operating cost by 38.07% and increases the tractor utilization rate by more than 80.66%, which verifies the correctness of the model and the effectiveness of the algorithm.

Keywords

In-plant Transport of Automotive Parts, Bidirectional Drop-and-Pull Transport, Synchronous Scheduling, Tabu Search, Vehicle Configuration Optimization

1. Introduction

With the comprehensive popularization of the Just-in-Time (JIT) production mode in the automotive manufacturing industry, OEMs have put forward higher requirements for the punctuality, low cost and flexibility of in-plant parts logistics. As the core link connecting the parts logistics center and the final assembly workshop of complete vehicles, in-plant parts transportation directly determines the production continuity of the assembly line and the manufacturing cost of complete vehicles. In the traditional integrated truck transport mode, vehicles and drivers need to wait throughout the loading and unloading process, resulting in a low proportion of effective driving time, insufficient equipment utilization, and redundant labor and equipment costs, which have been difficult to adapt to the large-volume and high-frequency in-plant transport demand of automobile OEMs.

As the core theory of lean production in the automotive industry, the essence of JIT application in in-plant transportation is to realize the coordination between transport rhythm and production rhythm, which is the core goal of transport balance in bidirectional loading and unloading scenarios. Daniel T. Jones et al. clearly stated in the lean production theory that in-plant material handling must meet the principles of on-time, on-quantity and on-sequence, and pointed out that unbalanced transportation is the core obstacle to the implementation of JIT^[1]. Liu Mingzhou constructed a dynamic JIT distribution system based on RFID technology, and dynamically adjusted transport instructions through real-time data collection to alleviate transport imbalance caused by demand fluctuations^[2]. Zhou Binghai proposed a static semi-set feeding strategy for mixed-flow assembly lines^[3]. Liu Xiangzheng integrated lean logistics into the in-plant operation of parts, and pointed out that path standardization and solidified loading and unloading processes are the keys to transport balance^[4].

Drop-and-pull transportation realizes parallel loading/unloading and driving through the decoupled operation of tractors and trailers, which is the core technology to solve the problems of long waiting time and low utilization rate in in-plant transportation. Its scheduling strategy directly determines the transport efficiency and balance of bidirectional loading and unloading scenarios. Scheuerer S proposed a two-stage solution method combining heuristic algorithm and Tabu Search for the trailer transport routing problem, providing a basic algorithm framework for drop-and-pull scheduling^[5]. Parragh S N and Cordeau J F studied the trailer routing problem with time windows, and designed a large neighborhood search algorithm to improve the solution accuracy. Their time window relaxation strategy can reduce transport fluctuations caused by loading and unloading overtime^[6]. Bartolini E and Schneider M established a bidirectional drop-and-pull model with capacity constraints, providing a theoretical basis for scenario adaptation of in-plant bidirectional loading and unloading^[7]. Liang Bo took the in-plant transportation of a steel plant as a case, and adopted Tabu Search algorithm to optimize the circular drop-and-pull path, verifying the efficiency advantage of drop-and-pull transportation^[8]. Hu Zeng et al. focused on the in-plant transportation of large manufacturing enterprises, constructed a synchronous scheduling model of tractors, empty trailers and loaded trailers, and solved it by combining Tabu Search and greedy strategy, providing core ideas for the coordination

of loading/unloading and transportation in bidirectional loading and unloading^[9]. Yang Zhenhua et al. proposed a dynamic drop-and-pull scheduling model for the uncertainty of loading and unloading time, which improved the scenario adaptability^[10]. Zhou Yushuang et al. constructed a quantity allocation model of tractors and trailers, providing an algorithm reference for vehicle allocation optimization^[11]. Most drop-and-pull transport studies concentrate on cross-regional routing, neglecting vehicle allocation and synchronous scheduling for in-plant two-point bidirectional closed-loop scenarios. They rarely consider tractor-trailer decoupling timing under hard time windows, and existing algorithms suffer from low feasibility-verification efficiency for large-scale in-plant transport. This paper builds a hard-time-window tractor-trailer scheduling model minimizing total costs, develops an improved Tabu Search with event-driven simulation, and verifies its performance via an OEM case.

2. Problem Description and Mathematical Model Construction

2.1 Problem Description

The research object of this paper is the bidirectional closed-loop drop-and-pull transportation scenario of two core nodes in an automobile OEM: Node A is the auto parts logistics center, and Node B is the complete vehicle assembly plant. The transport demand is divided into two categories: one is forward transport, which transports trailers fully loaded with parts from point A to point B to meet the production demand of the assembly workshop; the other is reverse transport, which transports trailers fully loaded with empty workstation fixtures from point B back to point A to complete the recycling of workstation fixtures. The two types of transport demand are bidirectionally symmetrical.

A single complete cycle of a tractor is divided into two starting scenarios as shown in Figure 1, and the core logic is “decouple and go immediately, cycle without waiting”:

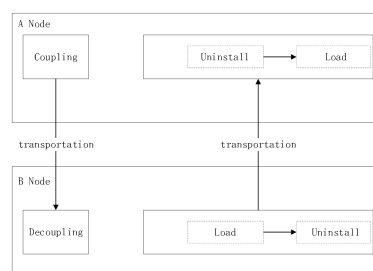


Figure 1 Circular Drop-and-pull Operation Process under Bidirectional Loading and Unloading Scenarios

2.2 Model Assumptions

To ensure the rationality and solvability of the model, combined with the actual scenario of in-plant transportation, the following assumptions are proposed:

- (1) At the initial moment ($t=0$), there are idle tractors on standby at both points A and B, and available trailers that have completed loading and unloading operations, meeting the start-up demand of the first

day;

- (2) All transport tasks are subject to hard time window constraints and must be completed within the daily effective working time without delay;
- (3) All operation times are fixed without fluctuation, and additional time losses such as vehicle failures, road congestion, and driver breaks are not considered;
- (4) The coupling and decoupling operations of tractors and trailers are completed serially, and neither can perform other tasks during the operation;
- (5) The trailer loading and unloading operation is a fixed serial process: after arriving at point A, first unload empty workstation fixtures, then load parts; after arriving at point B, first unload parts, then load empty workstation fixtures. The whole loading and unloading process is completely decoupled from the tractor.

2.3 Model Parameters and Decision Variables

Parameter Symbol	Parameter Meaning	Unit
Q	Daily total transport demand of parts from A to B	trips/day
T_{total}	Daily effective working time	minutes
t_{on}	Single coupling operation time	minutes
t_{off}	Single decoupling operation time	minutes
t_{run}	One-way transport time between points A and B	minutes
t_{oper}	Total loading and unloading operation time of a trailer at a single node	minutes
$t_{\text{cycle_tractor}}$	Single round-trip cycle time of a tractor without waiting	minutes
c_1	Daily usage cost per tractor	yuan/vehicle·day
c_2	Daily usage cost per trailer	yuan/vehicle·day
$K_{\text{min}}, K_{\text{max}}$	Upper and lower limits of the number of tractors	vehicles
$M_{\text{min}}, M_{\text{max}}$	Upper and lower limits of the number of trailers	vehicles

2.4 Mathematical Model Formulation

Taking the minimum total operating cost for completing daily transport tasks as the core objective, the function expression is:

$$\min Z = c_1 \cdot K + c_2 \cdot M + c_3 \cdot 2L \cdot Q$$

The total driving cost of tractors, with the total driving mileage of $2L \cdot Q$ for completing Q bidirectional

transport trips, is a constant term, which can be simplified and ignored when optimizing vehicle allocation. The objective function can be simplified as:

$$\min Z = c_1 \cdot K + c_2 \cdot M \quad (1)$$

$$\sum_{k=1}^K \sum_{t=0}^{T_{\text{total}}} \sum_{m=1}^M z_{k,m,t,0} \geq Q, \quad \sum_{k=1}^K \sum_{t=0}^{T_{\text{total}}} \sum_{m=1}^M z_{k,m,t,1} \geq Q \quad (2)$$

$$N_{\text{tractor_max}} = \left\lfloor \frac{T_{\text{total}}}{2t_{\text{on}} + 2t_{\text{off}} + 2t_{\text{run}}} \right\rfloor \quad (3)$$

$$K \cdot N_{\text{tractor_max}} \geq Q \quad (4)$$

$$W_k \leq 0.05 \cdot T_{\text{total}}, \quad \forall k \in \{1, 2, \dots, K\} \quad (5)$$

$$\sum_{t=0}^{T_{\text{total}}} x_{k,t} + W_k = T_{\text{total}}, \quad \forall k \in \{1, 2, \dots, K\} \quad (6)$$

$$N_{\text{trailer_max}} = \left\lfloor \frac{T_{\text{total}}}{2t_{\text{on}} + 2t_{\text{off}} + 2t_{\text{run}} + 2t_{\text{oper}}} \right\rfloor \quad (7)$$

$$M \cdot N_{\text{trailer_max}} \geq Q \quad (8)$$

$$t + t_{\text{on}} + t_{\text{run}} + t_{\text{off}} + t_{\text{oper}} \leq T_{\text{total}}, \quad \forall z_{k,m,t,0} = 1 \quad (9)$$

$$t + t_{\text{on}} + t_{\text{run}} + t_{\text{off}} + t_{\text{oper}} \leq T_{\text{total}}, \quad \forall z_{k,m,t,1} = 1 \quad (10)$$

$$\sum_{m=1}^M \sum_{d=0}^1 z_{k,m,t,d} \leq 1, \quad \forall k \in \{1, 2, \dots, K\}, \forall t \in [0, T_{\text{total}}] \quad (11)$$

$$\sum_{k=1}^K \sum_{d=0}^1 z_{k,m,t,d} \leq 1, \quad \forall m \in \{1, 2, \dots, M\}, \forall t \in [0, T_{\text{total}}] \quad (12)$$

$$y_{m,tA} + y_{m,tB} + \sum_{k=1}^K \sum_{d=0}^1 z_{k,m,t,d} \leq 1, \quad \forall m \in \{1, 2, \dots, M\}, \forall t \in [0, T_{\text{total}}] \quad (13)$$

$$K, M \in \mathbb{N}^+, x_{k,t}, y_{m,tA}, y_{m,tB}, z_{k,m,t,d} \in \{0, 1\}, W_k \geq 0, \quad \forall k \in \{1, 2, \dots, K\} \quad (14)$$

3. Algorithm Design

Aiming at the two-point bidirectional closed-loop drop-and-pull transportation scenario between the logistics center and the complete vehicle plant, this paper takes the quantity allocation of tractors and trailers as the optimization core, takes completing the daily transport volume as the hard constraint and minimizing the total operating cost as the objective, and constructs a tractor-trailer synchronous scheduling model with hard time windows. This problem belongs to the constrained integer combinatorial optimization problem with NP-hard property, and traditional exact algorithms are

difficult to solve large-scale numerical examples within a reasonable time. Therefore, this paper adopts the Tabu Search (TS) algorithm for solution. This algorithm expands the solution space through neighborhood search, combines a tabu list to avoid cyclic search and local optimum, and ensures global convergence through aspiration criteria, which can efficiently adapt to the synchronous scheduling demand of in-plant drop-and-pull transportation.

3.1 Solution Encoding Design

This paper takes the total number of tractors allocated and the total number of trailers allocated as the core optimization variables. In view of the scenario characteristics of two-point bidirectional drop-and-pull, a two-dimensional integer vector is used to complete the solution encoding, and the encoding form is: $X=[K,M]$

Where K is the number of tractors allocated, and M is the number of trailers allocated, both are positive integers. Each set of encoding $[K,M]$ corresponds to a tractor-trailer allocation scheme. The optimization objective of the algorithm is to find the encoding vector with the minimum total cost that meets the hard constraints in the feasible solution space. This encoding method is highly matched with the optimization objective of this paper, with low encoding dimension and high search efficiency, which can directly map the vehicle allocation decision of drop-and-pull transportation, and is convenient for subsequent neighborhood operations and feasibility verification.

3.2 Feasibility Verification and Decoding of Solutions Based on Greedy Strategy

For any encoded solution $X=[K,M]$, it is necessary to verify whether it can complete the specified daily transport demand Q within the daily effective working time T_{total} . Referring to the vehicle selection strategy based on greedy algorithm [9], combined with the event-driven simulation mechanism, this paper completes the feasibility verification of the solution and the decoding of operation sequence.

3.2.1 Definition of Vehicle State Sets

Referring to the definition of vehicle position sets in existing research, combined with the operation characteristics of bidirectional drop-and-pull, two types of vehicle state sets are defined:

Tractor state set:

$$Q = \{(k, loc, status) | k \leq K, loc \in \{A, B\}, status \in \{idle, coupling, transporting, decoupling\}\}$$

Where (k,loc,status) represents tractor numbered k, currently located at node loc (A for logistics center, B for complete vehicle plant), with operation status as status.

Trailer state set:

$$P = \left\{ (m, loc, status) | m \leq M, loc \in \{A, B\}, status \in \{idle_available, coupling, transporting, decoupling, loading_unloading\} \right\}$$

Where (m,loc,status) represents trailer numbered m, currently located at node loc, with operation status as status; idle_available means the trailer has completed loading and unloading operations and is in an available state for coupling.

3.2.2 Greedy Vehicle Matching Strategy

To meet the core requirement of "tractors operate in cycles as much as possible, trailers can stop and wait", a greedy matching strategy of "first come first matched, tractor no-wait priority" is designed:

- (1) For idle tractors at node loc, priority is given to matching trailers in idle_available state at the same node to maximize tractor utilization;
- (2) Point A (logistics center) prioritizes the execution of fully loaded parts transport (A→B) tasks, and point B (complete vehicle plant) prioritizes the execution of empty workstation fixture return transport (B→A) tasks, to ensure the bidirectional closed-loop and supply-demand matching of transport tasks;
- (3) After the trailer arrives at the destination, it immediately performs serial loading and unloading operations. During loading and unloading, the tractor does not need to wait. After decoupling, the tractor can immediately participate in new matching tasks, realizing the decoupled synchronous scheduling of tractors and trailers.

3.2.3 Event-Driven Simulation Verification Process

Based on the above state sets and matching strategy, event-driven simulation is used to verify the feasibility of the solution. The core process is:

1. Initialization: At $t=0$, K tractors and M trailers are allocated to nodes A and B according to the bidirectional balance principle, with initial states of idle/available. The initial coupling matching event is triggered and added to the event priority queue;
2. Event cycle processing: Process five core events in chronological order: coupling start, coupling end, transport arrival, decoupling end, and loading/unloading completion. Synchronously update vehicle status, complete trip counting, and generate new events;
3. Termination judgment: If the completed trip count $\geq Q$ and the current time $t \leq T_{\text{total}}$, the solution is determined to be a feasible solution; if the event queue is empty and no new tasks can be triggered, or $t > T_{\text{total}}$ and the transport volume has not been completed yet, the solution is determined to be an infeasible solution.

3.3 Initial Solution Generation

To ensure that the initial solution of the algorithm iteration is a feasible solution and improve the convergence efficiency of the algorithm, combined with the cycle period characteristics of bidirectional drop-and-pull, an initial solution generation method is designed. The steps are as follows:

- (1) Calculate the single round-trip cycle period of a tractor without waiting:

$$t_{\text{cycle_tractor}} = 2t_{\text{on}} + 2t_{\text{off}} + 2t_{\text{run}}$$

Where t_{on} is the single coupling time, t_{off} is the single decoupling time, and t_{run} is the one-way transport time between the two points;

- (2) Calculate the theoretical minimum number of tractors:

$$K_0 = \left\lceil \frac{Q \cdot t_{\text{cycle_tractor}}}{T_{\text{total}}} \right\rceil$$

- (3) Perform feasibility verification on the theoretical initial solution $[K_0, M_0]$. If it is not feasible, modify it in the order of "first increase the number of trailers, then increase the number of tractors" until a feasible initial solution $x_0 = [K_0, M_0]$ is obtained;
- (4) Determine the search range of the solution: $K \in [1, 2K_0]$, $M \in [1, 2M_0]$, and further improve the algorithm efficiency by limiting the search space.

3.4 Neighborhood Search Rules

Neighborhood search is the core of the Tabu Search algorithm. In view of the characteristics of two-dimensional integer encoding, this paper designs four basic neighborhood operations to generate candidate solutions, and combines the operation constraints of drop-and-pull transportation to design neighborhood solution filtering rules to avoid generating invalid solutions.

3.4.1 Neighborhood Operation Design

For the current iterative solution $x_{\text{current}} = [K_c, M_c]$, the neighborhood solution set $N(x_{\text{current}})$ is generated through the following four operations:

1. Increase the number of tractors by 1: $x_1 = [K_c + 1, M_c]$, which must satisfy $K_c + 1 \leq K_{\max}$;
2. Decrease the number of tractors by 1: $x_2 = [K_c - 1, M_c]$, which must satisfy $K_c - 1 \leq K_{\min}$;
3. Increase the number of trailers by 1: $x_3 = [K_c, M_c + 1]$, which must satisfy $M_c + 1 \leq M_{\max}$;
4. Decrease the number of trailers by 1: $x_4 = [K_c, M_c - 1]$, which must satisfy $M_c - 1 \leq M_{\min}$.

3.5 Solution Evaluation Function

Taking the minimum total operating cost for completing transport tasks as the core objective, this paper designs the solution evaluation function as follows [9]:

$$f(x) = Z + h \cdot p$$

Definition of each parameter in the formula:

- (1) $X = [K, M]$ is the encoded solution to be evaluated;
- (2) Z is the total operating cost;
- (3) h is the single penalty value, which takes a positive number much larger than the unit cost of vehicles, ensuring that infeasible solutions are preferentially eliminated in the iteration;
- (4) p is the infeasible penalty term. If solution x cannot complete the transport task within the specified time, $p = 1$; if solution x is a feasible solution, $p = 0$.

3.6 Tabu List Design

This paper adopts a fixed-length First-In-First-Out (FIFO) tabu list, and the tabu objects are the complete encoded solutions $x = [K, M]$ that have been searched. The tabu length L is set to 7. The core function of the tabu list is to prohibit the algorithm from repeatedly searching the same solution within the tabu length, avoiding cyclic search and local optimum traps.

3.7 Algorithm Termination Conditions

Dual termination conditions are set, and the iteration stops when either condition is met:

- (1) The number of iterations reaches the preset maximum iteration number of 100;
- (2) The global optimal solution has not been updated for 20 consecutive iterations, which means the algorithm has converged to the global optimum.

3.8 Overall Execution Flow of the Algorithm

The complete execution steps of the Tabu Search algorithm designed in this paper are as follows: Input scenario parameters, cost parameters and algorithm control parameters, and generate a feasible initial solution x_0 ; Initialize algorithm variables: current solution $x_{\text{current}} = x_0$, global optimal solution $x_{\text{best}} = x_0$, add the initial solution to the tabu list, set the iteration counter and no-improvement counter to 0; Enter the main iteration loop, perform neighborhood operations on the current solution, and generate a neighborhood solution set; Perform feasibility verification on all neighborhood solutions, and calculate the fitness value through the evaluation function; According to the tabu rules and aspiration criteria, screen out the current solution x_{next} for the next iteration; Update the current solution and the global optimal solution, add the new solution to the tabu list, and synchronously update the counters; Judge whether the termination conditions are met. If yes, stop the iteration and output the global optimal solution and the minimum total cost; if not, return to step 3 to continue the iteration.

4. Numerical Example Analysis

4.1 Example Description

To verify the feasibility of the mathematical model and algorithm proposed above, this paper conducts data collection and analysis based on the actual in-plant transport data of a domestic automobile OEM as the numerical example. The complete vehicle plant of the enterprise is about 2 kilometers away from the eastern logistics center, connected by an underground passage, and the whole is regarded as a closed park. The eastern logistics center is responsible for the storage and distribution of transit parts for the complete vehicle plant; the complete vehicle plant requires high-frequency and small-batch transportation of parts to the assembly line.

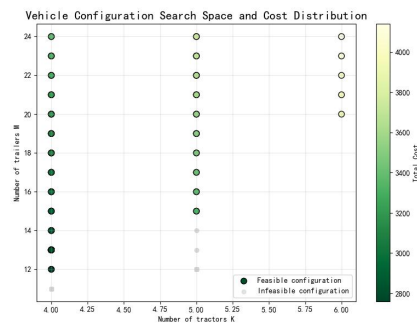
At present, there are 11 winged van trucks for transit parts distribution in the park, and the unit transport cost is high due to long waiting time at loading and unloading points and low vehicle utilization. It is planned to adopt drop-and-pull transportation mode in the plant and optimize the quantity allocation of tractors and trailers to complete all tasks at the lowest cost. The daily parts transport demand $Q=50$ trips, daily effective working time $T_{\text{total}}=480$ minutes; daily usage cost per tractor $c_1=390$ yuan/vehicle, daily usage cost per trailer $c_2=50$ yuan/vehicle. The average operation time parameters of each step are shown in Table 1:

Table 1. Average Operation Time of each Step (unit: minutes)

Procedure	Coupling	Decoupling	One-way transport	Single-node loading/unloading
Time	5	5	6	30

4.2 Calculation Results

In the Tabu Search solution part, this paper sets the tabu length to 7, and the termination conditions are the maximum iteration number of 100 and the continuous no-improvement termination number of 50. Using Python software for simulation calculation, the optimal quantity allocation of tractors and trailers is obtained, as shown in Figure 2 and Table 2.

**Figure 2. Vehicle Allocation Search Space and Cost Distribution****Table 2. Optimal Vehicle Allocation and Cost Results**

Optimization Indicator	Value
Optimal number of tractors	4 vehicles
Optimal number of trailers	12 vehicles
Minimum daily total operating cost	2160 yuan
Daily completed trips	52 trips
Average waiting time of tractors	12.8 minutes

Calculations show one tractor can finish 15 round trips in 480 min; four tractors yield 60 trips to meet the 50-trip demand. Twelve trailers achieve a 1:3 tractor-trailer matching. Tractor waiting time accounts for merely 2.67% of working time, greatly boosting vehicle utilization.

4.3 Algorithm Convergence Analysis

The iterative convergence curve of the algorithm in this paper is shown in Figure 3. It can be seen from the figure that the algorithm has converged to the global optimal solution at the 12th iteration, and no better solution appears in subsequent iterations, indicating that the Tabu Search algorithm designed in

this paper has fast convergence speed and strong global search ability, and can efficiently solve the vehicle allocation optimization problem in this scenario.

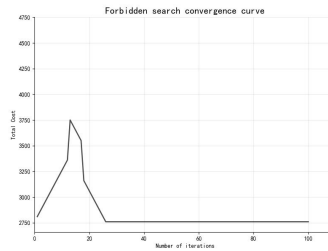


Figure 3. Tabu Search Convergence Curve

4.4 Comparison with Traditional Transport Mode

To verify the optimization effect of the drop-and-pull transport mode, the optimal scheme of this paper is compared with the winged van truck transport mode, and the results are shown in Table 3.

Table 3. Comparison between Drop-and-pull Transportation and Traditional Transport Mode

Comparison Indicator	Winged van truck transport	Drop-and-pull transport mode
Total number of vehicles required	11 trucks	4 tractors + 12 trailers
Daily total operating cost	3488 yuan	2160 yuan
Maximum daily round trips per vehicle	7 times	15 times
Proportion of effective driving time	16.67%	97.33%
Vehicle waiting time	60 minutes/vehicle	12.8 minutes/vehicle

5. Research Conclusions

Aiming at the bidirectional loading and unloading drop-and-pull transportation scenario between the auto parts logistics center and the complete vehicle plant of automobile OEMs, this paper constructs a tractor-trailer synchronous scheduling optimization model with hard time windows, designs a Tabu Search algorithm adapted to this scenario for solution, and verifies the effectiveness of the model and algorithm through practical numerical examples. The main research conclusions are as follows:

The model constructed in this paper fully considers the decoupled operation characteristics of tractors and trailers in bidirectional loading and unloading scenarios, can accurately describe the operation process and core constraints of in-plant drop-and-pull transportation, and provides a theoretical model for vehicle allocation optimization of in-plant drop-and-pull transportation in automobile OEMs. The designed Tabu Search algorithm verifies the feasibility of the solution through event-driven simulation,

optimizes the neighborhood search rules and tabu rules, has fast convergence speed and strong global search ability, and can efficiently solve the combinatorial optimization problem in this scenario.

The actual numerical example results show that under the scenario of 50 daily transport trips and 480 minutes of working time, the optimal vehicle allocation is 4 tractors + 12 trailers. Compared with the traditional integrated truck transport mode, it can save 38.07% of operating costs and increase the proportion of effective driving time of tractors by more than 80.66%, verifying the significant advantages of the drop-and-pull transport mode in the in-plant transportation of automotive parts.

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