RESEARCH ON VEHICLE SCHEDULING AND ROUTE OPTIMIZATION FOR URBAN-RURAL INTEGRATED LOGISTICS DISTRIBUTION

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Abstract - With the increasing demand of logistics demand between urban and rural areas, research on logistics distribution has become increasingly essential. This article focuses on the logistics distribution network that combines urban and rural areas. For the problem of vehicle scheduling and path optimization, three objective functions were proposed: customer satisfaction, total distribution cost, and vehicle loading rate. Then, an improved non-dominated sorting genetic algorithm II (NSGA2) was developed for solving, and experiments were conducted on the simulation example. The results demonstrated that the improved NSGA2 solved the simulation example well. After dispatching three vehicles, the customer satisfaction level and vehicle loading rate of the obtained route were both above 0.8, and the total distribution cost was 1,928.61 yuan, which was reduced by 4.08% compared with the total cost obtained by the NSGA2. The results verify the effectiveness of the proposed method. These findings demonstrate the effectiveness of the method proposed in this paper and its potential application in practical urban-rural integrated logistics.

Keywords: Urban-rural integration, Logistics distribution, Vehicle scheduling, Route optimization, Genetic algorithm.

1. Introduction

Under the influence of urban-rural integration, the traffic between urban and rural areas is integrated [1], and economic exchanges have become more frequent. Moreover, the rapid development of e-commerce [2] has led to the progress of rural logistics [3] and also provided more convenient conditions for the exchange of various kinds of goods and commodities in urban and rural areas. Cities have a demand for agricultural products such as vegetables and fruits from rural areas, while rural areas have a demand for industrial products such as farming tools and daily chemicals from cities. The continuously expanding logistics demands from both sides are presenting some new requirements to logistics distribution companies [4]. At present, the urban and rural logistics network needs to be further improved, and the government has also provided encouragement and support in the construction of urban and rural logistics. However, the existing urban and rural logistics mostly adopt the one-way distribution mode. The form of urban-rural joint distribution is still less, and the demand for urban and rural logistics has not been effectively integrated. In the process of logistics distribution, the number of vehicles scheduled, and the choice of routes determine the cost [5]. Vehicle scheduling and route optimization refer to the rational scheduling of vehicles of logistics enterprises and the optimization of distribution routes, which can reduce costs and improve efficiency [6]. It is a hot issue in the current research on logistics distribution [7]. Piao et al. [8] employed an optimized ant colony optimization algorithm to solve the logistics distribution route. Through experiments, it was found that this method has good performance and can find a shorter route. Cai [9] put forward a heuristic elastic particle swarm optimization (EPSO) algorithm in the route planning of logistics transport vehicles. Compared with the genetic algorithm and PSO algorithm, it was found that this algorithm can obtain the global optimal path faster and has better efficiency. Aiming at the vehicle routing problem in cold chain logistics, Liu et al. [10] built a model combined with carbon transaction cost and solved it by the simulated annealing (SA) algorithm. They found that the total distribution cost was positively correlated with carbon price. Wang et al. [11] proposed a multi-commodity flow optimization model based on fairness for the route optimization problem in food and beverage distribution services, solved it by using the dynamic programming algorithm, and verified the performance of the method through tests on multiple networks. In this paper, vehicle scheduling and route optimization models were established for urban-rural integrated logistics distribution, and an improved non-dominated sorting genetic algorithm II (NSGA2) was developed to solve the models. The effectiveness of the proposed models and the solution algorithm was verified through the analysis of an example. When applied to the actual urban-rural integrated logistics distribution, the algorithm can make some contributions in terms of cost saving and efficiency improvement to promote better and faster development of urban and rural logistics.

2. Urban-rural Integrated Logistics Distribution Problem

2.1 Urban and Rural Logistics Analysis

Urban development relies heavily on industrial production, and agricultural products in urban areas are highly dependent on external inflows and are in high demand [12]. On the other hand, rural development is centered around agricultural activities, with outputs of agricultural products and by-products. However, rural areas lack conditions for producing industrial products such as agricultural tools and daily chemicals. As a result, there is a significant demand in rural areas for urban industrial products. This creates a mutually dependent two-way logistics demand between urban and rural areas.

Currently, urban and rural logistics primarily rely on unidirectional transportation. This means that industrial products are transported to rural terminal outlets for distribution through self-owned fleets or third-party logistics companies or self-pickup by consumers. Similarly, agricultural products are transported to city supermarkets using self-owned fleets or third-party logistics companies to facilitate the entry of agricultural products into the city. In this one-way logistics approach, the transportation of industrial and farming products is separate, leading to a high empty rate of logistics and distribution vehicles [13]. This unidirectional system fails to achieve simultaneous, two-way circulation of industrial and agricultural products, resulting in high logistics costs and low logistics efficiency. Consequently, it is increasingly unable to meet the growing demands of urban and rural logistics.

2.2 Urban-Rural Integrated Logistics Distribution

Urban-rural integrated logistics distribution refers to simultaneous pickup and delivery to urban and rural customers under the condition of considering the two-way logistics demand in urban and rural areas, thus reducing the cost in urban and rural logistics distribution. In the urban-rural logistics network, urban and rural logistics' starting and ending points overlap in both directions. Therefore, it is very feasible to adopt the urban-rural integrated logistics distribution method, which has the following advantages.

(1) Improve the efficiency of logistics distribution

Implementing two-way logistics distribution that combines urban and rural areas can effectively integrate distribution resources, consolidate urban and rural distribution demands, and streamline processing, thereby improving distribution efficiency.

(2) Reduce logistics distribution costs

By employing the two-way logistics distribution method, the empty-loading ratio of vehicles can be reduced, preventing wastage caused by vehicle returns or empty loads and reducing unit costs.

(3) Create social benefits

Implementing the two-way logistics distribution method facilitates better planning for logistics distribution services, minimizing resource wastage and environmental pollution, and create social benefits.

3. Vehicle Scheduling and Path Optimization Model

This paper focus on addressing the problem of vehicle scheduling and path optimization for urban-rural integrated logistics. The issue involves a distribution center and multiple urban and rural nodes. The distribution process is illustrated in Figure 1.

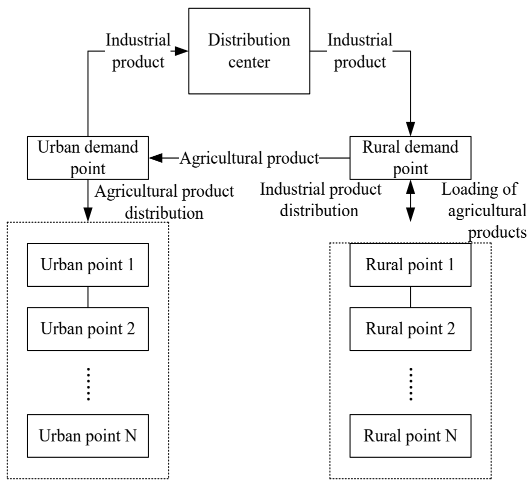

Figure 1: Distribution process

As shown in Figure 1, the distribution center sends vehicles to the rural demand point, distributes industrial products to each rural node, loads agricultural products needed in the city, distribute farm products to the urban demand point, and returns to the distribution center. In the modeling, this paper makes the following assumptions.

(1) The demand for agricultural and industrial products at urban and rural demand points is known. The industrial product inventory at the distribution center and the agricultural product inventory in rural areas can both meet the needs of both parties.

(2) The location of each node is known.

(3) Industrial and agricultural products can be delivered in the same vehicle.

(4) Penalty costs will incur if vehicles arrive later than the time window.

The parameters required for modeling are listed in Table 1.

Table 1. Model parameters

Parameter	Definition
$I = \{i \mid i = 1,2,\cdots,m\}$	Rural demand point set
$J = \{j \mid j = 1,2,\cdots,n\}$	Urban demand point set
$V = \{v \mid v = 1,2,\cdots,k\}$	Distribution center vehicle set
$G = \{0,1,2,\cdots,m,m+1,\cdots,m+n\}$	The set of all nodes, where 0 refers to the distribution center.
$d_{a,b}$	The distance between point a and b
D_v	Maximum distance traveled per vehicle
q_i	Demand quantity of industrial goods in point i
q_j	Demand quantity of agricultural products in point j
p_i	Agricultural product load quantity of point i
P_i	Agricultural product supply quantity of point i
Q_v	Maximum cargo capacity per vehicle
C_0	Fixed cost per vehicle
C_1	Unit transportation cost per vehicle
β_1	Unit waiting cost
β_2	Unit penalty cost
t_a	Time consumed by the vehicle arriving at a
$[E_a, L_a]$	The time window of point a
W_0	The load of the vehicle leaving the distribution center: $W_0 = \sum_{i=0}^{m}\sum_{j=1}^{m} q_j X_{ijv}$
W_i	The load of the vehicle leaving demand point i
Y_{av}	1: the distribution of point a is delivered by vehicle v; 0: else
X_{abv}	1: the vehicle drives from point a to point b directly; 0: else

In terms of the objective function, the following three aspects are considered in this paper.

(1) Customer satisfaction

In logistics distribution, it is important to meet the time window requested by customers as much as possible. The satisfaction degree is taken as 1 if the vehicle arrives earlier than the time window and as 0 if it arrives later than the time window. The satisfaction degree decreases gradually within the time window. The objective function obtained is:

$$MaxH_1 = max \sum_{a=1}^{m+n} S(t_a), \quad (1)$$

$$S(t_a) = \begin{cases} 1, t_a \le E_a \\ (L_a - t_a)/(L_a - E_a), E_a < t_a \le L_a \\ 0, t_a > L_a \end{cases}. \quad (2)$$

(2) Total distribution cost

In the logistics distribution process, the costs involved include transportation costs per vehicle, fixed costs, and waiting or penalty costs incurred earlier or later than the time window. The following objective function is obtained:

$$MinH_2 = min[C_1(\sum_{v=1}^{k} D_k) + kC_0 + \beta_1 \sum_{a=1}^{m+n} max(E_a - t_a, 0) + \beta_2 \sum_{a=1}^{m+n} max(t_a - L_a, 0)] \quad (3)$$

$$D_k = \sum_{v=1}^{k}\Big(\sum_{i=1}^{m} d_{0i} X_{0iv} + \sum_{a=1}^{m}\sum_{b=1}^{m} d_{ab} X_{abv} + \sum_{a=1}^{m}\sum_{b=m+1}^{m+n} d_{ab} X_{abv} + \sum_{a=m+1}^{m+n}\sum_{b=m+1}^{m+n} d_{ab} X_{abv} + \sum_{j=m+1}^{m+n} d_{j0} X_{j0v}\Big)$$
(4)

(3) Vehicle loading rate

In the process of logistics distribution, a longer the time of loading goods in the total trip of vehicle transportation means a higher vehicle loading rate and a higher utilization rate of the vehicle. The objective function is:

$$MaxH_3 = max\left\{\left(1 - \frac{\sum_{v=1}^{k}\sum_{j=m+1}^{m+n} d_{j0} X_{j0v}}{D}\right) \times 100\%\right\}. \quad (5)$$

The relevant constraints for the above three objective functions are listed in Table 2.

Table 2. Model constraints

Restrictive condition	Hidden meaning
$\sum_{i=1}^{m} P_i \geq \sum_{j=m+n}^{m+n} q_j$	Supply at rural nodes can meet the demand of urban nodes.
$\sum_{v=1}^{k} Y_{av} = 1$ $\sum_{a=0}^{m+n} X_{abv} = Y_{bv}$ $\sum_{a=0}^{m+n} X_{abv} = Y_{av}$	Each node and each path is served by one and only one vehicle
$\sum_{a=1}^{m+n} X_{0av} = \sum_{a=1}^{m+n} X_{a0v} = 1$	Vehicles' starting and end points are both distribution centers.
$Q_v \geq W_i \geq W_0 - q_i + p_i - M \times X_{0iv}$ $Q_v \geq W_j \geq W_i - q_i + q_j - M \times \sum_{v=1}^{k} X_{ijv}$ $W_0 \leq Q_v$	Vehicles cannot be overweight during distribution
$\sum_{i=1}^{m} X_{0iv} = \sum_{i=1}^{m}\sum_{j=1}^{m} X_{ijv} = \sum_{j=m+1}^{m+n} X_{j0v} = 1$ $\sum_{i=1}^{m} X_{0iv} = \sum_{j=m+1}^{m+n} X_{0jv} = \sum_{j=m+1}^{m}\sum_{i=1}^{m} X_{jiv} = 0$	The distribution route is distribution center → rural demand point → urban demand point → distribution center.
$D_k \leq D_v$	Each vehicle cannot travel more than its maximum driving distance.

4. Solution Algorithm Based on Improved NSGA2

The model established above is a multi-objective problem, which can be transformed into a single-objective problem, and then a suitable intelligent algorithm can be chosen to solve it. However, this method is easy to fall into the local optimum. NSGA2 is an improvement of the NSGA [14], which has the advantages of fewer parameters, higher solving speed, and higher accuracy [15] and has been widely and maturely used in multi-objective solving [16], so this paper uses the NSGA2 to solve the vehicle scheduling and path optimization model established above. Its basic process is as follows.

(1) A population is randomly initialized for non-dominated sorting, and the congestion distance is computed.

(2) Several non-dominated layers are selected, and individuals are selected based on congestion distances as the elite population.

(3) A new population is obtained by genetic manipulation.

(4) The above steps are repeated on the new population until the termination condition is met.

NSGA2 uses the congestion degree comparison operator to improve the diversity of non-inferior solutions, but this approach may lead to worse solution distribution. In order to obtain a better solution, this paper designs an improved NSGA2, which improves the calculation of the congestion degree distance. In the original NSGA2, the congestion degree distance is computed by the following formula:

$$I_i = \sum_{j=1}^{m}\left(\left|f_j^{i+1} - f_j^{i-1}\right|\right), \tag{6}$$

where f_j^{i+1} is the function value of the $i+1$-th point at the j-th objective. It is improved as:

$$I_i' = \frac{I_i}{\frac{1}{V_i} - 1}, \tag{7}$$

$$V_i = 1/r \sum_{i=1}^{r}\left(\left|f_j^{i+1} - f_j^{i-1}\right| - I_i\right)^2, \tag{8}$$

where V_i is the variance of the congestion degree distance of the individual near i at different dimensions.

5. Case Analysis

The improved NSGA2 was programmed and solved using MATLAB software. The population size was set to 100, the number of iterations was set to 300, and the crossover and mutation probabilities were set to 0.9 and 0.05, respectively. An arithmetic example was designed using simulated data to validate the algorithm due to the difficulty of obtaining actual data. The urban-rural integrated logistics distribution network was assumed to cover an area of 100 km × 100 km. This network consisted of one distribution center, seven rural nodes, and twenty urban nodes. The location of each node is depicted in Figure 2, and the attributes of each node are presented in Tables 3 and 4. Additionally, the other data required by the model were set, as shown in Table 5.

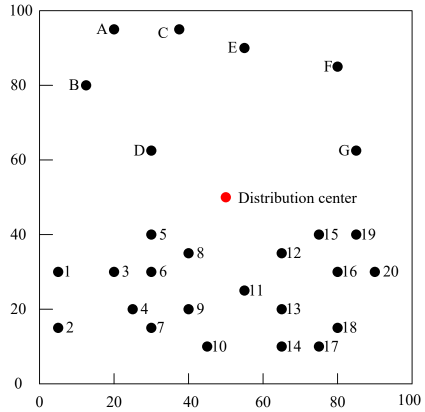

Figure 2: Location of each node

Table 3. Attributes of rural nodes

Rural node	q_i/t	P_i/t	$[E_a, L_a]$
A	850	1200	[5,145]
B	750	850	[10,140]
C	500	350	[0,120]
D	450	450	[15,120]
E	600	600	[20,120]
F	550	700	[10,140]
G	700	600	[15,140]

Table 4. Attributes of urban nodes

Rural node	Urban node	q_j/t	$[E_a, L_a]$
A	1	300	[90,120]
	4	600	[80,160]
	9	300	[70,110]
B	2	400	[65,180]
	5	450	[75,180]
C	3	100	[100,150]
	6	100	[90,120]
	7	100	[90,120]
	10	50	[120,180]
D	8	220	[60,140]
	20	230	[100,180]
E	11	200	[70,180]
	13	400	[60,170]
F	12	300	[70,180]
	16	100	[80,180]
	17	300	[70,160]
G	14	150	[60,140]
	15	100	[80,180]
	18	100	[40,120]
	19	250	[50,180]

Table 5. Other parameter settings of the model

Other parameters of the model	Value
Maximum distance traveled per vehicle D_v	600 km
Maximum cargo capacity per vehicle Q_v	3 t
Fixed cost per vehicle C_0	80 yuan
Unit transportation cost per vehicle C_1	3 yuan/km
Unit waiting cost β_1	20 yuan/h
Unit penalty cost β_2	20 yuan/h

Based on this example, 20 repetitions of calculation were performed, and the optimal result was taken. The vehicle scheduling and path are shown in Figure 3.

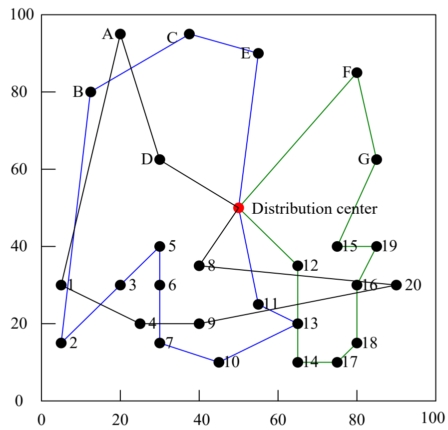

Figure 3: Solution results of the improved NSGA2

According to Figure 3, the vehicle scheduling and path optimization results obtained by the improved NSGA2 are as follows.

Vehicle 1: Distribution center → D → A → 1 → 4 → 9 → 20 → 8 → distribution center

Vehicle 2: Distribution center → E → C → B → 2 → 3 → 5 → 6 → 7 → 10 → 13 → 11 → distribution center

Vehicle 3: Distribution center → F → G → 15 → 19 → 16 → 18 → 17 → 14 → 12 → distribution center

In this example, the results obtained from the improved NSGA2 solution required scheduling three vehicles, each with individual objective values (Table 6).

Table 6. Results of the objective function

	Customer satisfaction	Total distribution cost	Vehicle loading rate
Vehicle 1	0.93	531.84	0.82
Vehicle 2	0.90	774.56	0.88
Vehicle 3	0.88	622.21	0.86

Based on the information in Table 6, the improved NSGA2 algorithm achieved a total distribution cost of 1,928.61 yuan for the three vehicles. The customer satisfaction level was above 0.85, indicating that the vehicle scheduling and routing arrangement can effectively meet the customer's time window requirements and reduce resource waste.

Using the same example, the improved NSGA2 was compared with other multi-objective solving algorithms, including:

(1) multi-objective genetic algorithm (MOGA) [17],

(2) NSGA [18],

(3) NSGA2.

The results are presented in Table 7.

Table 7. Comparison with other solving algorithms

	Vehicle scheduled	Customer satisfaction	Total distribution cost	Vehicle loading rate
MOGA	Vehicle 1	0.75	557.68	0.77
	Vehicle 2	0.76	562.58	0.76
	Vehicle 3	0.78	563.25	0.75
	Vehicle 4	0.86	425.32	0.77
	Vehicle 5	0.77	521.28	0.76
Total cost			2,630.11	
NSGA	Vehicle 1	0.81	557.18	0.80
	Vehicle 2	0.82	504.25	0.85
	Vehicle 3	0.83	551.25	0.82
	Vehicle 4	0.85	678.25	0.82
Total cost			2,290.93	
NSGA2	Vehicle 1	0.88	552.22	0.85
	Vehicle 2	0.85	646.25	0.85
	Vehicle 3	0.82	812.25	0.80
Total cost			2,010.72	
Improved NSGA2	Vehicle 1	0.93	531.84	0.82
	Vehicle 2	0.90	774.56	0.88
	Vehicle 3	0.88	622.21	0.86
Total cost			1,928.61	

Based on the information in Table 7, in the solution obtained by the MOGA, the dispatch of five vehicles was required, resulting in a high total distribution cost (2,630.11 yuan). The customer satisfaction level of vehicle 4 was the highest at 0.86, while the remaining vehicles had satisfaction levels below 0.8. The vehicle loading rate was also below 0.8. In the solution obtained by the NSGA, the dispatch of four vehicles was required, resulting in a total cost of 2,290.33 yuan. Customer satisfaction level and vehicle loading rate were improved compared to the MOGA solution. The NSGA2 and the improved NSGA2 solutions required only three vehicles to complete the delivery task. However, the improved NSGA2 achieved a higher customer satisfaction level and vehicle loading rate compared to the NSGA2. Additionally, the total cost was reduced by 4.08%, indicating the effectiveness of the improvement to the NSGA2.

6. Conclusions

In this paper, the research focuses on the problem of vehicle scheduling and path optimization in an urban-rural integrated logistics distribution network. A model was developed, and an improved NSGA2 was designed to solve it. The simulation example demonstrated that the improved NSGA2 performed better, resulting in a solution with a high customer satisfaction level, a high vehicle loading rate, and a low total distribution cost. These findings indicate that the proposed approach meets the practical requirements of logistics distribution and has the potential for further promotion and application in real-world scenarios.

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