Optimization for Bi-Objective Express Transportation Network Design

Jian Zhong*, Xu Wang and Xinrui Li

***Abstract*—With the rapid development of the courier industry, customers are placing higher demands on the cost and delivery time of courier services. Therefore, this paper based on the classical signal-allocation incomplete hub network design protocol to develop the optimization model for bi-objective express transportation network design problem (BO-ETNDP), which aims to minimize the operation cost and maximum arrival time. A novel bi-objective nonlinear mixed-integer optimization model for BO-ETNDP is developed considering the impact of the heterogeneous vehicles and the hub's sorting efficiency on the operation cost and arrival time. To solve the model, a preference-based multi-objective algorithm (PB-MOA) is devised. In the case study, the applicability of the proposed methodology is verified in a real-world leading express company.**

***Index Terms*—Express network, transportation network design, bi-objective optimization, hub's sorting efficiency**

I. Introduction

The courier industry, as an important support for the internet economy, has been in a rapid development stage. According to data released by the State Post Bureau of China, in 2020, the courier industry completed a total of 83.36 billion pieces of business for the year. However, throughout 2020, China's courier industry received 716 complaints, of which 28.21% expressed customers' dissatisfaction about the long delivery time. Therefore, how to improve the timeliness of express logistics services is a challenge faced by courier companies.

Optimizing the logistics network is an effective way to improve the efficiency of its operations. However, the courier industry has its own unique characteristics, traditional network design models [1] are not applicable. Such as the sorting efficiency of the hub is an important decision variable in the courier industry. Higher sorting efficiency reduces the time spent on sorting packages in the hub, but with that it comes a higher cost from purchasing sorting equipment. The operation cost and arrival times of packages are significantly affected by the sorting efficiency. There is no relevant literature that makes the sorting efficiency of hubs a decision variable when designing transportation networks [2-6]. In addition, few studies have considered the use of heterogeneous vehicles with different capabilities to meet transport needs.

To the best of our knowledge, there is no existing studies have integrated these factors into the transportation network design. Therefore, a novel bi-objective nonlinear mixed-integer optimization model for bi-objective express transportation network design problem (BO-ETNDP) is developed based on the classical signal-allocation incomplete hub network design protocol [7]. To solve the model, a preference-based multi-objective algorithm (PB-MOA) is devised. The data set from a real-world leading express company is applied to verify the applicability of the proposed model and algorithm.

The remainder of this paper is organized as follows. Section II present the operation cost function and the arrival time function. Section III presents the optimization models. In Section IV, the PB-MOA is introduced. The discussion is presented in Section V. Section 6 is the conclusion.

II. Proposed Approximation function

To make the mathematical model clearer, we categorize the notation used in the model and algorithms and display them in Table I and Table II. The value of these parameters in Table I is used in the case study.

TABLE I: Description of Parameters

Par.	Description
N	Set of nodes
H	Set of candidate hubs
w_{ij}	Demand flow from node i∈N to node j∈N
d_{ij}	Distance between nodes i∈N and j∈N
M	Set of vehicle types
c_a	Transportation cost per kilometer for the a^{th} vehicle
q_a	Capacity of the a^{th} type vehicle
mc_a	Monthly fixed cost of the a^{th} type vehicle
c_b	Transportation cost per kilometer for the b^{th} vehicle
q_b	Capacity of the b^{th} type vehicle
mc_b	Monthly fixed cost of the b^{th} type vehicle
FH_k	Monthly fixed cost of the k^{th} hub, k∈H
FD_i	Monthly fixed cost of the i^{th} node, i∈N
lt	Departure time of vehicles when leaving a node
dt	Hold time of parcels that must be observed in hubs
s	Service time spent by a vehicle in a hub
dε	Unit cost discount for improving the sorting efficiency
ϴ	Unit cost for sorting packages in nodes
dϴ	Unit cost discount for sorting packages in hubs
v	Speed of the vehicle
p_c	Preference coefficient of operation costs
p_t	Preference coefficient of the maximum arrival time

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TABLE II: DESCRIPTION OF DECISION VARIABLES

Var.	Descriptions
e_k	Integer, the sorting efficiency of hub k (pieces/hour)
f_{ikl}	Integer, number of packages sent from node i∈N that pass through hubs k∈H and l∈H
X_{ik}	Binary, equals 1 if node i is assigned to hub k∈H and 0 otherwise
Y_{ijkl}	Binary, equals 1 if parcels of node i∈N sent to node j∈N pass through hubs k∈H and l∈H and 0 otherwise
Z_{kl}	Binary, equals 1 if an inter-hub link is operating from hub k∈H to hub l∈H and 0 otherwise

The operation cost C_1 in the model of BO-ETNDP is composed of five parts, as shown in Eq. (1): monthly fixed cost of hubs and nodes (FN_1), fixed cost of opening the transportation line (FL_1) which includes opening the transportation line between two hubs and the transportation line between a hub and a node, fixed cost (FS_1) for purchasing the sorting equipment (if there is a large amount of sorting work at the hubs, economies of scale can be formed, so the unit cost discount for improving the sorting efficiency in the hub is considered), transportation cost (TS_1), and sorting cost of packages (SC_1). Among them, the calculation formulas of these costs are shown in Eqs. (1.1)–(1.5).

$$C_1 := FN_1 + FL_1 + FS_1 + TS_1 + SC_1 \tag{1}$$

$$FN_1 := \sum_{k\in H} FH_k X_{kk} + \sum_{i\in N} FD_i \tag{1.1}$$

$$FL_1 := \sum_{k\in H}\sum_{l\in H}\left\lceil\frac{\sum_{i\in N} f_{ikl}+\sum_{i\in N} f_{ilk}}{q_m}\right\rceil * mc_m + \sum_{i\in N}\sum_{k\in H}\left\lceil\frac{\sum_{l\in H} f_{ikl}}{q_m}\right\rceil * mc_m \tag{1.2}$$

$$FS_1 := \sum_{k\in H} e_k * \varepsilon * d\varepsilon \tag{1.3}$$

$$TS_1 := \sum_{i\in N} \begin{matrix}\sum_{j\in N}\sum_{k\in H}\sum_{l\in H}\left(c_m d_{ik} + c_m d_{lj}\right)\left\lceil\frac{w_{ij}}{q_m}\right\rceil Y_{ijkl} \\ +\sum_{k\in H}\sum_{L\in H} c_m d_{kl}\left\lceil\frac{\sum_{i\in N} f_{ikl}}{q_m}\right\rceil\end{matrix} \tag{1.4}$$

$$SC_1 := \sum_{i\in N}\sum_{j\in N} w_{ij} * \theta * d\theta \tag{1.5}$$

To reduce the uncertainty of arrival time, the arrival time function is formulated based on the business process of express logistics services [8, 9], which composed of collection time, branch transportation time, primary sorting time, trunk transportation time, secondary sorting time, branch transportation time, and delivery time. Each component of the arrival time is then estimated based on historical data. We formulate the relationship between the parcel arrival time function at'_{ij} and the decision variables in Eq. (2) below:

$$at'_{ij} := \sum_{l\in H} et_l X_{jl} + bt_{lj} \quad \forall i,j \in N. \tag{2}$$

The relationship between bt_{lj} and decision variable X_{jl} is shown in Eq. (2.1). Besides, et_l is related to the start time of sorting packages in hub $l \in H$ and the time spent in the sorting process. As packages from other hubs do not arrive in hub $l \in H$ in the meantime, the end time of these packages sorted in hub $l \in H$ is different. Therefore, we set the longest time of these packages spent in hub $l \in H$ as et_l, which is calculated in Eq. (2.2).

$$bt_{lj} := \frac{\sum_{l\in H} d_{jl} X_{jl}}{v} \quad \forall j \in N \tag{2.1}$$

$$et_l := \max_{\forall k\in H}\{st_{kl} + hw_{kl}/e_l\} \quad \forall l \in H \tag{2.2}$$

The relationship between hw_{kl} and decision variables Y_{ijkl} is shown in Eq. (2.3). Since st_{kl} is related to s, their relationship is shown in Eq. (2.4).

$$hw_{kl} := \sum_{i\in N}\sum_{j\in N} w_{ij} Y_{ijkl} \quad \forall k,l \in H \tag{2.3}$$

$$st_{kl} := et_k + ht_{kl} + \mathrm{s} \tag{2.4}$$

The relationship between ht_{kl} and decision variables Y_{ijkl} is described in Eq. (2.5). et_k is related to the start time of sorting packages in hub $k \in H$ and the time spent in the sorting process. Since the packages from other nodes do not arrive in hub $k \in H$ at the same time, the end time of these packages being sorted at hub $k \in H$ is different. Therefore, we set the longest time that these packages spend in hub $k \in H$ as et_k, which is shown in Eq. (2.6).

$$ht_{kl} := \left(\sum_{k\in H}\sum_{l\in H} d_{kl} Y_{ijkl}\right)/v \quad \forall i,j \in N \tag{2.5}$$

$$et_k := \max_{\forall k\in H}\{ st_{ik} + hw_{ik}/e_k\} \tag{2.6}$$

The relationship between hw_{ik} and decision variables f_{ikl} is displayed in Eq. (2.7). Since st_{ik} is related to bt_{ik} and s, their relationship is shown in Eq. (2.8).

$$hw_{ik} := \sum_{l\in H} f_{ikl} \quad \forall i \in N, k \in H \tag{2.7}$$

$$st_{ik} := bt_{ik} + \mathrm{s} \quad \forall i \in N \tag{2.8}$$

Then, we formulate the relationship between bt_{ik} and the decision variables X_{ik} as shown in Eq. (2.9).

$$bt_{ik} := \left(\sum_{k\in H} d_{ik} X_{ik}\right)/v \quad \forall i \in N \tag{2.9}$$

Finally, the relationship between at'_{ij} and the decision variables is expressed in Eq. (3).

$$at'_{ij} := \sum_{l\in H} \max_{\forall k\in H}\left\{\max_{\forall k\in H}\left\{\frac{\sum_{k\in H} d_{ik} X_{ik}}{v} + \frac{\sum_{l\in H} f_{ikl}}{e_k} + s\right\} + \frac{\sum_{k\in H}\sum_{l\in H} d_{kl} Y_{ijkl}}{v} + \frac{\sum_{i\in N}\sum_{j\in N} w_{ij} Y_{ijkl}}{e_l} + s\right\} * X_{jl} + \frac{\sum_{l\in H} d_{jl} X_{jl}}{v} \quad \forall i,j \in N \tag{3}$$

III. OPTIMIZATION MODELS

The method of modeling transportation network design problems can be traced back to the 1990s. O'Kelly [10] proposed a quadratic discrete optimization model for the hub location problem. Some other linearization strategies are used to deal with the quadratic discrete optimization model have achieved good results [11–14]. In this paper, we have also adopted the path-based method to develop our optimization model for BO-ETNDP.

A typical scenario of BO-ETNDP is considered. There are n demand nodes, each of which is a candidate hub station. Besides, there is demand for transporting some commodity between each pair of demand nodes. Considering these transportation demands can be large or small, two types of vehicles with different capacities are available. In actual operation, vehicles with large capacity are given priority to meet transportation demands. However, if the loading rate is too low, it will be more economical to choose vehicles with small capacity to transport.

BO-ETNDP aims to find an optimal solution with minimum operation costs and a minimum maximum arrival time. The optimal solution found provides insights into where to locate the hubs, how to design the sorting efficiency of hubs, how to connect hubs and demand nodes, and how to route flows.

Some constraints need to be included. Firstly, the most basic constraint is that each transportation demand must be satisfied. Secondly, once the package arrives at the hub, it must be dispatched within the company's specified hold time. Thirdly, the topology between hub stations is non-fully connected. Finally, the topology of the non-hub nodes needs to satisfy the constraints of the single allocation strategy.

For the convenience of modeling, we make some assumptions which are common in the literature of BO-ETNDP. 1) After all packages at a hub are sorted, they can be transported to the next hub or demand node. 2) When sorting operations are performed at a hub, the hub follows the first-come-first-sorting principle. 3) The number of docks at a hub is sufficient regardless of the queue time of vehicles waiting for an empty dock. It implies that BO-ETNDP is unconstrained in capacity of hubs

$$\text{Min } f_1 := OC_1 \tag{4}$$

$$\text{Min } f_2 := \max_{\forall i,j \in N} \{ at'_{ij} \} \tag{5}$$

S.T.

$$\textstyle\sum_{k\in H} \sum_{l\in H} Y_{ijkl} = 1 \quad \forall i,j \in N \tag{6}$$

$$\textstyle\sum_{k\in H} X_{ik} = 1 \qquad \forall i \in N \tag{7}$$

$$\textstyle\sum_{l\in H} f_{ikl} - \sum_{l\in H} f_{ilk} = \sum_{j\in N} \sum_{l\in H} w_{ij} Y_{ijkl} - \sum_{j\in N} \sum_{l\in H} w_{ij} Y_{ijlk} \qquad \forall i \in N, k \in H \tag{8}$$

$$\left(\textstyle\sum_{l\in H} \sum_{i\in N} f_{ikl} + \sum_{l\in H} \sum_{i\in N} f_{ilk}\right) / e_k \le rt \ \forall k \in H \tag{9}$$

$$X_{ik} \le X_{kk} \qquad \forall i \in N, k \in H \tag{10}$$

$$Y_{ijkl} \le X_{ik} \qquad \forall i,j \in N, k,l \in H \tag{11}$$

$$Y_{ijkl} \le X_{jl} \qquad \forall i,j \in N, k,l \in H \tag{12}$$

$$Z_{kl} \le X_{kk} \qquad \forall k,l \in H \tag{13}$$

$$Z_{kl} \le X_{ll} \qquad \forall k,l \in H \tag{14}$$

$$Z_{kl} = \begin{cases} 1, & \sum_{i\in N} \sum_{j\in N} Y_{ijkl} \ge 1 \\ 0, & \sum_{i\in N} \sum_{j\in N} Y_{ijkl} = 0 \end{cases} \qquad \forall k,l \in H \tag{15}$$

$$X_{ik} \in \{0,1\}, \forall i \in N, k \in H \tag{16}$$

$$Y_{ijlk} \in \{0,1\} \qquad \forall i,j \in N, k,l \in H \tag{17}$$

$$e_k \ge 0 \qquad \forall k \in H \tag{18}$$

$$f_{ikl} \ge 0 \qquad \forall i \in N, k,l \in H \tag{19}$$

The objective function (4) minimizes the operation cost and objective function (5) minimizes the maximum arrival time. Constraint (6) imposes that each demand between any two nodes is satisfied. Constraint (7) ensures that each non-hub node is assigned to a single hub. Constraint (8) is the flow balance equation. Constraint (9) enforces that the service time in a hub is satisfied within the maximum service time. Constraint (10) guarantees that the nodes are assigned only to installed hubs. Constraints (11) and (12) represent the allocation strategy of the link. Constraints (13) and (14) ensure that each inter-hub link is operated only in-between hubs. Constraint (15) indicates that if the path exists, the inter-hub link must be opened. Constraints (16) and (17) represent the binary variables. Constraints (18) and (19) represent the non-negative variables.

IV. Preference-Based Multi-objective Algorithm

Since objective function (5) is non-linear, these models are multi-objective non-linear mixed-integer optimization models (MO-NL-MIOM). To solve these models, we devise a method that we call PB-MOA and stands for preference-based multi-objective algorithm.

PB-MOA embeds branch-and-cut algorithm in the framework of a ranking algorithm. In the ranking algorithm, for each objective, a preference value is specified by the decision-maker, and the objective with maximum preference value remains as the only objective of the model. In such a case, the branch-and-cut algorithm is applied to solve the single objective mixed-integer optimization model. Then, the optimal solution and a certain number of feasible solutions remain to construct the Pareto frontier. Finally, the optimal criterion constructed according to the decision-maker's preference is used to select an optimal solution from the Pareto frontier.

The data in this experiment is collected from a Chinese express company. We collected the company's data for a whole month during October 2020, which includes 34 demand nodes across the country, 6 candidate hub stations, and 1122 original-destination (OD) pairs. The distribution of demand nodes and candidate hub stations is shown in Fig. 1. The red and black dots are demand nodes, and the black dots represent candidate hubs.

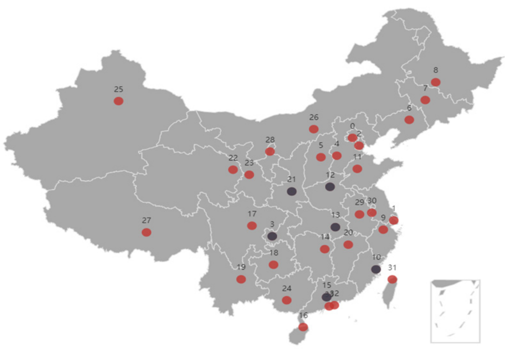


Fig. 1. The distribution of demand nodes.

In the case of study, the PB-MOA is coded using Python 3.7. The branch-and-cut algorithm of the PB-MOA is implemented using Gurobi version 9.1.0. The value of parameters is shown in the Table III.

TABLE III: THE VALUE OF PARAMETERS

Par.	Description	Value
N	Set of nodes	Data set
H	Set of candidate hubs	Data set
w_{ij}	Demand flow from node i∈N to node j∈N	Data set
d_{ij}	Distance between nodes i∈N and j∈N	Data set
M	Set of vehicle types	{a, b}
c_a	Transportation cost per kilometer for the a^{th} vehicle	6 (CNY)
q_a	Capacity of the a^{th} type vehicle	1000 (unit)
mc_a	Monthly fixed cost of the a^{th} type vehicle	20000
c_b	Transportation cost per kilometer for the b^{th} vehicle	9 (CNY)
q_b	Capacity of the b^{th} type vehicle	5000 (unit)
mc_b	Monthly fixed cost of the b^{th} type vehicle	60000 (CNY)
FH_k	Monthly fixed cost of the k^{th} hub, k∈H	700000 (CNY)
FD_i	Monthly fixed cost of the i^{th} node, i∈N	300000 (CNY)
lt	Departure time of vehicles when leaving a node	18:00
dt	Hold time of parcels that must be observed in hubs	12 (h)
s	Service time spent by a vehicle in a hub	0.2 (h)
dε	Unit cost discount for improving the sorting efficiency	0.8
ɵ	Unit cost for sorting packages in nodes	0.5(CNY)
dɵ	Unit cost discount for sorting packages in hubs	0.8
v	Speed of the vehicle	80 (km/h)
p_c	Preference coefficient of operation costs	0.7
p_t	Preference coefficient of the maximum arrival time	0.3

The index of gap is used to evaluate the quality of the solution. The calculation method of the gap is shown in Eq. (20).

$$Gap = \frac{f_o(s_i) - \min\{F_o\}}{\min\{F_o\}} \qquad \forall s_i \in P, o \in \{1,2\}. \qquad (20)$$

The results are shown in Table IV. The first column records the name of the important information for the optimal solution. The second column shows the value of the important information. The last column indicates the unit of the value. The value for the minimum operation cost, f_1, is about 113.45 million. The value for the maximum arrival time, f_2, is 80.5 hours. The order of selected hubs is 12 and 13. The sorting efficiency of these selected hubs is 32109 and 1072249 pieces/hour. The cost of computing time (CPU) is close to 681 seconds.

TABLE IV: THE OPTIMAL SOLUTION FOR THE MODEL

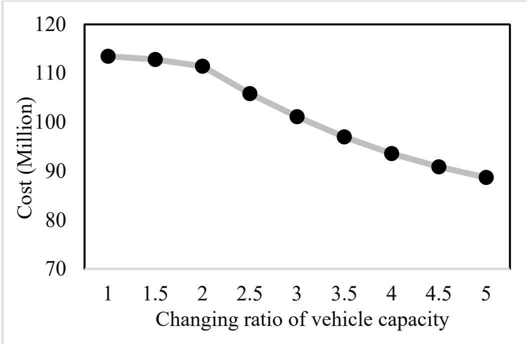
Items	value	Unit
f_1	113.45	Million
f_2	80.5	Hour
Selected hubs	12,13	--
Sorting efficiency	32109,1072249	Pieces/hour
CPU	681	Second

V. DISCUSSION

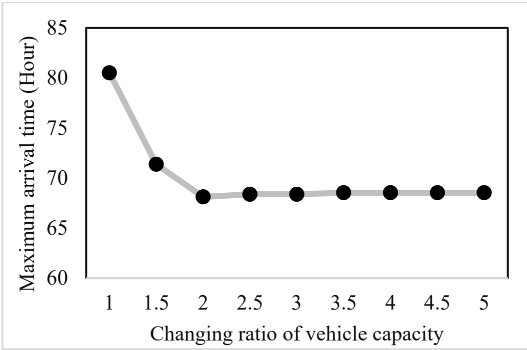
The values of parameters are expected to change with the development of the express industry. To analyze the impact of these parameters on ETNs performance, a series of experiments are conducted in this section to reveal the impact mechanism.

A. Vehicle Capacity

According to the data from the Chinese express company, the vehicle with the largest capacity can transport up to about 5,000 express items per trip. Also, courier companies are trying to use transportation with a larger capacity to transport express items (e.g., trains, high-speed trains, etc.). What impact will this initiative have on ETNs performance? To this end, we conduct a series of experiments by modifying the maximum capacity of the vehicle. We assume values of the ratios as [1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5]. When the maximum transportation capacity changes, the transportation cost and fixed costs should also change in the same proportion. The experimental results are shown in Fig. 2.



(a) Impact of vehicle capacity on f_1



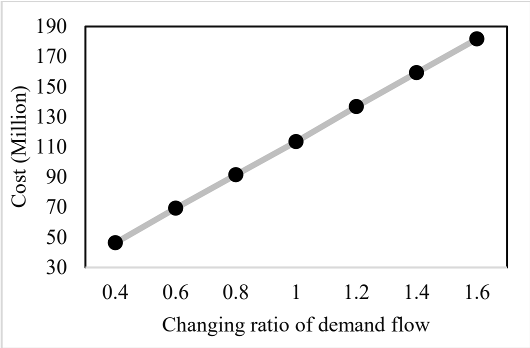
(b) Impact of vehicle capacity on f_2

Fig. 2. Impact of vehicle capacity on ETNs performance.

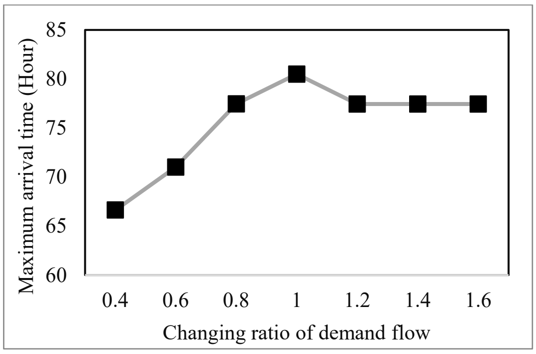
Obviously, there are benefits to reducing costs and reducing maximum arrival times when using larger capacity vehicles. However, if the proportion of vehicle capacity exceeds two times, the maximum arrival time will not change.

B. Demand Flow

As the courier market changes, the demand flow from node $i \in N$ to node $j \in N$ may increase or decrease. Therefore, we conduct a series of experiments by adjusting the demand flow. Likewise, we assume that the demand flow between each origin-destination pair varies in proportions of [0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6]. The experimental results are shown in Fig. 3.



(a) Impact of demand flow on $\boldsymbol{f_1}$



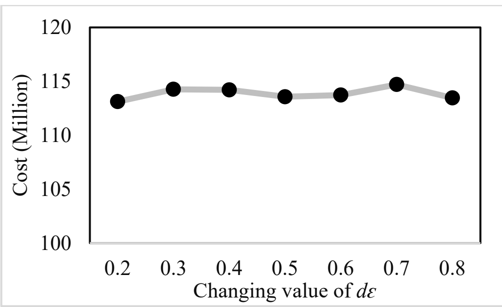
(b) Impact of demand flow on $\boldsymbol{f_2}$

Fig. 3. Impact of demand flow on ETNs performance.

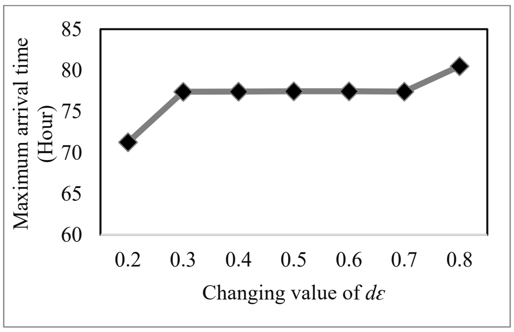
The cost increase with the growth of demand flow. However, when demand varies by more than a factor of one, the maximum arrival time is reduced to 75 hours and does not vary with the increase in demand flow.

C. Other Parameters

In addition, the variation of some parameters, including $d\varepsilon$, $d\theta$, and dt, also has an impact on the network performance. Therefore, we also conduct a series of experiments by modifying the values of these parameters. The results are shown in Figs. 4–6.



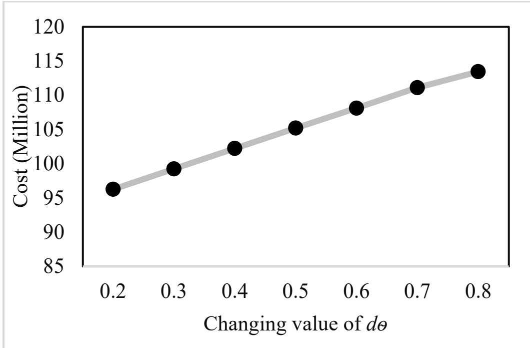
(a) Impact of $d\varepsilon$ on $\boldsymbol{f_1}$



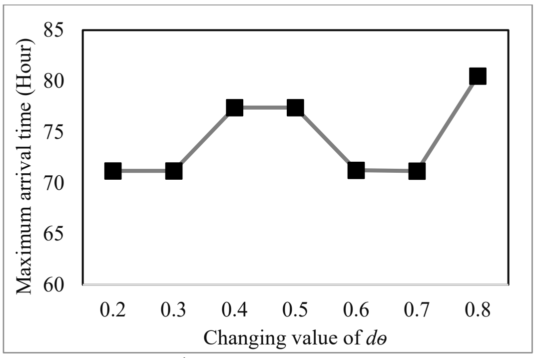
(b) Impact of $d\varepsilon$ on $\boldsymbol{f_2}$

Fig. 4. Impact of $d\varepsilon$ on ETNs performance

The value of the unit cost discount for improving the sorting efficiency ($d\varepsilon$) has little effect on costs, but the maximum arrival time rises as $d\varepsilon$ increases.



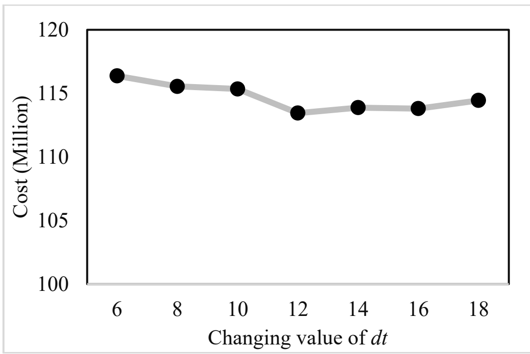
(a) Impact of $d\theta$ on $\boldsymbol{f_1}$



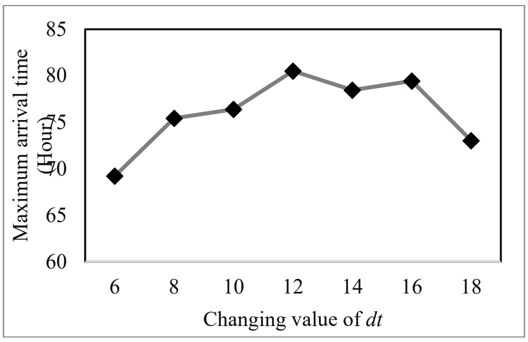
(b) Impact of $d\theta$ on $\boldsymbol{f_2}$

Fig. 5. Impact of $d\theta$ on ETNs performance.

The value of the unit cost discount ($d\theta$) for sorting packages in hubs has a positive effect on the cost. But the change in maximum arrival time is irregular, when the value of $d\theta$ increases.



(a) Impact of dt on $\boldsymbol{f_1}$



(b) Impact of dt on $\boldsymbol{f_2}$

Fig. 6. Impact of dt on ETNs performance.

As the retention time (dt) of parcels that must be sorted at hubs increases, costs will increase. However, there is no benefit to reducing costs if the retention time exceeds 12 hours.

Therefore, for parameter $d\varepsilon$, if the company puts more effort to obtain a lower discount to improve sorting efficiency, it does not bring significant benefits. However, for parameter $d\theta$, this courier company should consider more ways to reduce the cost of sorting packages, which could result in higher cost savings. For parameter dt, setting a strict hold time for parcels at hubs has no significant impact on the maximum arrival time, but instead pushes up operation costs.

VI. Conclusion

In this paper, we propose a novel bi-objective nonlinear mixed-integer optimization models for BO-ETNDP under multiple structures, which considers the impact of the hub's sorting efficiency on operation cost and arrival time. These models are more in line with the characteristics of the courier industry. To solve these models efficiently, a preference-based multi-objective algorithm (PB-MOA) is devised, which embeds the branch-and-cut algorithm and Pareto dominance theory in the framework of the ranking algorithm. The PB-MOA can obtain high-quality feasible solutions, and accurately measure its optimality gap. In the case study, the applicability of our methodology is validated in a leading express company. The study also finds that vehicle capacity and demand flow have a significant impact on the structure of ETNs.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jian Zhong conducted the research and all mathematical model, algorithm. Xinrui Li wrote the paper. Xu Wang analyzed the data and the English grammar. All authors had approved the final version.

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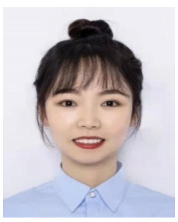

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