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Research Article

Highway Passenger Transport Based Express Parcel Service Network Design: Model and Algorithm

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Highway passenger transport based express parcel service (HPTB-EPS) is an emerging business that uses unutilised room of coach trunk to ship parcels between major cities. While it is reaping more and more express market, the managers are facing difficult decisions to design the service network. This paper investigates the HPTB-EPS network design problem and analyses the time-space characteristics of such network. A mixed-integer programming model is formulated integrating the service decision, frequency, and network flow distribution. To solve the model, a decomposition-based heuristic algorithm is designed by decomposing the problem as three steps: construction of service network, service path selection, and distribution of network flow. Numerical experiment using real data from our partner company demonstrates the effectiveness of our model and algorithm. We found that our solution could reduce the total cost by up to 16.3% compared to the carrier's solution. The sensitivity analysis demonstrates the robustness and flexibility of the solutions of the model.

1. Introduction

Highway passenger transport based express parcel service (HPTB-EPS) is a recently emerging business model for highway passenger transportation companies to fully utilise their transport capacity so as to survive and thrive in the fierce competition of passenger transportation market. This new business model is derived from the highway passenger transportation by taking advantage of the spare capacity of coach trunk to transport small parcels. The parcels are collected and dispatched at the stations in the major cities and can be transported within the same day or overnight.

In China, HPTB-EPS has been developing rapidly in the recent years thanks to the soaring e-commerce activities. The size of express parcels market has exceeded one billion CNY and is increasing by 30% annually [1]. The advantages of passenger transport system in delivering small express parcels lie in the following (1) the parcel transport distances required are usually within 100–600 km, which is well covered by coach services; (2) the passenger transportation networks between major cities are well established, which makes the long-distance transport feasible using transshipment; (3) the passenger transport within the networks is well scheduled; (4) the security of the parcels can be guaranteed by the control system in the passenger transport. As a result, many passenger transport companies are planning to do or have already started express parcel services. Due to the limited coverage of individual companies, collaboration or alliance is the commonly used method. Companies in a regional area usually form an alliance to do the business. In July 2014, an HPTB-EPS alliance was formed by 16 passenger transport companies in Central China, starting the process of networked operations of HPTB-EPS (News from Changjiang Times; see http://www.changjiangtimes.com/2014/07/483222.html). In November 2015, a new brand "Yue Yun Xiao Jian" was launched by Guangdong Highway Transport Association, led by Yue Yun Transport Company, to take advantage of their 459 stations and their running coaches as well as their well-developed transport network (News from Tencent's Stock; see http://stock.qq.com/a/20151117/038982.htm). In July 2015, a service platform called "Kuai Ke Yi Da" was launched by a strategic alliance formed by Zhejiang Kuaike Yi Da Technology Ltd. and 11 major passenger transport companies

(News from Zhejiang Sina, see http://zj.sina.com.cn/news/2015-07-25/detail-ifxfhxmp9549628.shtml). The services mainly focus on small parcel express, including same-day delivery and rural-urban delivery. In fact, this HPTB-EPS alliance is taking the advantages of network resources, cost, and time from existing passenger transport networks; therefore, HPTB-EPS is very promising and is and will be playing an important part in the express parcel market.

Despite the promising prospect of HPTB-EPS, to make good profit, the carrier (an independent firm running the HPTB-EPS on behalf of the participated firms) needs to design the service network, that is, which route should open the service, on what frequency, and how to transport the parcels in the network. One reason is that opening a service on a route is costly because the costs of resources devoted to the business are calculated by the participated firms including the route license fee which is a lump sum fee for the use of the route and the delivery cost by each shift since the parcels need to be loaded and unloaded by the driver. Another reason is that not all routes have enough demand. One more reason is that, based on the opened services, how to transport the parcels in the network, that is, network traffic distribution, should be decided so that the promised service level is met. In terms of decision level, this service network design problem belongs to the tactical level with the planning period of 1 year, half a year, or even one month if the demand changes quickly.

Compared to traditional express delivery network, HPTB-EPS network has some unique characteristics. First, HPTB-EPS is attached to the passenger transport, which has been scheduled. Therefore, the fleet decision in traditional network models becomes a constraint in this problem. Second, due to the consolidations in the transshipment nodes, the link between different services and the operations during this link should be explicitly considered in this problem. The resulting service network with explicit service decision procedure illustrated in Section 3.2 is different from the physical network, while for most freight networks they are more or less the same with each other. Third, the service is constrained by the capacity and frequency of passenger transport, which is further complicated if the parcel needs to go through different services. Due to these new features, traditional network design models cannot be applied directly to this new problem. According to our investigation in our partner companies of this research, the managers have to use a general rule of thumb to make such decision by opening all direct services between the origins (O) and destinations (D) where there is demand. However, this generates a fixed cost including the fee paid for the coach licence to use the route and cost related to the frequency.

This paper will investigate the HPTB-EPS network design problem. Our research makes the following contributions to the literature: first, we explicitly characterise the HPTB-EPS network using a node decomposition method. Due to consolidation in the nodes, operations and links between operations should be modelled. Traditional service network design model cannot capture this feature. We decompose the node into different types of logic nodes: arrival nodes, departure nodes, and operations node. As far as we know, this is the first approach to use node decomposition to study HPTB-EPS network design problem. Second, we formulate the HPTB-EPS network design problem as a mixed-integer programming model. Based on the decomposed nodes, a cost minimisation model is built on the virtual network, incorporating the capacity and frequency constraints. The resulting mixed-integer programming model, although looking similar to traditional service network design model at first glance, has different decisions and constraints. This is the first model tailored for HPTB-EPS network design problem. Third, a decomposition-based heuristic algorithm is proposed to solve the model. Due to the complexity of the model, we decompose the problem into three steps: construction of the service network, selection of service path, and distribution of the network flow. Although decomposition-based heuristic idea is not new, it is the first time to be used in our model. Overall, our research uses existing techniques to solve an untapped problem, extending the boundary of related theories and techniques.

The paper is organized as follows: in Section 2, we review the relevant literature; Section 3 describes the problem; Section 4 presents the proposed model and algorithm; Section 5 gives the computational case study for comparing our solution with the current practice and conducting sensitivity analysis. Finally, conclusions are drawn in Section 6.

2. Literature Review

This research belongs to the broad category of service network design (SND) or more broadly network design (ND) problem. Magnanti and Wong [2] are the first to convert the transport network decision problem to an integer programming problem and propose a generic design model, which was known as SNDP (service network design planning). The core idea is to incorporate the time and space information into the network design formulation. This problem has been studied in many different settings. For example, Crainic and Rousseau [3] propose a generic model for freight transportation service network design with frequency. Chen et al. [4] formulated the spatially dependent reliable shortest path problem (SD-RSPP) as a multicriteria shortest path-finding problem in road networks with correlated link travel times. Kim and Barnhart [5] based on the characteristics of flight network develop a charter airline service network design model as mixed-integer programming. Lai and Lo [6] study the ferry service network design problem. Crainic [7] classifies the service network design problems as static and dynamic problems with the former focusing on transport route, service frequency, and the projection of demand on the network flow and the latter focusing on the time dimension. Recently, Ng and Lo [8] study the transportation service network design problem using robust optimisation assuming that only the mean and support of passenger demand are known. Broadly speaking, three types of models, path formulation, node-arc formulation, and tree formulation, have been proposed in the literature [9]. Different decisions should be made in this general problem, for example, service selection, frequency, or speed, consolidation, and traffic flow distribution. Based on different application settings, different combinations of decisions have been modelled

(see the reviews in [7, 9–13]). In the recent years, asset management issues are incorporated into the SND problems, resulting in the so-called service network design with asset management (SNDAM), for example, [14, 15]. Also, travellers' behaviour is incorporated in the demand management and modelled in the service network design problem. Liu and Zhou [16] propose a new modelling framework to account for the bounded rationality of travellers in a dynamic transit service network with tight capacity constraints. Similar to the traditional freight transportation network design, the HPTB-EPS network problem needs to make such decisions as service design, service frequency, and traffic distribution. But the main difference lies in the fact that the HPTB-EPS is attached to the passenger transportation, where the schedule of fleet becomes constraint rather than a decision. In addition, the service frequency is usually derived from the demand and the fleet capacity without affecting the objective. But, in HPTB-EPS network, as analysed below, the frequency goes into the objective, impacting other decisions. Furthermore, the operations in network nodes are negligible in most freight network models, while they are the main focus of HPTB-EPS network. Therefore, the extant models cannot be directly adopted into solving the HPTB-EPS problems.

Besides the modelling issues, solution to the model is another key problem due to the NP-hard nature of this kind of problem. Exact and efficient algorithms have not been found, except for some specific formulations in certain settings. Several heuristics are proposed, for example, Lagrangian relaxation [17, 18], Benders decomposition methods [19], branch-and-bound algorithms [20], and branch-and-price-and-cut method [21]. For more comprehensive review in the solution methods, the readers are referred to Zhu [13]. In the recent years, decomposition-based algorithms have gained more research attention. Teypaz et al. [22] propose a decomposition scheme for large-scale service network design problem with asset management. The problem is decomposed into three steps including construction of the network, choice of the transported commodities, and construction of the vehicle planning. Some other decomposition approaches are also used, for example, decomposition of transport modes. Wieberneit [9] reviews the different decomposition methods. Based on the idea of decomposition, this paper decomposes the HPTB-EPS network design problem as three steps, construction of the service network, selection of service paths, and distribution of the network flow, and proposes an effective algorithm to solve the proposed model.

To the best of our knowledge, not much effort has been dedicated yet to this emerging problem. Zuo and Yang [23] study the competition and marketing strategy for carriers implementing HPTB-EPS based on a survey. Yang et al. [1] propose a model to optimise the parcel delivery paths for HPTB-EPS given the services provided. Cheng et al. [24] propose a policy of picking up parcels for express courier service in dynamic environments. In their research, the service network is given and the main focus is on the network flow distribution. In this paper, the HPTB-EPS network design problem is studied by explicitly considering the service path selection and network flow distribution decisions, as well as the service frequency and service level.

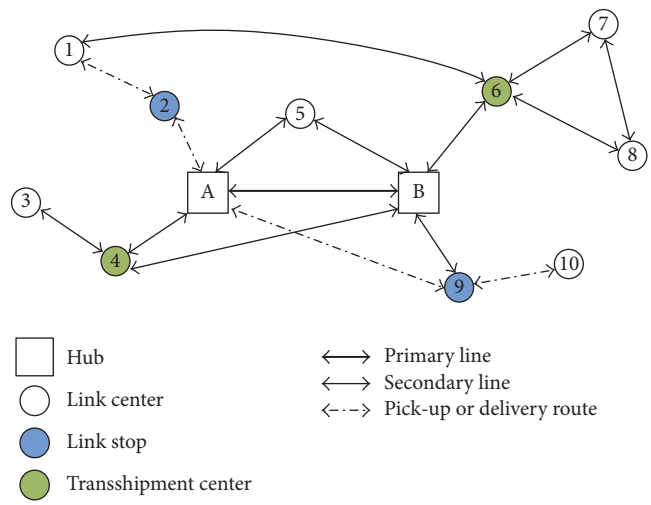

Figure 1: Example of HPTB-EPS network with hub-and-spoke structure.

3. The Problem Description

We describe the HPTB-EPS network design problem of a large road passenger transport system which is operated by an independent company. The company could be a joint venture of passenger transport company alliance. As stated in Introduction, the company needs to pay the passenger transport companies for the use of their resources, mainly the route license and operations cost during the transport. The objective is to fulfil the demands from their origins to their destinations using the existing road passenger transport system at a minimum cost. This service network design problem consists of three parts: the first is *service analysis*, including the analysis of service type, time, design cost, and capacity, the second is *service path selection*, that is, selecting a path from the origin to destination, and the third is *network flow distribution*, that is, the movement of parcels through which service routes and hubs.

However, different from other service networks, many operations of HPTB-EPS network such as loading or unloading and stop and temporary storage generate costs and consume time in the nodes, which should be explicitly considered and modelled. Consider a general hub-and-spoke structured network for HPTB-EPS as in Figure 1. Parcels are collected or dispatched at collection centres that are origin or destination of parcels. Parcels can be transported directly from the origin to destination or indirectly via a hub. This kind of mixed hub-and-spoke network is quite popular due to both the cost advantage of H/S network and the time advantage of direct network. Generally, the coaches do not stop to load or unload parcels between two nodes (stations in two cities) due to the passengers' satisfaction issues. In practice, however, the coaches do stop to load or unload parcels at certain stop for short time, which can be neglected. This practice has impact on the service design. We call this kind of node a collection stop, which is not a main station, as stated in the blue circle in Figure 1. Another type of node is called transshipment centre, used to transfer the parcels from one coach to others due to lack of direct route.

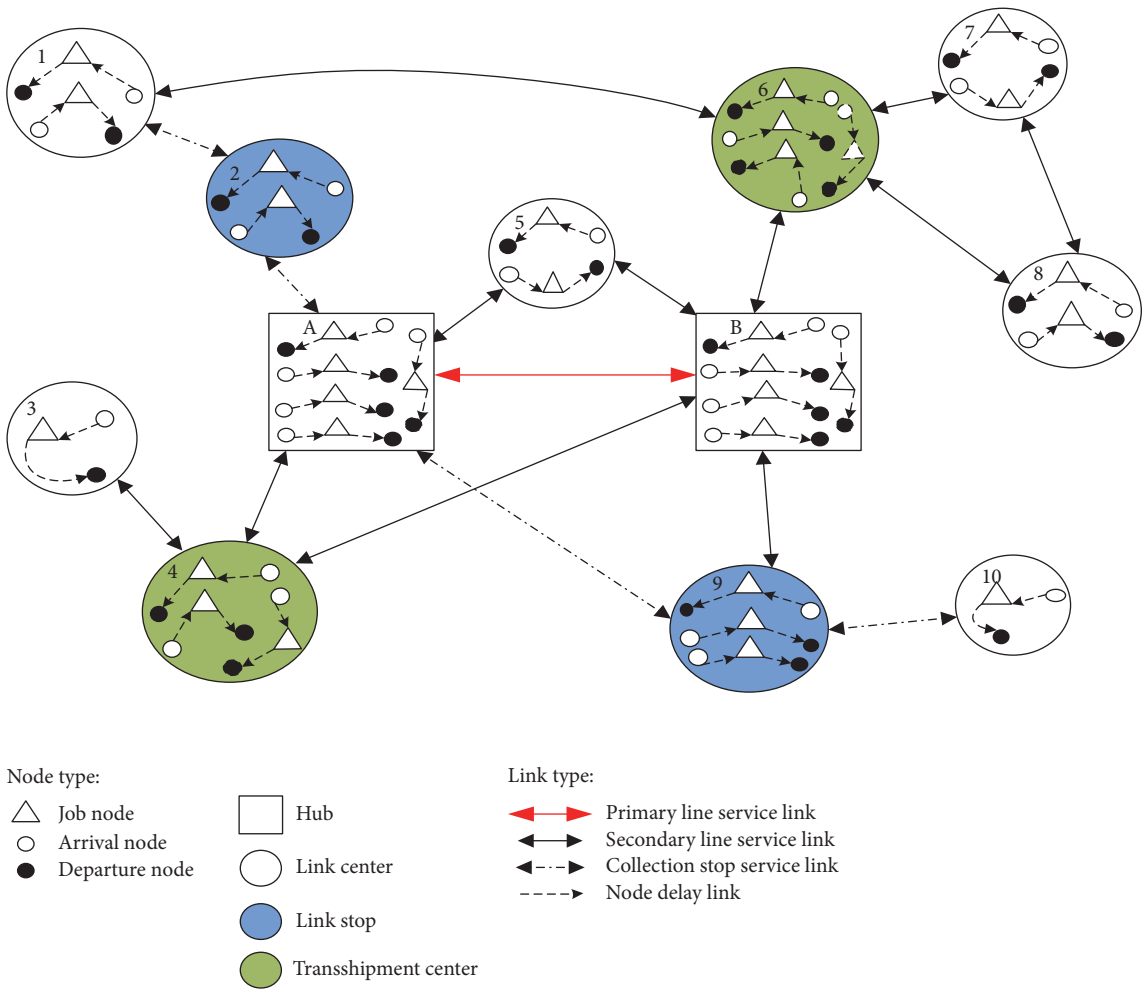

Figure 2: Decomposed HPTB-EPS network.

Another type of node is called transshipment centre in the green circle, used to transfer the parcels from one coach to others due to lack of direct route. Different with a hub, blue and green nodes have much less links and operations. Their core functions are to connect and transfer. Besides hub, we totally have four types of nodes and the parcels can go through different routes.

3.1. HPTB-EPS Space-Time Network. To capture the space-time feature of HPTB-EPS network and express what kind of operation should be done in each station, nodes are further decomposed into arrival nodes, departure nodes, and job nodes denoting the arrival and departure of the parcels as well as corresponding operations on them, respectively. Thus, the nodes can be connected by arcs with time and space, as illustrated in Figure 2.

In Figure 2, the nodes in a station denote the arrival, departure, and operation activities. The single-headed dashed arrow denotes the time delay of the parcel in that station, either due to operations such as unloading, sorting, consolidation, storage, and loading or waiting for next coach. To represent the time-dependent characteristic of the problem, we use a time-space network that is commonly used in the literature [14]. Figure 3 depicts the time and space characteristics of the HPTB-EPS network presented in Figure 2 without explicating the operations in the nodes.

The z-axis denotes the time of t, and the X, Y-plain characterizes the physical locations of the nodes and routes. To simplify the figure, we only depict the decomposition of stations 1, 2, and A and label one service path from station 1 to station B using solid arrow lines, where the thick line means transport service between stations and thin line means time delay in a station. In Z-axis, 0 means the original place, the first symbol "a," "j," or "d" denotes arrival, job, or departure nodes, and the number and letter in brackets or symbol denote the station. Based on the time-space characteristics, we can see that the total time for a parcel includes the transportation time between stations and the time delay between the arrival node and the departure node.

3.2. Service Decision. A service in this context is defined as a supply of parcels transportation from one station to another station using the existing passenger transportation. Service decision here is the key decision procedure in HPTB-EPS network design which is to design the service paths to fulfil various demands. To fulfil a certain demand in an OD

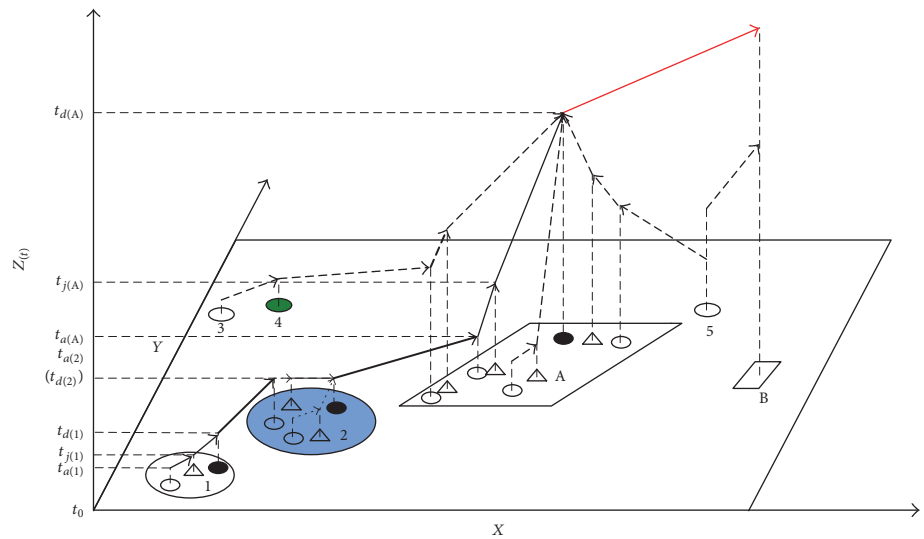

FIGURE 3: Example of time-space network.

pair, the carrier needs to select a set of transport services and service links (operations such as coach waiting, loading and unloading, temporary storage, and parcel consolidation) between transportation services, which forms a service path, also known as service route.

3.2.1. Service Analysis. Using S_d ($s_d \in S_d$) denotes delay link in a station, connecting the arrival node and the departure node. The set S ($s \in S$) denotes the transport services, which may include a few link stops. Thus, all links (set A) in a service network include transport service S and delay link S_d. The essence of the problem is how to use the network resources to fulfil service demand of network. The attributes of such network include the service type, spatial distribution, time, cost, and capacity.

(1) Service Type. Based on passenger transportation system, parcel express services can be classified into direct transport service and transshipment service. The former means that the parcels can be transported directly on nonstop routes, while the latter refers to the fact that parcels need to be transferred between the origin and destination.

(2) Service Spatial Distribution. The service network is based on the existing passenger transport system. Therefore, the service path is closely related to passenger transportation. Service network with decomposed nodes reflected its service spatial distribution shown as certain characteristics of OD pairs and related services paths, by which differences were made from the physical network of passenger transportation. The link A ($a \in A$), $A = S_d \cup S$, and node N ($n \in N$) (the decomposed nodes) form a logical abstract network $G(N, A)$ that is different from the physical network.

(3) Time. The time attribute of a parcel service network includes service time consumed and service time sequence; the former looks at the service from the perspective of time delay, associated with the speed of the coach and the distance between the OD as well as the delay in the station, while the latter defines the arriving and departing time sequence a parcel went through each station; for example, in Figure 3, for service path s from station 1 to A, the time sequence is $t_s(t_0, t_{a(1)}, t_{d(1)}, t_{a(2)})$. The time sequence is closely related to the timetable of the passenger transport A_t for all routes and constrained by the station time-window I_t; that is,

$$t_s \in I_t \cup A_t, \tag{1}$$

where I_t is the set of starting and closing times for all stations and A_t is the set of departing and arriving times at each station the passenger transport goes through along all routes.

(4) Service Design Cost. Opening a service s on a certain route, a fixed cost Φ_s usually occurs, which is the fee payed for the coach licence to use the route, and also variable cost Ψ_s occurs, which is the cost on the usage of coaches, which is related to service frequency f_s. These costs are called service design cost and can be formulated as follows:

$$C_s = \Phi_s + \Psi_s f_s. \tag{2}$$

It should be noted that, for different types of services, the design costs may be different.

(5) Service Capacity. Because the parcel service is attached to the passenger transport, the service capacity is the remaining room of the coach trunk. Usually, the remaining capacity V_s is two-thirds of the trunk space.

(6) Service Level. Service level refers to the quality of the parcel transport under the current network resources, including timely indicator and reliability. In this research, time is the only measure for service level. Using T^m denotes the service level for OD pair $m \in M$, indicating the promised time from origin to destination. Using t_a denotes the time gone through link $a \in A$ by the parcel, including the transport time and

delayed time in nodes. Thus, the total travel time for a parcel should be less than the service level; that is,

$$\sum_{a \in A} t_a \leq T^m, \quad \forall m \in M. \tag{3}$$

3.2.2. Service Paths Selection. In practice, opening direct service in all the OD pairs is neither economic nor possible in some cases. Therefore, the carrier needs to select a set of transport services and delay links, forming a sequence as a service path (denoted by P_m) to fulfil the demand. The set of transport services will impact the service path on time, cost, and capacity, which will in turn impact the service level:

(1) Time: the incoordination between service frequency f_s and time sequence t_s may cause failure of service combination. Therefore, when combining services, the service sequences f_s and t_s should be coordinated

(2) Cost: when combining services, the cost will include the service design cost and the cost generated in the delay link including the operations in the nodes

(3) Capacity: when the service paths only contain single service, the service path capacity is determined by the service capacity, while when the service path includes more services, its capacity is determined by the minimum of the service capacities

3.2.3. Network Flow Distribution. Network flow distribution is to assign the parcel transport demand to different service paths so that the demands can be fulfilled with the required service level. Network flow is used to describe the demands in the network, characterising the different attributes of demand including time-space distribution, type, and size.

Usually, an OD matrix can be used to describe the demand origins and destinations. Here, we use I to denote the set of all stations including the hub and transshipment centre as well as collection stops and M to denote demand OD set, and there will be $M = I^2$. The time used between each OD pair is dependent on the selected service path and therefore is determined by the corresponding time sequence t_s. The network flow means the total demand for each OD pair. In practices, there are different types of demands. In this paper, the demands are seen as commodity and there is no difference. We use Q^m to denote the size of demand m.

The essence of network flow distribution is to select appropriate service paths to meet with the different service levels. First, the network flow distribution needs to consider the service capacity so as to avoid congestion in certain node. Use w_a^m to denote the assigned demand m on the link a. The total demand assigned to service s cannot exceed the total capacity in the decision period; that is,

$$\sum_{m \in M} w_s^m \leq V_s f_s, \quad \forall s \in S. \tag{4}$$

Second, the total time on the selected service path (denoted by t_p) should not exceed the service level; that is,

$$t_p \leq T^m. \tag{5}$$

Here, we should note that the decision period for network flow distribution is on a daily basis and repeats every day due to the passenger transport nature.

4. The Model and Heuristic Algorithm

Based on the analysis of Section 3, we develop mathematical model for the HPTB-EPS network design problem. To simplify the problem, we make the following assumptions.

Assumption 1 (the physical transport network is given). This assumption is reasonable, since the HPTB-EPS network is attached to the passenger transport system. The layout, size, and link of the passenger stations are designed before the service is launched. Therefore, we can take them as given.

Assumption 2 (each city has only one station). In practice, most of the cities have only one station. Although some cities may have more than one station, the coaches can only arrive at or depart from one station. This assumption has very little impact on the solution.

Assumption 3 (the service capacity is given). Because the service relies on the spare room of coach trunk, we can calculate the average service capacity for each service based on history running record. Therefore, it can be seen as given and deterministic. Usually, it is 2/3 room of coach trunk in our partner company.

Assumption 4 (the demand is stable in the planning period). Because significant demand change will cause the redesign of the HPTB-EPS network, in the tactical planning horizon, we can think that the demand is stable.

Assumption 5 (the pick-up from and delivery to the customers of the parcels are not considered). This is reasonable, because usually the customers are asked to take the parcels to or collect them from the collection centre by themselves.

4.1. The Model. The following notations are used in our model:

(1) Sets

I: the set of all stations, $i \in I$

M: the set of all demand OD pairs, $m \in M$. (m_o, m_d) are the origin node and destination node for OD pair m

N: the set of all the nodes in the network including the arrival, departure, and job nodes

N_a: the set of arrival nodes, $N_a \subset N$

N_d: the set of departure nodes, $N_d \subset N$. The number of departure nodes is dependent on the service frequency at the departing station

S: the set of all transport services, $s \in S$.

S_d: the set of all delay links including loading, unloading, sorting, and transshipment. This set is determined by N_a and N_d

A: the set of all links, including the transport service and the delay links, that is, $S \subset A$, $S_d \subset A$

P_m: the set of all the service paths p meeting the service level of OD pair m, $p \in P_m$

(2) Parameters

Q^m: the quantity of demand on OD pair m

T^m: the service level for OD pair m

T: the decision period for the network flow assignment (usually $T = 12$ hours due to the fact that passenger transport only operates in day time)

t_a: the time of passing link $a \in A$

$I_t = \{t_{\min}, t_{\max}\}$: the station time-window

A_t: the set of departing and arriving times at each station the passenger transport goes through along all routes

F_s: the passenger transport frequency on service s

Φ_s: fixed cost for opening service s

Ψ_s: frequency-related variable cost for opening service s

C_a: the unit cost of passing the link $a \in A$

V_s: the capacity for service s, that is, the remaining room of one coach trunk or the parcel quantity loading in the remaining room of one coach truck

$\eta_a^{m,p}$: indicator of whether the selected service path $p \in P_m$ for demand m contains link a; if yes, its value is 1; otherwise, it is 0

w_a^m: the quantity of assigned demand m on link $a \in A$

(3) Decision Variables

δ_s: the design variable for service s:

$$\delta_s = \begin{cases} 1, & \text{open service } s \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

f_s: the frequency for service s

x_p^m: the assigned demand of OD pair m on service path p, $x_p^m = (x_1^m, x_2^m, \ldots, x_p^m)$.

In terms of the objective, cost minimisation is usually used as the optimisation objective in service network design problem in practice. Based on our interview of the research partner carrier, cost minimisation is of great importance instead of pricing issues due to the fact that the price is already low enough because of the severe competition in this industry. As the demand is increasing and the service network is expanding, trading off cost and service level is a great challenge for the company. In our setting, therefore, cost minimisation is the main objective of the carrier.

As analysed in Section 3, the total cost includes two parts: the fixed service design cost and the operations cost which occurs on a daily basis, assuming that the tactical planning horizon is T_P (days). Therefore, the objective function is either total cost minimisation during the planning horizon or the daily average cost minimisation. In this paper, the latter is adopted.

The model is as follows:

$$\min \quad Z = \frac{1}{T_P}\left(\sum_{s\in A}\delta_s\Phi_s\right) + \sum_{s\in A}\delta_s\Psi_s f_s + \sum_{m\in M}\sum_{a\in A}C_a w_a^m \tag{7}$$

$$\text{s.t.} \quad \sum_{p\in P_m} x_p^m = Q^m, \quad \forall m \in M \tag{8}$$

$$\sum_{p\in P_m} x_p^m \eta_a^{m,p} = w_a^m, \quad \forall a \in A,\ m \in M \tag{9}$$

$$\sum_{m\in M} w_a^m \le V_s f_s, \quad \forall a, s \in S \tag{10}$$

$$\delta_s f_s \le F_s, \quad \forall s \in S \tag{11}$$

$$\sum_{a\in A} t_a \eta_a^{m,p} \le T^m, \quad \forall m \in M,\ \forall p \in P_m \tag{12}$$

$$t_s \in I_t \cup A_t \tag{13}$$

$$w_a^m, f_s, V_s, x_p^m \in I^+, \quad \forall s \in S,\ \forall a \in A,\ m \in M,\ p \in P_m \tag{14}$$

$$\delta_s \in \{0, 1\} \quad \forall s \in S. \tag{15}$$

Constraint (8) balances the network flow and the service paths, showing the network flow conservation principle; that is, the demand Q^m equals the sum of assigned demand x_p^m on service path P_m so that all the demand will be assigned to appropriate service path. Constraint (9) balances demands between the links and the service paths so that the sum of assigned demand on service paths containing link a should be equal to the demand assigned to the link a. Constraint (10) is the capacity constraint, meaning that the total assigned demand should not exceed the service capacity. Constraint (11) is the frequency constraint; that is, the service frequency should not exceed the passenger transport frequency. Constraint (12) is the service level constraint, meaning that the total service time should not exceed the promised service level on that OD pair. Constraint (13) is the time-window constraint, meaning that the service time sequence should fall in the station and route time-window. Constraint (14) defines the network flow distribution rules; that is, the distribution decisions should take integer values. Constraint (15) indicates that the service design variable is a 0-1 binary variable.

4.2. Heuristic Algorithm. Due to the complexity of the mixed-integer program, there is no exact solution method to solve real practice instances and various heuristics have been proposed for different cases in the literature [9]. In this paper, we use the idea similar to Teypaz et al. [22] by decomposing the problem into three steps as follows: (1) construction of the service network, (2) selection of service path, and (3) distribution of the network flow. The advantages of this method have been discussed in detail in Teypaz et al.'s work [22]. The idea of the algorithm is presented in Figure 4.

```
Construct initial service network
for all (m in O-D demand set with m_o ≠ m_d) do
  find the corresponding s for each m.
  use Warshall-Floyd algorithm to calculate the shortest distance (load distance) D for each m, store shortest path as operating
  path P;
  if (Q^m == 0) then
  set all the service design decisions in the shortest path as 0, service frequency f_s = 0, operating path P = null;
  else
    set all the service design decisions in the shortest path as 1,
    define service frequency on the path based on service level as f_sT and service frequency on the path based on demand as f_sQ,
    round up to an integer;
    if (f_sT > f_sQ) then
      set the path service frequency as f_sT, i.e. ⌈T/T^m⌉
    else
      set the path service frequency as f_sQ, i.e. ⌈Q^m/V_s⌉ ();
    end-if
  end-if
end-do
```

Pseudocode 1: Pseudocode for initial service network construction.

```
Select Service Path
for all (m in O-D set) do
  use Warshall-Floyd algorithm to calculate shortest distance (load distance) D, and shortest path;
  if (time of shortest operating path t_a η_a^{m,p} > service level T^m) then
    modify service level, reconstruct the service network;
  else
    store shortest distance in D_1 and shortest path p_1;
    for all (services in shortest route P_1) do
      delete one service in shortest path P_1, recalculate shortest distance and shortest path,
      choose the shortest one as second-shortest distance D_2 and second-shortest path P_2;
      if (time of shortest operating path > service level T^m) then
        break;
      else
        store second short distance and second short path;
        for all (leg in shortest path P_2) do
          delete one leg in second short path P_2, recalculate shortest distance and shortest path,
          choose the shortest one as third-shortest distance D_3 and third short path P_3;
          ...
        end-do
      end-if
    end-do
  end-if
  Select one service path in several shortest paths and obtain distance of selected service path of O-D pair m;
end-do
```

Pseudocode 2: Pseudocode for service path selection.

The detailed heuristic algorithm is as follows.

Step 1 (initialisation). First, based on the physical transport network and passenger transport timetable, construct the logical network $G(N, A)$ and specify the parameters. Next, according to the logical network and the OD demand matrix, set δ_s, f_s, and t_s as 0 and specify the initial service level T^m, $m \in M$, based on market survey (a survey about consumer expectation on delivery time between each OD pair is conducted before opening such service. The average expected time will be used as the initial service level).

Step 2 (construct an initial service network). According to the OD demand set, find the shortest path between the existing OD pairs, open corresponding services in the path, and arrange the path service frequency so that all the demand can be met. An initial service network will be generated. The pseudocode for this step is illustrated in Pseudocode 1.

Step 3 (select service path). For each $m \in M$, according to the demand Q^m and service level T^m, using K-shortest path routing algorithm (Floyd-Warshall algorithm), select the feasible service path p_m from the service paths P. The pseudocode is presented in Pseudocode 2.

```
Network Flow Distribution
for all (m in O-D set) do
  decompose selected service path into service(s);
  if (service path contains single service) then
    service design decision δ_s = 1;
  else
    set all the service design decisions for the services included in the path as 1.
  end-if
end-do
for all (δ_s = 1) do
  for all (paths of OD through this service) do
    if (the path service frequency of the OD > f_s) then
      f_s = the path service frequency of the OD;
    else
      f_s unchanged;
    end-if;
    assigned flow (w_a^m) = the sum of the demand on the path of OD through this service;
  end-do
  f_s based on flow (f_sv) = flow divided by the capacity for service s, V_s, rounded up;
  if (f_s based on flow (f_sv) > f_s) then
    replace f_s by f_sv;
  else
    f_s unchanged;
  end-if
  if (f_s > F_s) then
    change selected service path or make f_s equal to F_s, and distribute exceeding flow to other service path,
    record the distance of new service path as exceeding flow;
  else
    calculate service capacities of each service, service capacities = service frequency f_s × coach capacity for service s, V_s;
  end-if
end-do
```

Pseudocode 3: Pseudocode for network flow distribution.

Step 4 (network flow distribution). The network flow distribution must meet the service level constraint and the service capacity constraint. If the current service path p_m can meet the demand, then set all the service design decisions; otherwise, the carrier can either increase the frequency or open a new service. In addition, the carrier can decrease the service level for those unassigned demands and assign them to other service paths. The pseudocode is presented in Pseudocode 3.

Step 5. Compute the total cost for each network solution with feasible paths for each OD and select the network design solution with minimum total cost. If this solution can meet the service level, then it will be the final solution; otherwise, adjust the service level and go to Step 2 until a cost minimisation solution that also fulfils the service level is found.

5. Case Study

Our model and algorithm are tested in our research partner company that operates express parcel transport service using passenger transport in Liaoning Province, China. The physical network of the passenger transport is depicted in Figure 5.

The nodes in Figure 5 represent the main stations (nodes) in different cities of physical network and the highways (arcs) between cities. There are 27 direct routes between the 14 cities, double-directed with 253 daily shifts. The distances and running times are listed in Table 1. To analyse the service and service path, Figure 5 is further decomposed as Figure 6. Based on the company's operations history data in 2013, we calculate the shift numbers for each OD pair, daily demand Q^m, average service level T^m, and the OD distances in the H/S network with stops in Tables 2–6, respectively.

Other cost parameters are listed in Table 7.

The decision period for the network flow distribution is one day, that is, 12 hours.

To evaluate the performance of our approach, we compare our solution with the carrier's solution as well as a constrained solution.

The Carrier's Solution. Currently, the carrier is using a general rule of thumb to design the service network opening all direct routes according to the OD demand. Collection occurs at the origin and destination stations. Therefore, the carrier's

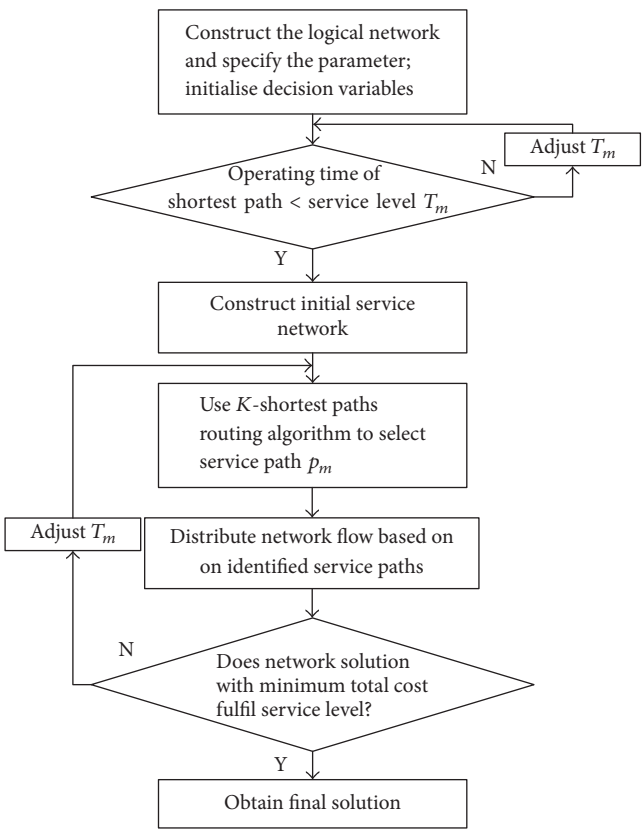

Figure 4: Flow chart of the heuristic algorithm.

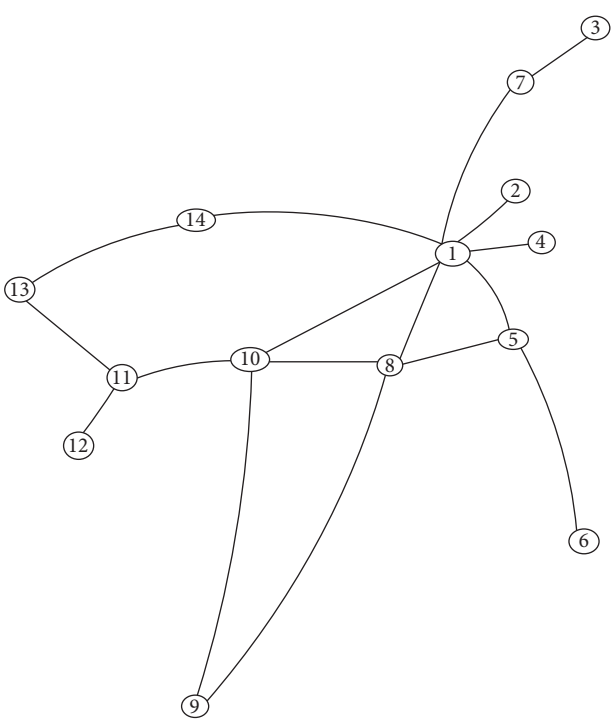

Figure 5: Physical network structure of passenger transport.

service matrix $E_0(\delta_s)$ and its corresponding service frequency $E_0(f_s)$ are as follows:

$$E_0(\delta_s) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}.$$

$$E_0(f_s) = \begin{bmatrix} 0 & 3 & 3 & 0 & 0 & 2 & 3 & 0 & 2 & 3 & 2 & 2 & 2 & 2 \\ 3 & 0 & 0 & 3 & 0 & 2 & 0 & 2 & 1 & 2 & 2 & 2 & 2 & 2 \\ 3 & 0 & 0 & 1 & 2 & 1 & 0 & 2 & 1 & 2 & 1 & 0 & 1 & 1 \\ 0 & 3 & 1 & 0 & 3 & 2 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 3 & 0 & 3 & 0 & 2 & 2 & 0 & 2 & 2 & 2 & 2 \\ 2 & 2 & 1 & 2 & 3 & 0 & 1 & 2 & 0 & 0 & 1 & 0 & 1 & 1 \\ 3 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 2 & 2 & 3 & 2 & 2 & 0 & 0 & 2 & 0 & 2 & 0 & 2 & 0 \\ 2 & 1 & 1 & 0 & 2 & 0 & 1 & 2 & 0 & 2 & 2 & 2 & 2 & 2 \\ 3 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 2 & 1 & 0 & 2 & 1 & 0 & 2 & 2 & 0 & 0 & 0 & 3 & 2 \\ 2 & 2 & 0 & 0 & 2 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 2 & 1 & 0 & 2 & 1 & 1 & 2 & 2 & 0 & 3 & 0 & 0 & 3 \\ 2 & 2 & 1 & 0 & 2 & 1 & 0 & 0 & 2 & 0 & 2 & 0 & 3 & 0 \end{bmatrix} \quad (16)$$

Although opening as many as possible direct services can reduce the service time and transfer operation cost, the fixed cost is very high. As a benchmark, we design a constrained strategy that allows the hub to transfer parcels without setting up stops and transshipment centre.

Constrained Solution. It concerns passing through hubs without setting up stops and transshipment centre. For nondirect OD route, the hub is used to transfer the parcels, and collection is allowed in stations on the K-shortest route. Using the proposed heuristic algorithm, we can get the

Table 1: Passenger transport distance and running time between ODs (km, min).

OD	Distance (km)	Running time (min)
(1, 2)	80	110
(1, 3)	190	160
(1, 6)	242	210
(1, 7)	140	125
(1, 9)	400	320
(1, 10)	162	120
(1, 11)	230	210
(1, 12)	287	250
(1, 13)	252	260
(1, 14)	222	190
(2, 4)	60	80
(4, 5)	120	120
(4, 6)	300	250
(4, 8)	156	150
(5, 6)	190	150
(5, 9)	392	290
(5, 12)	347	250
(6, 8)	260	210
(8, 11)	220	180
(8, 13)	310	240
(9, 10)	311	220
(9, 11)	390	300
(9, 12)	450	315
(9, 13)	482	340
(9, 14)	486	340
(11, 13)	93	90
(13, 14)	151	120

design variable matrix $E_1(\delta_s)$ and its corresponding service frequency $E_1(f_s)$ as follows:

$$E_1(\delta_s) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$E_1(f_s) = \begin{bmatrix} 0 & 3 & 3 & 0 & 0 & 2 & 3 & 0 & 2 & 3 & 2 & 2 & 2 & 2 \\ 3 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 3 & 2 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 3 & 0 & 0 & 2 & 0 & 0 & 1 & 0 & 0 \\ 2 & 0 & 0 & 2 & 3 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 2 & 0 & 0 & 0 & 0 & 2 & 0 & 2 & 0 \\ 2 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 & 0 & 3 & 0 \\ 2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 3 & 0 & 0 & 3 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 0 \end{bmatrix}. \tag{17}$$

Our Solution. H/S transport with 1 hub and 13 nodes allows stop and transshipment. Collection is allowed in the collection stop and transshipment centre. Using the algorithm, we can calculate the design variable matrix $E_2(\delta_s)$ and its corresponding service frequency $E_2(f_s)$ as follows:

$$E_2(\delta_s) = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$E_2(f_s) = \begin{bmatrix} 0 & 3 & 3 & 0 & 0 & 2 & 3 & 0 & 2 & 3 & 2 & 2 & 2 & 2 \\ 3 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 2 & 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 2 & 1 & 0 & 0 \\ 2 & 0 & 0 & 2 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 2 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 0 & 3 & 0 \\ 2 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 3 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 0 \end{bmatrix}. \tag{18}$$

Table 2: Passenger transport shift numbers between OD pairs (times).

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1		18	3	0	0	25	19	0	11	26	19	9	19	19
2	18		0	12	0	0	0	0	0	0	0	0	0	0
3	3	0		0	0	0	0	0	0	0	0	0	0	0
4	0	12	0		2	2	0	3	0	0	0	0	0	0
5	0	0	0	2		4	0	0	4	0	0	1	0	0
6	25	0	0	2	4		0	2	0	0	0	0	0	0
7	19	0	0	0	0	0		0	0	0	0	0	0	0
8	0	0	0	3	0	2	0		0	0	4	0	4	0
9	11	0	0	0	4	0	0	0		3	8	3	4	3
10	26	0	0	0	0	0	0	0	3		0	0	0	0
11	19	0	0	0	0	0	0	4	8	0		0	26	0
12	9	0	0	0	1	0	0	0	3	0	0		0	0
13	19	0	0	0	0	0	0	4	4	0	26	0		5
14	19	0	0	0	0	0	0	0	3	0	0	0	5	

Table 3: Average daily demand Q^m for each OD pair m (items).

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	56	48	0	0	180	136	0	232	167	178	133	159	87
2	56	0	0	43	0	38	0	50	39	6	38	40	6	9
3	48	0	0	37	19	4	0	18	71	15	12	0	42	29
4	0	70	29	0	14	10	0	25	0	0	0	0	0	0
5	0	0	11	18	0	33	0	19	32	0	10	8	6	7
6	180	75	7	16	27	0	20	79	0	0	5	0	8	6
7	136	0	0	0	0	17	0	0	11	0	0	0	14	0
8	0	68	11	27	39	50	0	0	65	0	40	0	39	0
9	232	65	40	0	32	0	18	80	0	0	77	21	36	27
10	167	34	34	0	0	0	0	0	0	0	0	0	0	0
11	178	72	9	0	9	12	0	22	35	0	0	0	87	97
12	133	31	0	0	7	0	0	0	27	0	0	0	0	0
13	159	10	38	0	12	8	14	45	31	0	129	0	0	76
14	87	17	7	0	5	6	0	0	33	0	123	0	72	0

Table 4: Service level T^m for each OD pair m (hours).

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	4	4	—	—	6	4	—	8	4	6	6	8	6
2	4	0	—	4	—	10	—	6	12	8	8	10	10	8
3	4	—	0	—	8	12	—	10	14	10	12	—	14	12
4	—	4	—	0	4	6	—	4	—	—	—	—	—	—
5	—	—	8	4	0	4	—	6	10	—	10	8	10	10
6	6	10	12	6	4	0	12	6	—	—	16	—	16	16
7	4	—	—	—	—	12	0	—	14	—	—	—	14	—
8	—	6	10	4	6	6	—	0	6	—	6	—	6	—
9	8	12	14	—	10	—	14	6	0	6	8	8	8	8
10	4	8	10	—	—	—	—	—	6	0	—	—	—	—
11	6	8	12	—	10	16	—	6	8	—	0	—	4	8
12	6	10	—	—	8	—	—	—	8	—	—	0	—	—
13	8	10	14	—	10	16	14	6	8	—	4	—	0	4
14	6	8	12	—	10	14	—	—	8	—	8	—	4	0

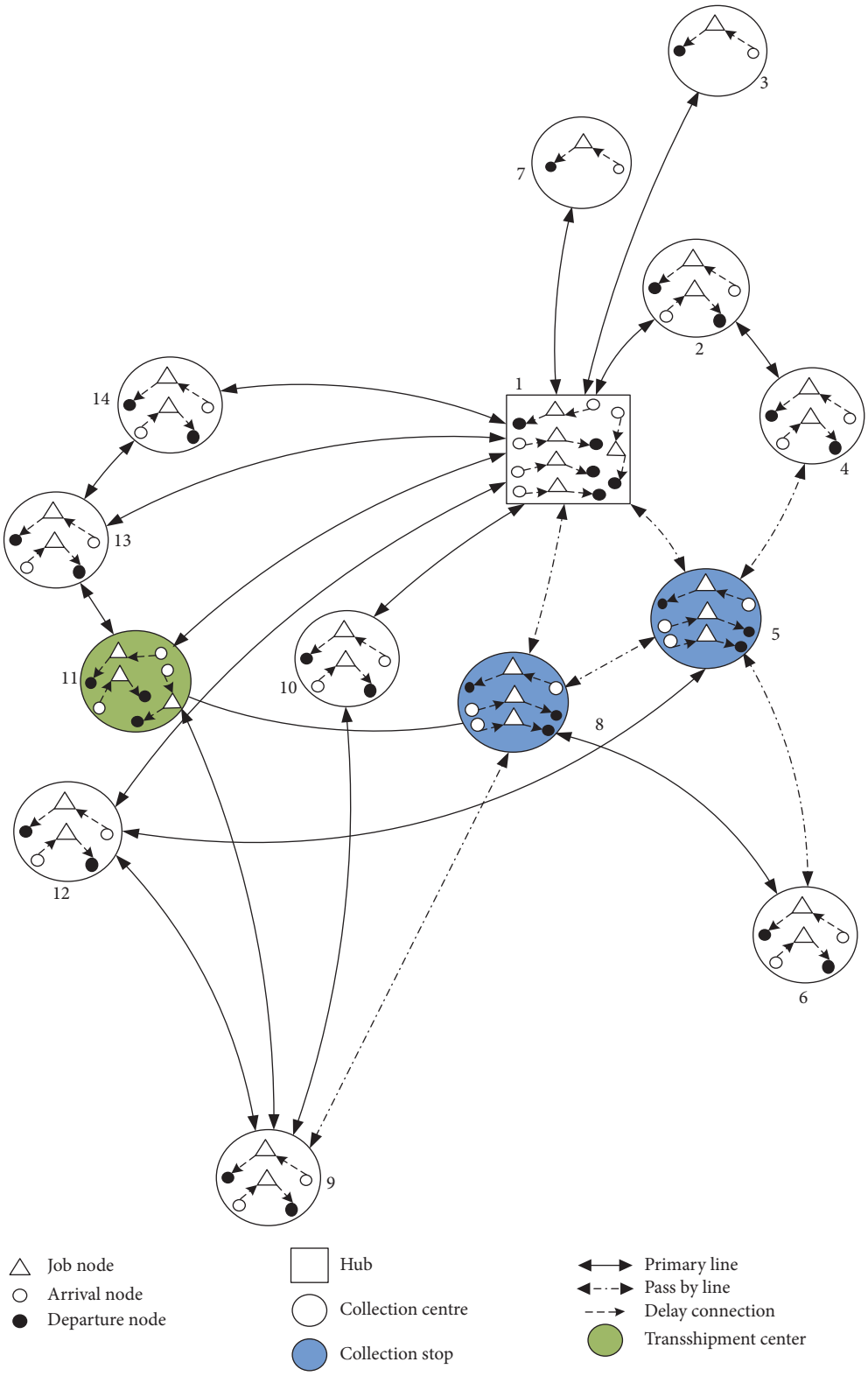

Figure 6: Decomposed network.

Table 5: Service capacity in each OD pair (items).

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	9000	1500	0	0	12500	9500	0	5500	13000	9500	4500	9500	9500
2	9000	0	0	6000	0	0	0	0	0	0	0	0	0	0
3	1500	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	6000	0	0	1000	1000	0	1500	0	0	0	0	0	0
5	0	0	0	1000	0	2000	0	0	2000	0	0	500	0	0
6	12500	0	0	1000	2000	0	0	1000	0	0	0	0	0	0
7	9500	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	1500	0	1000	0	0	0	0	2000	0	2000	0
9	5500	0	0	0	2000	0	0	0	0	1500	4000	1500	2000	1500
10	13000	0	0	0	0	0	0	0	1500	0	0	0	0	0
11	9500	0	0	0	0	0	0	2000	4000	0	0	0	13000	0
12	4500	0	0	0	500	0	0	0	1500	0	0	0	0	0
13	9500	0	0	0	0	0	0	2000	2000	0	13000	0	0	2500
14	9500	0	0	0	0	0	0	0	1500	0	0	0	2500	0

Table 6: Distance between OD pair for hub-spoke service network with stopping station (km).

OD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	80	190	80	110	242	140	0	400	162	230	287	252	222
2	80	0	0	60	0	322	0	120	480	242	310	367	332	302
3	190	0	0	210	300	432	0	240	590	352	420	0	442	412
4	80	60	210	0	120	300	0	156	0	0	0	0	0	0
5	110	0	300	120	0	190	0	90	392	0	300	347	312	300
6	242	322	432	300	190	0	382	260	0	0	420	0	445	460
7	140	0	0	0	0	382	0	0	540	0	0	0	392	0
8	0	120	240	156	90	260	0	0	310	0	220	0	310	0
9	400	480	590	0	392	0	540	310	0	311	390	450	482	486
10	162	242	352	0	0	0	0	0	311	0	0	0	0	0
11	230	310	420	0	300	420	0	220	390	0	0	0	93	244
12	287	367	0	0	347	0	0	0	450	0	0	0	0	0
13	252	332	442	0	312	445	392	310	482	0	93	0	0	151
14	222	302	412	0	300	460	0	0	486	0	244	0	151	0

Table 7: Cost parameters in the case study.

Item	Unit cost	Unit
Operations cost at station	6	Yuan/item
Unit transport cost C_s	0.05	Yuan/km/item
Fixed cost for opening a service (Φ_s/route/day)	32.3	Yuan/route/day
Trunk usage cost	0.4	Yuan/km/shift

The computation results are listed in Table 8.

(1) Cost Structure Analysis

Service Network Design Cost ($Z_1 + Z_2$). The opened services for the constrained solution and our solution are 52 and 44, and the average design costs per day are 13332.4 Yuan and 10487.6 Yuan, reduced by 54.1% and 63.9%, respectively, compared to the carrier's solution whose average cost is 29047 Yuan. It can be seen that our solution can greatly reduce the number of services and design costs.

Service Network Operations Cost Z_3. The operations costs for carrier's solution and constrained solution are the same because the network flow distributions are the same, while our solution results in a cost reduction per day of 4814 Yuan by adding collection stops and transshipment centres in the service paths. The reason behind it is that, by adding collection stops and transshipment centres, some parcels that should be transported via the hub may be assigned to other service paths that have lower operations cost.

Total Average Cost Z. Through the cost structure analysis, we can see that the network operations cost is the major part, accounting for 89.6% and 91.3% in the constrained solution and our solution, respectively. The total costs for the latter two solutions reduce by 11.0% and 16.3% compared to the carrier's

Table 8: Computation results for different heuristics.

Heuristics	Network structure	Service level constraint	Capacity constraint	Passenger transport frequency constraint	Total service frequency	Service number	Service paths number	Average cost per day			
								Fixed cost Z_1	Frequency related cost Z_2	Operations cost Z_3	Total cost Z
Carrier's solution	OD direct reach	Met	Not considered	Not met	218	110	110	3553.0	25494.0	114439.7	143486.7
Constrained solution	H/S without stop	Mostly met	Considered	Met	116	52	110	1679.6	11652.8	114439.7	127772.1
Our solution	H/S with stop	Met	Considered	Met	102	44	110	1421.2	9066.4	109625.7	120113.3

Table 9: The impact of demand Q^m on the HPTB-EPS network.

Solution number	Change of demand	Service frequency	Service capacity	Average cost			
				Z_1	Z_2	Z_3	Z
0	+0%	102	500	1421.2	9066.4	109625.7	558692.1
1	+20%	102	500	1421.2	9066.4	131550.8	580617.2
2	+50%	102	500	1421.2	9066.4	164438.6	613505.0
3-1	+100%	102	500	1421.2	9066.4	219251.4	668317.8
3-2	+100%	108	250	1421.2	9583.2	219251.4	668834.6
4	+150%	104	500	1421.2	9196.0	274064.3	723260.3
5	+200%	108	500	1421.2	9583.2	328877.1	778460.3
6	+250%	108	500	1421.2	9583.2	383690.0	833273.2
7	+300%	112	500	1421.2	9848.8	438502.8	888351.6
8	+350%	116	500	1421.2	10352.8	493315.7	943668.5
9	+400%	118	500	1421.2	10416.8	548128.5	998545.3

solution. Therefore, our approach to optimising the design of HPTB-EPS network is effective.

(2) The Balance between Service Level and Cost. The carrier's solution opens all direct services on each OD pair, meeting the service level with a much higher design cost. However, the cost can be reduced through our solution by adding collection stops and transshipment centres to appropriately select the service path while meeting the service level.

(3) Sensitivity Analysis on Demand Q^m. The demand has important impact on the HPTB-EPS network design and performance. In this section, we conduct a sensitivity analysis to see the impact of the demand on the solution. Based on the current demand data, we increase the demand from 0% to 400% (which is a current trend in Chinese express parcel market) and compute the service frequency and average costs which are listed in Table 9 (the relevant data could be obtained upon request).

From Table 9, we can see that, with the increase of demand, the fixed cost for opening service Z_1 does not change, meaning that no new services are opened, while the frequency-related cost Z_2 increases slightly; that is because the service frequency increases slightly to fulfil the increased demand. The operations cost Z_3 increases proportionally with the size of demand increase. That is because the operations cost is directly related to the demand.

Looking at the solutions, we know that when the demand increases by 100%, our original solution can still meet it; while the demand triples, the solution needs to increase the service frequency on routes 1-5-6 and 1-8-9. When the demand goes up further to 300%, the service frequencies on routes 1-2 and 1-13 also increase. Similar situation occurs when the demand increases by 400%. We can see that our approach has great robustness and flexibility to deal with the fluctuation of demand.

To investigate the impact of service capacity, we half the capacity of scenario 3-1 in scenario 3-2 and find that the service frequency and associated cost increase significantly, demonstrating the sensitivity of solution on the capacity. This means that, by increasing the capacity of trunk, both the service frequency and cost will be reduced.

6. Conclusions

In this paper, we investigate a particular service network design problem for HPTB-EPS. Using time-space network formulation, we decompose the physical network nodes and characterise the abstract service network to represent the spatiotemporal movement of parcels. Then, we propose the concept of service path which plays an important role in our analysis to characterise the realisation of demand fulfilment. Based on these, we develop mixed-integer programming with more details of service analysis, such as service type, spatial distribution, time, cost, and capacity. A heuristic algorithm based on decomposition is adapted to solve the proposed model.

We test our model using real data from our research partner company and compare our solution with the carrier's solution. The result shows that our solution can significantly reduce the average cost. By allowing transfer and appropriately selecting service paths, the carrier can reduce the cost while fulfilling demand. Our sensitivity analysis demonstrates that our approach is very robust and flexible with demand turbulence. In addition, the solution is quite sensitive to the service capacity.

However, our paper is not without limitations. First, only one-type commodity is considered in the model; therefore incorporating multiple commodities may be extended in the future research. Second, our solution is only compared with the carrier's solution. The effectiveness of our algorithm should be tested and improved in the future.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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