**Highway Passenger Transport based Express Parcel Service (HPTB-EPS) Network Design: Model and Algorithm**

**Abstract**: Highway Passenger Transport based Express Parcel Service (HPTB-EPS) is an emerging business which 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 shows that our model and algorithm are effective and better than the current decision rule. The sensitivity analysis demonstrates the robustness and flexibility of the solutions of the model.

**Key words**: Service network design, HPTB-EPS, decomposition-based heuristic algorithm

**1 Introduction**

Highway passenger transport based express parcel service (HPTB-EPS) is a recently emerging business model for highway passenger transport 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 transport 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, the HPTB-EPS has been developing rapidly in recent years thanks to the soaring e-commerce activities. The size of express parcels market has exceeded one billion CNY (Chinese Yuan) and is increasing 30% annually (Yang et al., 2013). The advantages of passenger transport system in delivering small express parcels lie in the facts that (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 transhipment; (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[[1]](#footnote-1). 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[[2]](#footnote-2). 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[[3]](#footnote-3). 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, i.e. which route should open the service, on what frequency and how to transport the parcels in the network. Because the costs of resources devoted to the business are calculated by the participated company including the route license fee which is a lump sum fee for the use of the route, the delivery cost by each shift since the parcels need to be loaded and unloaded by the driver, so opening a service on a route is costly and not all routes have enough demand. Therefore, the carrier needs to decide which route should open such service and on what frequency; In addition, based on the opened services, how to transport the parcels in the network, i.e. network traffic distribution should be decided so that the promised service level is satisfied. 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 transhipment nodes, the connection between different services and the operations during this connection should be explicitly considered in this problem. The resulted 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, cost related to the frequency etc.

 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 connections 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, which form a logical network which is different from the physical network. As far as we know, this is the first 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 logical network, incorporating the capacity and frequency constraints. The resulting mixed integer programming model, although looks similar to traditional service network design model at first glance, has different decisions and constrains. 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 solving this new problem. In sum, our research uses existing techniques to solve an untapped problem, extending the boundary of related theories and techniques.

 The remainder of 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 (1984) are the first to convert the transport network decision problem to an integer programming problem and propose a generic design model, which is 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 (1986) propose a generic model for freight transportation service network design with frequency. Kim and Barnhart (2007) base on the characteristics of flight network develop a charter airline service network design model as a mixed integer programming. Lai and Lo (2004) study the ferry service network design problem. Crainic (2000) classifies the service network design problem as static and dynamic problems with the former focusing on transport route, service frequency and the projection of demand on the network flow, while the latter focusing on the time dimension. Broadly speaking, three types of models: path formulation, node-arc formulation and tree formulation have been proposed in the literature (Wieberneit, 2007). Different decisions should be made in this general problem, e.g. service selection, frequency, speed, consolidation, traffic flow distribution etc. Based on different application setting, different combinations of decisions have been modelled (see the reviews in (Apivatanagul, 2008; Cordeau et al., 1998; Crainic, 2000; Crainic and Kim, 2007; Wieberneit, 2007; Zhu, 2011). In recent years, asset management issues are incorporated into the SND problems, resulted in the so-called *service network design with asset management* (SNDAM) (Andersen et al., 2009; Crainic et al., 2014). 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 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 in traditional SND models. 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 (Jarrah et al., 2009; Yan and Chen, 2002), Benders decomposition methods (Costa, 2005), branch-and-bound algorithms (Crainic et al., 2001) and so on. For more comprehensive review in the solution methods, the readers are referred to Zhu (2011). Recent years, decomposition-based algorithms have gained more research attention. Teypaz et al. (2010) 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 (2007) 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 yet been dedicated to this emerging problem. Zuo and Yang (2011) study the competition and marketing strategy for carriers implementing HPTB-EPS based on a survey. Yang et al. (2013) propose a model to optimize the parcel delivery paths for HPTB-EPS given the services provided. In their research, the service network is given and the main focus is on the network flow distribution. In our 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.

**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 the 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 satisfy 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, capacity etc.; the second is *service path selection*, that is, select a path from the origin to destination; and the third is *network flow distribution*, i.e. 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, stop and temporary storage etc., 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 which 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 (H/S) network is quite popular due to both the cost advantage of H/S network and the time advantage of direct network. Generally, the coaches don’t 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 as collection stop, which is not a main station, as stated in the blue circle in Figure 1. Another type of node is called transhipment centre, used to transfer the parcels from one coach to others due to lack of direct route.



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

Different with a hub, this kind of nodes have much less connections and operations. Its core function is to connect and transfer. In all, we have four types of nodes and the parcels can go through different routes.

**3.1** HPTB-EPS space-time network

To capture the unique feature of HPTB-EPS that operations 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.



Figure 2. Decomposed HPTB-EPS network

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 etc. or waiting for next coach. To represent the time-dependent characteristic of the problem, we use a time-space network which is commonly used in the literature (Andersen et al., 2009). Figure 3 depicts the time and space characteristics of the HPTB-EPS network presented in Figure 2 explicating the operations in the nodes.



Figure 3. Example of Time-Space network

In Figure 3, 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 the Z axis, 0 means the starting time at original place, the first symbol ‘a’, ‘j’ or ‘d’ denotes arrival, job or departure nodes, and the number or letter in brackets 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 transportation for parcels from one station to another station using the existing passenger transport. Service decision here is the key decision in HPTB-EPS network design which is to design the service paths to satisfy various demands. To satisfy a certain demand in an O-D pair, the carrier needs to select a set of services (transportation from one station to another) and connections (coach waiting, loading and unloading, temporary storage, parcel consolidation etc.) between transportation services, which forms a service path, also known as service route.

3.2.1 Service analysis

Using denote delay connection in a station, connecting the arrival node and the departure node. The set denotes the transportation services, which may include a few collection stops. Thus, the connections in a service network include transportation service and delay connection. The essence of the problem is how to use the network resources to satisfy network flow demand. The attributes of such network include the service type, space distribution, time, cost and capacity etc.

1. Service type

Based on passenger transportation system, parcel express services can be classified into direct transport service and transhipment service. The former means the parcels can be transported directly on non-stop routes, while the latter refers to that parcels need to be transferred between the origin and destination.

1. Service space distribution

The service network is based on the existing passenger transport system. Therefore, the space distribution of the services is closely related to that of the passenger transport. The connection and node (the decomposed nodes) form a logical abstract network which is different from the physical network.

1. 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 define 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 . The time points in the time sequence, should fall in the station time-window and the time-window of the passenger transport , that is

,

where is the set of station opening time and is the time interval to which the passenger timetable is belonging.

1. Service design cost

Opening a service between two stations usually occurs a fixed cost , including the fee payed for the coach licence to use the route, and variable cost , including the cost on the usage of coaches which is related to service frequency. These costs are called service design cost and can be formulated as follows:

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

1. Service capacity

Because the parcel service is attached to the passenger transport, the service capacity is the remaining room of the coach trunk. (Note: in our later example, the remaining capacity is two thirds of the trunk space).

1. Service level

Service level refers to the quality of the parcel transportation under the current network resources, including timely indicator, reliability etc. In this research, time is the only measure for service level, since it is the most important indicator consumer concerns. The total travel time for a parcel should be less than the service level.

3.2.2 Service paths selection

In practice, opening direct service in all the O-D pairs is neither economic nor possible in some cases. Therefore, the carrier needs to select a set of service and delay connection, forming a sequence as a service path (denoted by ) to fulfil the demand. The connection of services will impact the service path on time, cost and capacity, which will in turn impact on the service level.

1. Time. The incoordination between service frequency and time sequence may cause failure of service combination. Therefore, when combining services, the service sequences and should be coordinated.
2. Cost. When combining services, the cost will include the service design cost and the cost generated in the delay connection 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 allocate the transportation 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, size etc.

 Usually, an O-D set can be used to describe the demand origins and destinations. Here, we use to denote the set of all stations including the hub and transhipment centre as well as collection stops, and to denote demand O-D set, and there will be . The time used between each O-D pair is dependent on the selected service path, therefore determined by the corresponding time sequence . The network flow size means the total demand for each O-D 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 denote the size of demand between O-D pair .

 The essence of network flow distribution is to select appropriate service paths to satisfy demand 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 to denote the allocated demand on the connection . The total demand allocated to service cannot exceed the total capacity in the decision period; Second, the total time on the selected service path should not exceed the service level. 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.

1. **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 transportation network is given.

This assumption is reasonable since the HPTB-EPS network is attached to the passenger transportation system. The layout, size and connection 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 stations, 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 is reliance 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, so in the tactical planning horizon, we can think that the demand is stable.

**Assumption 5**: The pickup 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

 : the set of all stations,

 : the set of all demand O-D, . is the origin node and destination node for O-D pair

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

: the set of arrival nodes,

: the set of departure nodes, . The number of departure nodes is dependent on the service frequency at the departing station

 : the set of all parcel transport services, *s*.

: the set of all delay connections including loading, unloading, sorting, transhipment etc. This set is determined by and

: the set of all connections, including the transport service and the delay connections, i.e.

: the set of all the service path *p* satisfying the service level of O-D pair , *pPm*

*P*: the set of all the service paths.

1. Parameters

: the quantity of demand on O-D pair

: the service level for O-D pair

: the decision period for the network flow allocation (usually hours due to the passenger

transport only operates in day time.)

: the time a parcel passing connection

: the station time-window

 : time-window for passenger transport timetable.

: the passenger transport frequency on service

: fixed cost for opening service

: frequency related variable cost for opening service

: the unit cost of passing the connection

: the capacity for service , i.e. the remaining room of one coach trunk or the parcel quantity loading in the remaining room of one coach truck

: indicator of whether the selected service path for demand contain connection , if yes, its value is 1, otherwise, it is 0.

: the quantity of allocated demand on connection

1. Decision variables

: the design variable for service .

: the frequency for service

: the allocated demand of O-D on service path

In terms of the objective, cost minimisation is usually used as the optimization objective in service network design problem in practice. Based on our interview of the research partner carrier, cost minimization 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 parcel express industry. As the demand is increasing and the service network is expanding, cost balance and control 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 the tactical planning horizon is (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:

 (1)

 (2)

 (3)

(4)

 (5) (6) (7) (8)

Constraint (1) balances the network flow and the service paths, showing the network flow conservation principle, i.e. the demand equals the sum of allocated demand on service path so that all the demand will be allocated to appropriate service path. Constraint (2) balances demands between the connection and the service paths so that the sum of allocated demand on service paths containing connection should be equal to the demand allocated to the connection . Constraint (3) is the capacity constraint, meaning the total allocated demand should not exceed the service capacity. Constraint (4) is the frequency constraint, that is, the service frequency should not exceed the passenger transport frequency. Constraint (5) is the service level constraint, meaning that the total service time should not exceed the promised service level on that O-D pair. Constraint (6) is the time-window constraint, meaning that the time points in service time sequence should fall in the station and passenger timetable time-window. Constraint (7) defines the network flow distribution rules that the distribution decisions should take integer values. Constraint (8) defines 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 (Wieberneit, 2007). In this paper, we use the idea similar to Teypaz et al. (2010) 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 has been discussed in detail in Teypaz et al. (2010). The idea of the algorithm is presented in the Figure 4.



Figure 4. Flow chart of the heuristic algorithm

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 and specify the parameters. Next, according to the logical network and the O-D demand matrix, set , and as 0 and specify the initial service level based on market survey[[4]](#footnote-4).

Step 2: Construct an initial service network

According to the O-D demand set, find the shortest path between the OD, and open corresponding services in the path, and arrange the path service frequency so that all the demand can be satisfied. An initial service network will be generated. The pseudo code for this step is illustrated in Figure 5.

**Construct initial service network**

for all ( in O-D demand set with ) do

 find the corresponding for each .

use Warshall-Floyd algorithm to calculate the shortest distance (load distance) for each , store shortest path as operating path ;

if ( ==0) then

set all the service design decisions in the shortest path as 0, service frequency *fs*=0, operating path = 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 and service frequency on the path based on demand as , round up to the nearest integer;

if ( > ) then

 set the path service frequency as , i.e.

else

 set the path service frequency as , i.e. ;

end-if

end-if

end-do

Figure 5. Pseudo-code for initial service network construction

Step 3: Select service path

For each , according to the demand , service level , using *K*-shortest path routing algorithm (Warshall-Floyd algorithm) select the feasible service path from the service paths . The pseudo-code is presented in Figure 6.

**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 > service level ) then

 modify service level, reconstruct the service network;

 else

 store shortest distance in and shortest path ;

for all (services in shortest route ) do

delete one service in shortest path , recalculate shortest distance and shortest path, choose the shortest one as second-shortest distance and second-shortest path ;

if (time of shortest operating path > service level ) then

break;

else

store second short distance and second short path;

for all (services in shortest path ) do

delete one service in second short path , recalculate shortest distance and shortest path, choose the shortest one as third-shortest distance and third short path ;

……

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

Figure 6. Pseudo-code for service path selection

Step 4: Network flow distribution

The network flow distribution must satisfy the service level constraint and the service capacity constraint. If the current service path can satisfy the demand, then set all the service design decision; otherwise, the carrier can either increase the frequency, or open a new service. In addition, the carrier can decrease the service level for those unallocated demand and allocate them to other service paths. The pseudo-code is presented in Figure 7.

**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 =1;

else

 set all the service design decisions for the services included in the path as 1.

end-if

end-do

for all (=1) do

for all (paths of OD through this service) do

 if (the path service frequency of the OD >) then

 = the path service frequency of the OD;

 else

 unchanged;

 end-if;

 allocated flow ()=the sum of the demand on the path of OD through this service;

end-do

 based on flow ()=flow divided by the capacity for service , rounded up;

if ( based on flow ()>) then

replace by ;

else

 unchanged;

end-if

if (>) then

 change selected service path or make  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 frequencycoach capacity for service , ;

end-if

end-do

Figure 7. Pseudo-code for network flow distribution

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 satisfy 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 which also satisfies the service level is found.

**5 Case study**

Our model and algorithm are tested in our research partner company which operates express parcel transport service using passenger transport in Liaoning Province, China. The physical network of the passenger transport is depicted in Figure 8.



Figure 8. Physical network structure of passenger transport

The nodes in Figure 8 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 A1 in Appendix A. To analyse the service and service path, Figure 8 is further decomposed as Figure 9. Based on the company’s operations history data in 2013, we calculate the shift numbers for each O-D pair, daily demand , average service level and the O-D distances in the H/S network with stops in Table A2-A6, respectively.



Figure 9. Decomposed network

Other cost parameters are listed in Table 1.

Table 1 Cost parameters in the case study

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

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 O-D demand. Collection occurs at the origin and destination stations. The service frequency *fs* is at least 2. Therefore, the carrier’s service matrix and its corresponding service frequency) are as follows:

 = )=

Although opening as many as possible direct service 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 transhipment centre.

*Constrained solution*: transhipment via hubs without setting up stops and transhipment centre. For non-direct O-D 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 design variable matrix) and its corresponding service frequency) as below.

)= , )=

*Our solution:* H/S transport with 1 hub and 13 nodes allowing stop and transhipment. Collection is allowed in the collection stop and transhipment centre. Using the algorithm, we can calculate the design variable matrix) and its corresponding service frequency) as below.

)=)= 

The computation results are listed in Table 2.

Table 2 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 | Satisfied | Unconstrained | Unsatisfied | 218 | 110 | 110 | 3553.0 | 25494.0 | 114439.7 | 143486.7 |
| Constrained solution | H/S Without stop | Mostly satisfied | Constrained | Satisfied | 116 | 52 | 110 | 1679.6 | 11652.8 | 114439.7 | 127772.1 |
| Our solution | H/S With stop | Satisfied | Constrained | Satisfied | 102 | 44 | 110 | 1421.2 | 9066.4 | 109625.7 | 120113.3 |

1. Cost structure analysis

Service network design cost (): 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: 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 transhipment centres in the service paths. The reason behind it is that by adding collection stops and transhipment centres, some parcels which should be transported via the hub may be allocated to other service paths which have lower operations cost.

Total average cost: 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 cost for the latter two solutions reduce by 11.0% and 16.3% compared to the carrier’s solution. Therefore, our approach to optimising the design of HPTB-EPS network is effective.

1. The balance between service level and cost

The carrier’s solution opens all direct service on each O-D pair, satisfying the service level with a much higher design cost. However, the cost can be reduced through our solution by adding collection stops, transhipment centres to appropriately select the service path while meeting the service level.

1. Sensitivity analysis on demand

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 3 (the relevant data could be obtained upon request).

Table 3 The impact of demand on the HPTB-EPS network

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Solution No. | Change of demand | Service frequency | Service capacity | Average cost |
| *Z*1 | *Z*2 | *Z3* | *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 |

From Table 3, we can see that, with the increase of demand, the fixed cost for opening service does not change, meaning that no new services are opened, while the frequency related cost increases slightly, that’s because the service frequency increases slightly to satisfy the increased demand. The operations cost increases proportionally with the size of demand increase. That’s because the operations cost is directly related to the demand.

Looking at the solutions, we know that when the demand increase 100%, our original solution can still satisfy it, while the demand triples, the solution needs to increase the service frequency on route 1-5-6 and 1-8-9. When the demand goes up further to 300%, the service frequencies on route 1-2 and 1-13 also increase. Similar situation occurs when the demand increases 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. That means, 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 spatio-temporal 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 a mixed integer programming to model this problem. 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 satisfy 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, which many be extended to incorporate multi-commodity. Second, our solution is only compared with the carrier’s solution. The effectiveness of our algorithm should be tested and improved in the future.

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**Appendix A**

Table A1 Passenger transport distance and running time between ODs (km, min)

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

Table A2 Passenger transport shift numbers between O-D 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 A3 Average daily demand for each O-D pair (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 A4  Service level  foreach O-D pair (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 |

Table A5 Service capacity in each O-D 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 A6 Distance between O-D 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 |

1. . News from Changjiang Times, see http://www.changjiangtimes.com/2014/07/483222.html [↑](#footnote-ref-1)
2. . News from Tencent's stock, see http://stock.qq.com/a/20151117/038982.htm [↑](#footnote-ref-2)
3. . News from Zhejiang Sina, see http://zj.sina.com.cn/news/2015-07-25/detail-ifxfhxmp9549628.shtml [↑](#footnote-ref-3)
4. A survey about consumer expectation on delivery time between each O-D pair is conducted before opening such service. The average expected time will be used as the initial service level. [↑](#footnote-ref-4)