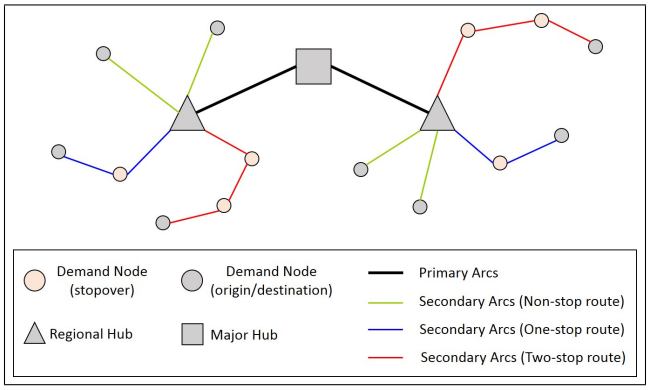
Service Network Design with Demand Allocation and Hub Location for an Express Package Carrier

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1. Introduction and Problem Definition

With the significant growth of e-commerce in retail sectors in the last two decades all over the world, the estimated value of e-commerce sales worldwide would be $ 4.2 and $ 4.9 trillion in 2020 and 2021 respectively, with an increase more than 200% compared to 2016 (Clement 2019). This growth in retail sector along with the increasing demand for express delivery service impose the carriers to design their service network and operate their fleet effectively and efficiently to meet the customer expectations. Motivated by the business problem of a major air express carrier, we consider an integrated air network design problem in which we consider routing, scheduling, demand node allocation and hub location decisions along with two routing policies for aircraft operations on an international hierarchical hub-and-spoke network for a major carrier (see Figure 1).

Figure 1 **Service network and sample routes.**



The spatial configuration of the network requires to consider routing and demand allocation decisions simultaneously. The main reason behind this requirement is that acquisition and operation cost of air fleet is tremendous even though the fleet consists of feeder aircraft. In adddition, all demand must be transported by the capacity of the given fleet. Besides, we propose to add a

third level to the hierarchical network for an effective fleet management. The new level incorporates location decisions on the network. We study this integrated problem in three phases, first we formulate the *base problem* which includes only aircraft routing and scheduling decisions. Base problem corresponds to service network design problems (SNDPs) in the literature (Armacost, Barnhart, and Ware 2002). Second, demand node allocation decisions are added into the formulation which takes place in *problem level 1*. And finally, minihub location decisions between regional hubs and some demand nodes on the network are incorporated into the formulation (see Figure 2). There are several studies which combines hub location/hub network design with either hierarchical networks (Alumur, Yaman, and Kara 2012) or express package delivery network design (Yu, Yang, and Yu 2016). Even though different combinations of these topics are already combined in the previous studies such as the combination of hub location and routing without scheduling (Rodríguez-Martín, Salazar-González, and Yaman 2014, Rothenbächer, Drexl, and Irnich 2016) and the combination of SNDP and location on a non-hierarchical network (Crainic et al. 2015, home location of vehicles or assets), the combination of all problem features listed above has never been addressed so far.

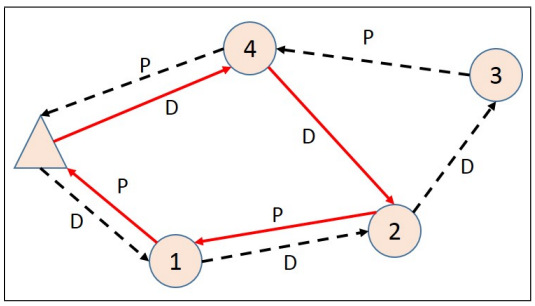
Figure 2 **Levels of the considered problem.**



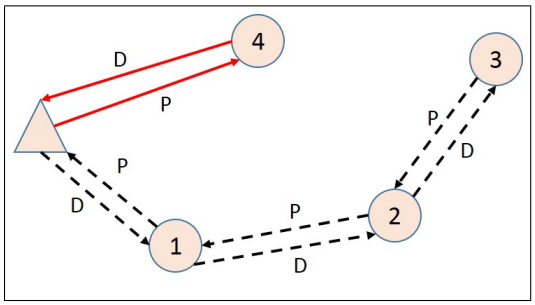
In addition to four type of decisions, we consider two types of routing policies. Any aircraft can be routed in two ways to achieve asset balancing on the network: (1) relaxed balanced routing (milk-runs), and (2) full balanced routing (dedicated routes). In the former, any aircraft can be operated on any pickup and delivery route pair as long as the origin of the pickup route and the destination of the delivery route are the same (see Figure 3(a)). In contrast, any aircraft must be operated on a pickup route which must be the associated return trip (opposite direction) of the delivery route in the latter (see Figure 3(b)).

Formally, our model decides the design of both primary and secondary arcs on the physical network by determining optimal routes and schedules for each type of fleet and considering projected demand volume, fleet, and operational restrictions including time commitments and the customs. In addition, the model also decides the location of minihubs on the second level and the node assignments both on second and third level. Last, the flow of volume is also determined inherently based on other decisions.

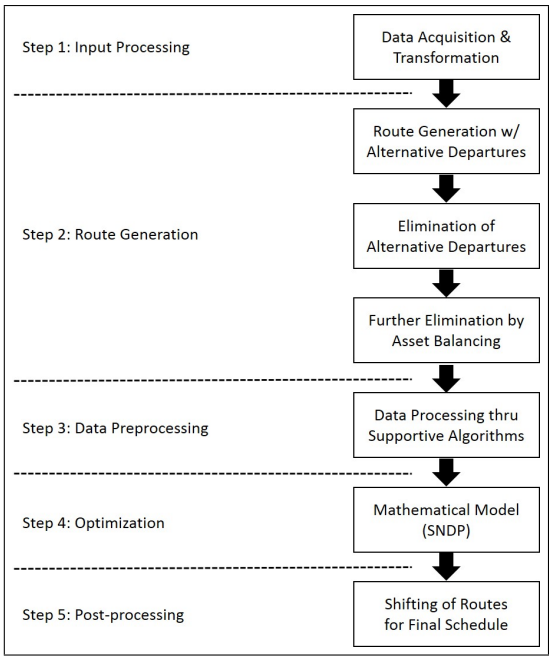
Figure 3 **Routing policies for asset balancing and flow of information within solution framework.**



(a) Relaxed balanced routing (milk-run).



(b) Full balanced routing (dedicated).



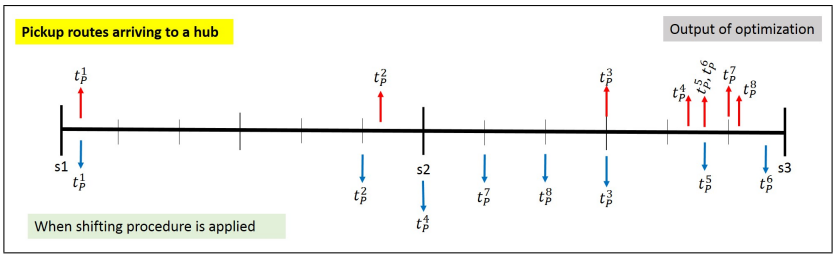
(c) The structure of the solution framework.

2. Solution Procedure and Implementation

We propose a multi-step solution procedure (Figure 3(c)) which includes: (1) data acquisition and wrangling, (2) feasible route (column) generation, (3) data preprocessing, (4) route-based service and hub network design formulation, and (5) route-conflict resolving (post-processing).

In the first step, the raw data is acquired from company's database and we implement wrangling on raw data to use it in our problem setting. Second, we generate all feasible routes by using an enumeration algorithm. It consists of three main parts: (1) feasible pickup route generation, (2) feasible delivery route generation, and (3) dummy route generation. In the first two parts, all feasible pickup and delivery routes are generated in three categories as non-stop, one-stop, and two-stop routes, respectively. In the third part, nine types of dummy routes which corresponds to activities other than transportation such as daytime waiting idle at demand node, overnight waiting idle at hub/minihub node, waiting during loading and loading operations at any node, and waiting during the sorting time window at hubs and minihubs. The entire feasible route set is obtained in two substeps, all feasible routes with alternative departure times are generated, first. Then, a portion of routes which depart from same node but have a different departure time are eliminated by implementing a standard rule. Third, all input data and the output of route generation step are processed for the route-based problem formulation. Route (path) based service network design problem is solved in the fourth phase by CPLEX OPL. Finally, the output is processed to eliminate departure/arrival time conflicts among the selected routes and the final solution for the problem is obtained (see Figure 4).

Figure 4 **An example on shifting of pickup routes.**



The proposed solution framework is implemented on the company's data and the results obtained for six problem setting are presented in Table 1 along with the company's current schedule as the benchmark case. The table briefly illustrates the success of the proposed solution procedure in each problem level. The company can save as many as two feeders, as much as six hours of flight time and as much as 5.12% of operating cost under different settings.

Table 1 **Results of each problem in terms of fleet, time and total operating cost.**

Problem	# of feeders	Flight time	Block time	Duration	Improvement in operating cost(%)	CPU time (sec)
Company	18	54:54:27	63:13:39	65:56:51	-	-
Problem 1	17	54:12:00	62:17:00	65:56:00	1.15	429
Problem 2	17	54:18:00	62:35:00	66:38:00	0.91	394
Problem 3	16	51:07:00	59:10:00	63:29:00	4.64	2058
Problem 4	16	51:26:00	59:38:00	64:02:00	4.20	2025
Problem 5	16	48:42:00	56:52:00	61:45:00	5.12	2363
Problem 6	16	48:56:00	57:05:00	61:50:00	4.78	2469

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