Computers & Operations Research 65 (2016) 42–52

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

A column generation post-optimization heuristic for the integrated aircraft and passenger recovery problem

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ARTICLE INFO

Available online 2 July 2015

Keywords:
Airline recovery
Fleet assignment
Aircraft routing
Passenger itineraries
Column generation

ABSTRACT

The use of hub-and-spoke networks by most major commercial airlines means that small disruptions can have a significant impact on their operational costs. These disruptions, such as delayed or cancelled flights, reduction in arrival and departure capacity, and unavailable crew or aircraft, occur frequently and when they do, airlines must recover their operations as quickly as possible. In this paper we model the joint aircraft and passenger recovery problem as a mixed integer program and we present a column generation post-optimisation heuristic to solve it. We also show how the model and the heuristic can be modified to consider passenger recovery only. The resulting heuristic improves the best known solutions for all instances of the 2009 ROADEF Challenge, within reasonable computing times.

1. Introduction

Hub-and-spoke networks allow airlines to serve large markets with a limited number of flight legs. Therefore, most commercial airlines use such networks which ensure a very efficient use of critical resources. However, this implies that small disruptions can have a significant network-wide impact on planned operations. These disruptions can be caused by cancelled or delayed flights, unavailable crews or aircraft due to unplanned maintenance, or adverse weather conditions, which can force airport closures or limit the number of arrivals and departures. These disruptions can also have significant impact on the airlines' operational costs. Ball et al. [5] estimated the total cost of US air transportation delays at $32.9 billion in 2007. When disruptions occur, the airlines must re-establish the planned schedule as quickly as possible, usually by the following day. The recovery period defines the time by which normal operations must resume. During this period, the airlines must plan the recovery operations for the aircraft, the crews and the passengers, and must also ensure that the aircraft and crews are positioned at the correct locations by the end of the recovery period in order to allow the planned schedule to resume.

As for several other tactical planning problems, the size and the complexity of recovery problems imply that they are usually solved in a sequential manner. Since they need to be solved very quickly, usually within a few minutes, exact optimization is impractical. It is therefore common to apply decomposition heuristics in such contexts. The aircraft recovery problem is usually solved first and the crew recovery problem is handled in a second stage. Aircraft recovery operations can include cancelling flight legs, delaying flight legs, aircraft swapping and modifying aircraft rotations (Ball et al. [6]) . The objective of the aircraft recovery problem is to determine new aircraft rotations, while minimizing cancellation and delay costs and satisfying the maintenance constraints, the arrival and departure constraints, and the flow and locations constraints.

There exists a rich literature on the aircraft recovery problem. Teodorović et al. [31] developed a network model that minimizes the total delay of passengers and solved the problem to optimality using a branch-and-bound heuristic. However no realistic instances could be solved through this approach. Jarrah et al. [17] used minimum-cost network models, one delay model and one cancellation model, and implemented an algorithm which solves the shortest path problem repeatedly in order to determine the necessary flows. A greedy randomized adaptive search procedure (GRASP) was also developed by Arguello et al. [4]. The algorithm is composed of a construction phase which arbitrarily selects a solution from a candidate list, examines neighbouring solutions and inserts the best one in the candidate list, followed by a local search phase. All the above authors solve the aircraft recovery problem for a homogeneous fleet. The heterogeneous fleet recovery problem was modeled by Cao et al. [9,10] as a quadratic programming program which considers delaying and cancelling flight legs. These authors applied an approximate linear programming algorithm proposed by Coleman and Hulburt [12] to solve the problem. Rosenberg et al. [27] modeled the aircraft recovery problem as a set packing problem and used an aircraft selection heuristic to determine a subset of aircraft in order to

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http://dx.doi.org/10.1016/j.cor.2015.06.014
0305-0548/

reduce the size of the integer program. Eggenberg et al. [14] presented a constraint specific recovery network model which they solved by column generation. Dozić et al. [13] developed a heuristic that interchanges parts of rotations and returns a list of good solutions, while Xiuli et al. [32] presented a hybrid heuristic combining GRASP and Tabu search.

After solving the aircraft recovery problem, the crew recovery problem can be solved by reassigning a subset of crews, deadheading crew members or using reserve crews. The objective of the crew recovery problem is to create new crew schedules while minimizing costs and the total number of schedule changes. Stojković et al. [30] presented the crew recovery problem as a set partitioning problem which they solved by a column generation method embedded within a branch-and-bound search tree. Lettovsky et al. [19] and Medard et al. [22] both formulated the problem as a set covering problem. The first authors applied a primal-dual subproblem simplex algorithm, while the second authors used depth-first tree search, reduced cost column generation and shortest path algorithms. Abdelganhy et al. [1] presented a mixed integer programming model and developed a rolling horizon approach which solves a sequence of optimization assignment problems. Other algorithms have also been applied to this problem (see, e.g., Nissen et al. [23] and Yu et al. [33]).

Finally, the passenger recovery problem is solved by reassigning those passengers whose itineraries have been cancelled or modified by the disruptions. Zhang et al. [36] developed an integer linear program and discussed two schemes. In the first, flight legs are cancelled and passengers are transported by surface mode. In the second, alternative hubs are selected and ground transportation is used between the initial and the alternate hub. Bratu et al. [8] used network flow techniques to solve the passenger recovery problem.

Solving the recovery problem in a sequential way typically leads to suboptimal solutions. Therefore considering the integrated recovery problem can yield substantial cost reductions for airlines. Petersen et al. [26] solved the integrated aircraft, crew and passenger recovery problem by means of a Benders decomposition scheme, with the scheduling problem as a master problem, and the aircraft, crew and passengers recovery problems as the subproblems. Zhang et al. [35] modeled the integrated problem as a set partitioning problem which they solved by means of a rolling horizon based algorithm. Other methods have been developed to solve two integrated recovery problems. Thus, for the joint aircraft and crew recovery problem, Luo et al. [20] modeled the problem as an integer linear program and applied a heuristic based on a restricted version of the model to solve it. Stojković et al. [30] developed a linear program model for this joint problem, whereas Abdelghany et al. [2] developed a multi-phase heuristic which integrates a simulation model and a resource assignment optimization model. As for the joint aircraft and passenger recovery problem, Zergodi et al. [34] presented an ant colony optimization algorithm that takes into consideration passenger delay and cancellation costs in the objective function, while Jafari et al. [15,16] presented a mixed integer programming model in which the variables represented aircraft rotations and passenger itineraries instead of flight legs. A detailed survey of the recovery problems can be found in Clausen et al. [11].

This paper presents a post-optimization heuristic for the joint aircraft and passenger recovery problem as defined by Palpant et al. [24] for the 2009 ROADEF Challenge. Nine teams took part in the final of this competition. The winning team, Bisaillon et al. [7], made use of a large neighbourhood search heuristic. The algorithms proposed by the remaining teams can be found on the web site http://chalenge.roadef.org/2009. Among these, only three teams were able to find the best solution for at least one instance. Mansi et al. [21], who came second, presented a two-stage method. In the first stage, they attempted to find a feasible solution using mixed integer programming (MIP). If no feasible solution was found, a repair heuristic was applied. The second stage improved the solution by using an oscillation strategy that alternates between a constructive and a destructive phase. Peekstok et al. [25] who ranked sixth, developed a simulated annealing algorithm. Their algorithm accepts aircraft, airport and passenger infeasibilities which are handled by introducing a second term in the objective function. The cost of infeasibility is increased in order to force the algorithm to find a feasible solution. Jozefowiez et al. [18], who finished in seventh position, developed a three-phase heuristic. In the first phase, the disruptions are integrated in the schedule. Flight legs are removed and itineraries are cancelled in order to return a feasible solution. The second phase attempts to reassign disrupted passengers to the existing flight legs and in the final phase, additional flight legs are added to the aircraft rotations in order to reassign the remaining disrupted passengers.

After the challenge, Acuna–Agost [3] presented a post-processing procedure combined with the three-phase heuristic of Jozefowiez et al. [18]. The problem was formulated as an integer programming model based on a minimum cost multi-commodity flow problem. Two algorithms were developed to reduce the number of variables and constraints by identifying incompatible or suboptimal network nodes for each commodity. The solution method was able to greatly improve the solutions obtained by Jozefowiez et al. [18]. Sinclair et al. [28] later presented a large neighbourhood search heuristic (LNS) based on that of Bisaillon et al. [7]. Several refinements were introduced in each phase so as to diversify the search. The resulting heuristic, which will be described in Section 4, provided the best solution for 21 of the 22 instances.

The contribution of this paper is to present a column generation post-optimization heuristic which, when applied after the LNS heuristic of Sinclair et al. [28], leads to much improved solution costs within reasonable computing times. We show that the solution costs obtained within the 2009 ROADEF challenge time limit can be greatly improved by slightly increasing the allotted computing time. The problem is formulated as a mixed integer programming model but can be modified, along with the heuristic, so as to only consider passenger recovery.

The remainder of the paper is organized as follows. The joint aircraft and passenger recovery problem is described in the following section while Section 3 presents the APRP model. Section 4 presents the solution methodology. Computational results are reported in Section 5, and conclusions follow in Section 6.

2. Problem description

We now formally describe the aircraft and passenger recovery problem (APRP) considered in the 2009 ROADEF Challenge. Given a planned schedule which includes passenger itineraries and aircraft routes, and a set of disruptions, the objective of the joint aircraft and passenger recovery problem is to determine new aircraft routes and passenger itineraries in order to provide an alternate feasible plan and to allow the return to the planned schedule by the end of the recovery period. Before presenting the model we introduce some terminology.

2.1. Airports

The airports form a node set $N = \{1, \ldots, n\}$ where each node represents an airport at a specific time. For each airport $i \in N, a_{ip}$ and b_{ip} represent respectively the maximum number of arrivals and the maximum number of aircraft departures in the time interval p, a 60-min period beginning on the hour.