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Disruption recovery at airports: Integer programming formulations and polynomial time algorithms

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ABSTRACT

We study disruptions at a major airport. Disruptions could be caused by bad weather, for example. Our study is from the perspective of the airport, the air services provider (such as air traffic control) and the travelling public, rather than from the perspective of a single airline. Disruptions cause flights to be subjected to ground holding or to be cancelled. We present polynomial time algorithms based on the primal–dual schema and show that the algorithms find an optimal solution if the problem is feasible. These algorithms return an optimal mix of which flights to be ground-held and which ones to be cancelled.

1. Introduction

Disruption Recovery at an airport involves recovery from perturbations to flight schedules caused by factors such as inclement weather. *Ground Holding* is a vital control strategy suggested by several authors for use in disruption recovery [11]. It consists of delaying the departure of a flight from its airport of origin, in anticipation of bad weather (or *reduced arrival capacity* in general) at the destination airport.

Types of disruptions. What types of disruptions to airport operations do we consider? Disruptions (to passenger flow) can be caused by various factors. We focus on disruptions that affect every airline. For example, staffing issues with airline ground staff are those suffered by a single airline, so we do not consider these.

A shortage of immigration officers[1] also causes airport disruption and affects all airlines equally. But we do not consider disruptions such as this. We only consider disruptions to landing and takeoff, such as those due to bad weather and runway(s) being closed for maintenance.

Ground holding is widely practised by the Federal Aviation Administration (FAA) in the United States. In Australia, it is mainly used for flights arriving at Sydney, Brisbane, Melbourne and Perth airports, implemented in a program called Metron [2].

Earlier models. The model developed by Navazio and Romanin-Jacur (the NRJ model) [15] is one of the earliest optimization models for ground holding. It minimizes the total cost of delaying flights, subject to restrictions on arrival capacities at airports. It assumes that the flying time of each flight is fixed, and hence any delay suffered by a flight is due to ground holding at the origin airport. For the sake of completeness the NRJ model is briefly reviewed in Section 2.2.

Unfortunately, the rather elegant model developed by Navazio and Romanin-Jacur (the NRJ model) does not account for some of the realities of operations at an airport such as Sydney. For example, it does not allow for flights to be cancelled, although such cancellations are not uncommon. Other realities include (a) curfew hours at airports during which time flights

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1 For example, at an airport such as Singapore where every flight is an international flight.

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are not permitted to land; and (b) the non-linear nature of the costing of flight delays. For example, the total delay cost for the second 30-min period is higher than that for the first 30-min period.

We note that some of the publications that appeared in the 1990s on Ground Holding used a linear delay cost model [3–5,15].

In recent years, there have been several studies that have studied disruptions from an airline's perspective. See Larsen et al. [6] for a survey. However, as in [9] and [10], we focus on a "common good perspective" that serves the interests of everyone: the airports, the airlines, the air service providers such as air traffic control, and last but certainly not the least, the travelling public.

In Chapter 3 of his Ph.D. thesis, White [19] discusses conditions under which various models (in particular, the linear relaxations of these integer programming models) in air traffic disruption recovery are guaranteed to return optimal solutions in polynomial time.

About a former publication of ours [9], the authors in [6] wrote: "A view which is seldom adopted in the recovery literature is the view of the airport. The paper by Filar et al. [9] describes techniques that enhance the utilization of airport capacities. The paper describes methods involving the traffic management, airport authorities and airlines".

Paper outline. After reviewing the NRJ model in Section 2.2, we rewrite their model with a different set of variables in Section 2.3. In Section 3, we discuss an enhanced version of the NRJ model that incorporates cancellations. For both these models, we provide polynomial time algorithms (in Sections 2.6 and 3.3 respectively) based on the primal–dual schema and show that the algorithms return optimal solutions.

Our contributions (what is new in this publication): Publications [9] and [10] simply model the problem as an Integer Program and use the CPLEX software to find a solution. However, here, we have developed our own combinatorial algorithms to solve the two problems (single airport ground holding, with and without cancellations). To our knowledge, this is the first known primal dual algorithm for this particular class of disruption recovery problems.

Notation

The following notation is used in the NRJ model and in the enhanced model:

T	Set of time periods, $T = \{1, \ldots, t, \cdots, \|T\|\}$
Z	Set of airports, $Z = \{1, \ldots, z, \cdots, \|Z\|\}$
F	Set of all flights considered, $F = \{1, \ldots, f, \cdots, \|F\|\}$
G	Set of flights that are flown (not cancelled)
F_z	Set of flights arriving at airport z
$F_{z,t}$	Set of flights scheduled to arrive at airport z in period t
$K_{z,t}$	Arrival capacity of airport z at period t
r_f	Planned arrival period of flight f ($r_f \in T$)
θ_f	Planned flying time of flight f, in periods
c_f	(linear) cost per period of delay of flight f
μ_f	Cancellation cost of f
S_f	Set of successors of flight f, $\|S_f\| = n_f$
P_f	Set of predecessors of flight f, $\|P_f\| = m_f$
$\sigma_{f,g}$	Service time (turn-around time) between flights f and g, in periods
Δ_f	Delay experienced by flight f, in periods
A_f	Actual arrival period of flight $f = r_f + \Delta_f$
$\Delta_{\max}$	Maximum allowed delay on any flight, in periods
L_f	$= r_f + \Delta_{\max}$
T_f	Set of time intervals in which flight f may land $= [r_f, L_f]$
T_F	Set of periods for which the capacity is fully utilized
CS	Complementary slackness

If $t \in T_F$, then the number of flights arriving in period t is equal to the arrival capacity $K_{z,t}$ for that period.

The *service time* $\sigma_{f,g}$ between flights f and g needs some explanation. The arrival of f and the departure of g occurs at the same airport. Flight g is a *successor* of f (and hence f is a *predecessor* of g). Flight g cannot depart before f arrives. A certain amount of service time is necessary between f's arrival and g's departure; for example, some passengers who arrive in f may transfer to g. Or, some crew members from f may transfer to g. Furthermore, if flights f and g use the same aircraft, then an airline requires a certain amount of time after f's arrival to prepare the aircraft for boarding for flight g (typically 15 min for a small aircraft and close to an hour for a large one).

2. Integer programming models for ground holding

Before presenting the models, we mention a few simplifications and assumptions that we make.

2.1. Simplifications and assumptions

(a) Linearity assumption: For each flight, the delay cost is linear with respect to time intervals. The cancellation cost is fixed. However in reality, delay and cancellation costs are non-linear with respect to time; see [7,8,17,21]. For instance, see Figures 7 and 8 in [8]; the authors there remark that after a five-hour delay, all passengers will switch (to a different flight or a different transportation mode). This concurs with our assumption in Section 3 that cancellation cost is equal to a delay cost of 4 h and 30 min.

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