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Simultaneous recovery model for aircraft and passengers ☆

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Abstract

Usually some unforeseen events make airlines to reconstruct their schedules. A mathematical model for airlines schedule recovery which recovers aircrafts and disrupted passengers simultaneously is presented in this study. Aircraft recovery decisions affect on passengers but disrupted passengers and recovering them were not explicitly considered in the most previous aircraft recovery models so recovery of these two resources – aircrafts and passengers – concurrently is one of our contributions.

The modeling is based on defining the recovery scope as well as employing aircraft rotations and passengers' itineraries instead of flights. These are two of our other contributions.

Our model examines possible flight re-timing, aircraft swapping, ferrying, utilization of reserve aircrafts, cancellation, and passenger reassignment to generate an efficient schedule recovery plan.

Model parameters are user-specific therefore it helps airlines to apply their policies in the model. Defining the recovery scope reduces the problem size and ensures that the schedule returns to normal within a certain time. The objective is in the form of cost minimization which involves three kinds of cost—operational aircraft recovery, flight cancellation, and delay as well as disrupted passengers. A data set with two disruption scenarios is used to test the proposed model. The computational results show that it is capable of handling the simultaneous aircraft and passenger recovery problem successfully.

Keywords: Airline scheduling; Disruption management; Aircraft and passenger recovery; Modeling

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1. Introduction

The operation of a passenger airline requires the allocation of resources and development of schedule plans over complex networks. Large airlines can operate over a thousand flight departures per day with several hundred aircrafts and thousands of cockpit and cabin crew employees. These resources are costly. The efficient utilization of costly resources is thus one of the key challenges faced by airlines hoping to control operating expenses to generate profits in an increasingly competitive fare environment [1]. Hence, airlines spend too much time, effort, and financial resources on planning.

Various events ranging from severe weather to the crewmember unavailability inhibit their ability to always satisfy their schedules and disrupt schedules. Disruption can be defined as an act of delaying or interrupting the continuity [2]. If such disruptions are not managed properly and timely, they will severely affect the airlines performance in terms of revenue, operational efficiency, and customer satisfaction. When disruptions occur, airlines adjust their flight operations by delaying flight departures, canceling flights, rerouting aircraft, reassigning crews or calling in new crews, and re-accommodating passengers. The objective is to get feasible, cost-minimizing plans that allow the airline to recover from the disruptions and their associated delays [3]. This problem has been studied since last three decades and in different names such as: Flight/Schedule/Airline Perturbation, Schedule Disturbances, Irregular Airline Operations Control, Operational Airline Scheduling, Day of Operations Scheduling, Real-Time Flight Scheduling, Flight Rescheduling, Disruption Management, Airline/Schedule/Flight Recovery.

Crew, aircraft, and passengers are the most important aspects of airline disruption management, but other resources such as ground staff, catering, and gates also need consideration. However these resources are usually more flexible and less expensive [4]. Nowadays, in the airline industry, recovery plans are determined in a primarily sequential manner, first recovering aircraft, then crew, and finally passengers ([5] cited in [6]).

Occurring schedule disruptions, the aircraft recovery problem is to decide flight re-timings and cancellations, and revised routings for affected aircraft. Rerouting options include ferrying, diverting, over-flying, and swapping. These adjustments must meet with maintenance requirements, station departure curfew restrictions, and aircraft balance requirements, especially at the beginning and at the end of the recovery period. At the end of the period, aircraft types should be positioned to resume operations as planned [3]. Teodorovic and Guberinic [7] were one of the first who studied the aircraft recovery from an operation research view. They considered a situation where an aircraft is taken out of service and made an effort to minimize the total passenger delay by swapping and delaying flights. The proposed model is solved exactly by a branch and bound (B&B) algorithm. More detailed explanation of concepts and models in aircraft recovery problem can be obtained in Yu and Qi [8], Kohl et al. [9], Anderson and Varbrand [10], Filar et al. [5], and Clarke [11].

Solving the aircraft recovery problems can result in disrupted passengers. Delaying or re-timing the departure of a flight will directly affect the passengers on that particular flight. It can also, indirectly, affect the passengers on the next flight in the route for the aircraft in question, if the planned ground time between the two flights is too short to cover for the delay [10]. Most of the above mentioned researches have not considered the effects of the aircraft recovery results on passengers; therefore their solutions impose significant indirect costs to airlines.

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Generally, in the disruption management literature passengers are given a low priority [4]. Passenger recovery problem is reassignment of disrupted passengers to alternative itineraries, beginning at the disrupted passenger locations after their available times, and terminating at their destination, or a location nearby. Disrupted passengers must be reassigned to itineraries other than initial ones because, one or more of the flights in their scheduled itinerary is canceled; or the time between consecutive flights in their scheduled itinerary is less than the minimum time required to walk between the arrival and departure gates. There are few studies on passenger recovery. Lettovsky [12] incorporated costs of reassigning passengers in to the flight cancellation cost, associated hotel and meal costs, and estimates of the loss of passenger goodwill. Barnhart et al. [13] model this problem as a multi-commodity network flow problem. Clarke [14] presents modeling strategies for re-accommodating disrupted passengers (disrupted by operations, or by schedule changes resulting from considerations such as revenue management). Bratu and Barnhart [15] have used a flexible heuristic, termed the Passenger Delay Calculator, which allows some passenger recovery policies (such as frequent flyers first, or first-disrupted-first-recovered) to be enforced.

The defect of previous studies such as above is that either they do not explicitly model passengers in their model or they solve passenger recovery module separately from aircraft recovery module. It means passengers are second priority and passenger reaccommodation is always done after aircraft recovery. Whiles if airlines can have a look on the whole picture of relationships and effects of aircrafts and passengers on each other in recovery process, they will have more options to make better decisions. As it is declared by some researches like Dorndorf et al. [16] and Kohl et al. [9], it seems that the challenges of integration, crew, and passenger are ready for more studies.

Lettovsky [12] presents a framework for an integrated approach although only parts of it are implemented. The formulation has three parts corresponding to each of the resources: crew assignment, aircraft routing, and passenger flow. In a decomposition scheme these three parts are controlled by a master problem denominated the Schedule Recovery Model [17]. Clarke [18,19] presents a model and algorithms for the airline schedule recovery problem. Flights can be canceled or delayed and a number of constraints are introduced to guarantee feasibility with respect to aircraft maintenance, accommodation of passengers, crew availability, slot allocation, and gate allocation. Hence, the model captures a very large number of resources. It has a rather simplistic model of all resources except for aircraft. The Descartes (DEcision Support for integrated Crew and AiRcrafT recovery) project ran from 2000 to 2003 by British Airways, Carmen Systems, and the Technical University of Denmark. The main objective was to develop a disruption management system based on a holistic approach. The system should integrate the decisions of the resources (aircraft, flight and cabin crew, and passengers) in one integrated feasible decision. Descartes almost consists of three dedicated recovery solvers and an integrated recovery module which constructs an integrated solution based on solutions from dedicated solvers. The focus of the system is not to generate the optimum solution in the strict academic sense, but rather to provide flexible tools that can add value to the business process of operations control at various airlines [4]. A more recent contribution by Bratu and Barnhart [6] describes two models for integrated recovery. Models are focused on passenger recovery while incorporating rules and regulations on aircraft and crew.

A limitation in most of the existing models is that passengers are not modeled clearly. Except Bratu and Barnhart [6] which focus on passengers, but relax restrictive operating restrictions and incorporate flight departure postponement and cancellation decisions.

In general there are two approaches in all integration models. In the first approach, the master problem (here the airline recovery) is decomposed to some sub-problems (here the recovery of each resource) and solved sequentially. The output of the one sub-problem (resource recovery) is input for the next one. Therefore to find the feasible solution which meets all the sub-problems, it is necessary to run each of the sub-problems for some iterations. This means using this approach in the airlines is a time-consuming process in a time-critical environment. Almost most of the mentioned studies like Lettovsky [12], Clarke [18,19] Descartes project explained in [4] have used first approach. The second approach tries to develop models which solve the whole problem in one time (recover all resources simultaneously) and it is what this study tries to achieve for aircraft and passengers.

This paper aims to develop a model which can generate solution for aircraft recovery problem while including disrupted passengers and to reaccommodate them simultaneously. Modeling is based on *aircraft rotations* and *passengers' itineraries* instead of flights as well as defining recovery scope. In Section 2 aircraft recovery problem including disrupted passengers is presented. Mathematical model is explained in Section 3. In Section 4 methodology and model prerequisites are described. Computational experience and obtained solutions are illustrated in Section 5. Finally, conclusions and possible extensions are presented in Section 6.

2. Aircraft recovery problem including disrupted passengers

Airline scheduling is a complex and time-consuming process as there are several factors and multiple constrained resources involved on it. According to Belobaba and Barnhart [20], airline schedule development process begins a year or more ahead. The schedule often faces with disruptions in operation phase. Now the object is to turn to the initial plan quickly and with the minimum cost. Recovery solutions need to be generated in less than 3 min, otherwise the recovery solution can become infeasible [6]. In airline recovery problem, time horizon is smaller than scheduling phase and is called disrupted period or recovery period. Coordinators in an operation control center usually have to make efforts to recover disruptions in this period and prevent their propagation in the airline schedule. As disruption or its affects can disrupt flights and their resources as well as passengers, so it is required to generate recovery plan for disrupted flights, disrupted resources, and disrupted passengers.

Fig. 1 presents flights of a small network that consists of seven flights (numbered from f1 to f7) and three aircrafts (A/C1–A/C3). The horizontal axis is time and the vertical is aircraft. Each flight is represented using a thick line where start and end of the line represent the departure and arrival times and airports, respectively. The letters in the parentheses under the line show the itinerary of passengers (P1, P2, P3, and P4). As shown in Fig. 1, flight f1 departs from airport G and arrives at airport H. Upon arrival of flight f1, aircraft A/C1 connects to flight f2 and passengers in itinerary P1 get to their next flight (f4).

Now suppose that flights f1 and f3 are delayed as shown in Fig. 2. Therefore one or more of the downline flights that use aircrafts out of flights f1 and f3 and passengers who have other flights in their itineraries after f1 and f3 would be affected.

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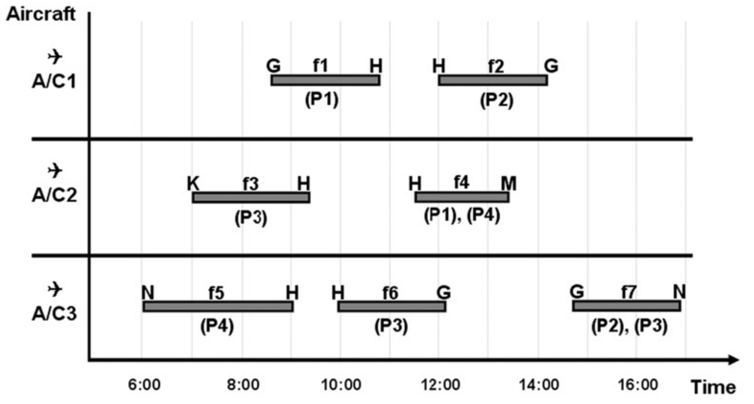

Fig. 1. Flights, aircrafts and passengers during normal operation conditions.

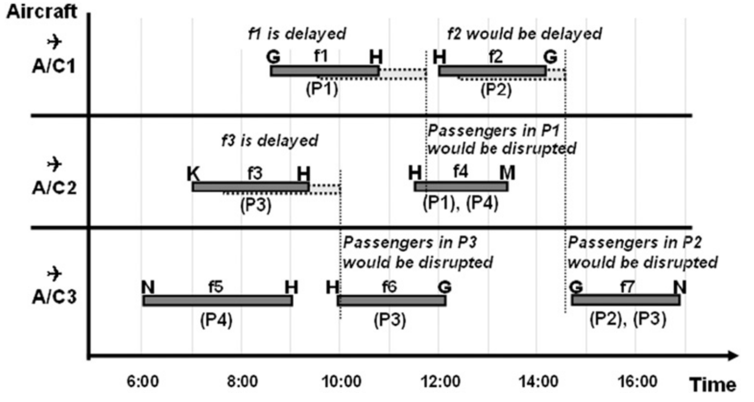

Fig. 2. Flights, aircrafts and passengers during irregular operation conditions.

Passengers in itinerary P1 have two flights f1 and f4. Based on delay in arrival of f1, passengers in P1 arrive after departure of f4. Hence, they cannot get to their destination (M) and it means passengers in P1 are disrupted. Aircraft A/C1 arrives late, so f2 will fly as soon as A/C1 becomes ready. Therefore flight f2 would be delayed. As a result, passengers in itinerary P2 will miss their next flight (f7) because they do not have enough time to get out off arrival gate and go to the departure gate. Also as late arrival of f3, passengers in itinerary P3 will miss their next two flights f6 and f7 so they become disrupted. This case demonstrates the downstream of a flight disruption from the view of aircrafts and passengers and the importance of integrating aircraft and passengers while recovering a state of irregular operations. Hence, our problem is to recover aircrafts which are the most expensive airline resource while recovering passengers who bring revenue to airline.

3. Mathematical model

The general idea of our modeling is based on Abdelghany et al. [21] and Bratu and Barnhart [6] work but we have employed *aircraft rotations* and *passengers' itineraries* instead of flights. Aircraft rotation is the sequence of flight legs that are flown by an aircraft beginning and ending at the same station. Itinerary is a sequence of flights from originating city to the destination city [22].

Also they [21,6] break the scheduling horizon in to number of stages then they solve each stage sequentially. Based on the results of the predecessor stage recovery solution, the subsequent stages will be updated and then solved. But our modeling involves all the recovery scope and solves it in one step.

The model includes flight recovery, aircraft recovery and passenger recovery problems but it does not include crew recovery, route planning, gate assignment, ground staff and catering planning problems.

3.1. Assumptions

When disruptions occur in order to control delays and their propagation, operations controllers have a number of recovery options available to them, the most common being: calling reserve aircraft (utilization of spare aircraft), swapping aircrafts (to trade aircrafts that have later assignments with aircrafts that have earlier broken assignments or aircrafts that have flights with too many passengers with aircrafts that have fewer passengers, either having the same type or different), ferrying (to fly an aircraft empty to an airport where it is needed), delaying (new departure/arrival times are quoted for the flight based on the ready times of its delayed aircraft, or ready times of newly assigned aircrafts) and cancellation (if no recovery is found for a violating aircraft within a reasonable time window, the only available decision is to cancel this flight and rebook its passengers on next flights or even on other airlines or an alternative way of transportation). These recovery actions are considered in developing the model in this study.

There are some time limitations to be considered in the model. Maximum delay allowed for a single flight, minimum time required for each flight and aircraft to turnaround, and minimum connection time is needed for passengers to leave a flight to arrive to the next flight, are assumed fixed.

3.2. Variables and parameters

The decision variables common to our model are as follows:

x_{kf}	1 if aircraft k is assigned to flight f and 0 otherwise
z_f	1 if flight f is canceled and 0 otherwise
td_f	actual departure time of flight f
ta_f	actual arrival time of flight f
y_p	1 if planned itinerary p is disrupted, and 0 otherwise
it_p^p	number of passengers who were initially assigned to itinerary p and served on it
it_p^r	number of passengers who were initially assigned to itinerary p but reassigned to itinerary r
trn_p	number of passengers who were initially assigned to itinerary p but must be served on other airlines or other transportation mode.

The parameters common to our model are as follows:

A_{kf}	Ready time of aircraft k to operate flight f
CAP_f	Number of remaining available seats on flight leg f
CC_f	Cost of canceling flight f
CD_f	Cost of 1-min delay of flight f
C_{kf}	Cost of assigning aircraft k to flight f
DT_f	Expected trip (block-to-block) time of flight f
F_s	The set of flights in recovery scope S
$IT(P)$	The set of flight legs in itinerary p
$IT(P, L)$	The last flight leg in itinerary p
$IT(P, n)$	The nth flight leg in itinerary p
K_s	The set of aircrafts to be used for recovery in scope S
N_p	Number of passengers on itinerary p
NP_f	Number of passengers in flight f
P	The set of passenger itineraries (contains more than one flights)
$R(p)$	The set of candidate recovery itineraries for itinerary p
RO_s	The set of aircraft rotations in recovery scope S
S	Recovery scope index
S_p	Estimated cost per disrupted passenger which are not reassigned
T_f	The scheduled departure time of flight f
U	Minimum connection time
V_k	The duty (usage) limit of aircraft k
δ_{rf}	An indicator to represent whether flight leg f is in itinerary r or not, equal 1 if flight leg f is in itinerary r and equal 0 otherwise

3.3. Mathematical formulation

The objective function of the model is to minimize the total cost associated to recovering all flights, aircrafts, and passengers in the recovery scope. It is the summation of aircrafts assignment cost, total delay cost, cancellation cost, and disrupted passengers. The first term in the objective function is to recover open positions of each disrupted flight by using the most efficient aircrafts in the system. The second and third terms promote reliable operations by minimizing flight delay and cancellation, respectively. The remaining terms recover disrupted passengers through reassigning them to the earliest available itinerary or transport them to the destination by any other way, other airlines or an alternative way of transportation.

$$
\begin{aligned}
MIN & \sum_{f\in F_s}\sum_{k\in K_s} C_{kf}x_{kf} + \sum_{f\in F_s} CD_f(1-z_f)\left[td_f - T_f\right]NP_f + \sum_{f\in F_s} CC_f\, z_f\, NP_f \\
& + \sum_{p\in P}\sum_{r} CD_f\, it_p^r(td_{it(r,l)} - td_{it(p,l)}) + \sum_{p\in P} S_p\, trn_p \\
& \text{Subject to :} \qquad (1)
\end{aligned}
$$

Constraints in (2) ensure that each available aircraft is assigned such that it covers sequential rotations which are not overlapped. In other words, the precedence flight departure time and maximum delayed allowed is considered:

$$x_{kf_{ro}} + \sum_{f'} x_{kf'_{ro'}} \leq 1 \tag{2}$$

$$f \in \textit{first flight of ro}, \quad \forall\, ro \in RO_s,$$

$$f' \in \{\textit{first flight of } ro' \in RO_s \,|\, T_{f'} > T_f,\ T_{\textit{last flight of ro}} + DT_{\textit{last flight of ro}} \geq T_{f'} + \textit{Maximum Delayed allowed}\}, \quad \forall k \in K \textit{ in } S$$

Constraints in (3) ensure that if a flight is canceled ($z_f = 1$), no aircraft is assigned to this flight:

$$1 - z_f = \sum_{k \in K_s} x_{kf} \quad \forall f \in F_s \tag{3}$$

Constraints in (4) define rotations aircraft usage. All flights in a rotation use one aircraft not different ones. By using the concept of rotation and defining rotations in the model, aircraft balance at each airport is satisfied:

$$x_{kfi+1} - x_{kfi} = 0 \quad \forall k \in K_s, \quad f_i \in ro \in RO_s \tag{4}$$

Constraints (5)–(8) determine the departure time of each flight. The departure time of a flight cannot be earlier than the ready time of its assigned aircraft as stated in Constraints (5):

$$td_f \geq A_{kf} x_{kf} \quad \forall f \in \textit{first flight of rotations in } F_s, \quad k \in K_s \tag{5}$$

Constraints in (6) ensure that when two rotations are flown by one aircraft, the second rotation cannot depart earlier than real arrival time of first rotation and also minimum connecting time will be satisfied:

$$td_{f_{ro}} \geq ta_{f'_{ro'}}\, x_{kf'_{ro'}}\, x_{kf_{ro}} + U \tag{6}$$

$$f \in \textit{first flight of ro} \in ROs,$$

$$f' \in \{\textit{last flight of } ro' \in RO_s \,|\, T_{f'} + DT_{f'} \leq T_f + \textit{Maximum Delayed allowed}\}, \quad \forall\, k \in K_s$$

In a rotation, the departure time of a flight cannot be earlier than the arrival time of its previous flight as stated in Constraints (7):

$$td_{f_{i+1}} \geq ta_{f_i} + U \quad \forall f \in \textit{flights of ro} \in RO_s \tag{7}$$

Constraints in (8) state that no flight is allowed to depart before its scheduled departure time:

$$td_f \geq T_f \quad \forall f \in F_s \tag{8}$$

Constraints in (9) ensure that if a flight is delayed, there is no duty limit violation for its aircraft. Also satisfaction of maintenance requirements of aircrafts can be met here:

$$ta_f \leq V_k x_{kf} + (1-x_{kf})\, UB(ta_f) \quad \forall f \in F_s,\ k \in K_s \tag{9}$$

Constraints in (10) relate the departure and arrival times for each flight:

$$ta_f = td_f + DT_f(1-z_f) \quad \forall f \in F_s \tag{10}$$

Constraints in (11) and (12) classify disrupted itineraries. Constraints in (11) examine the sufficiency of connection time in itineraries and Constraints in (12) check if there are any canceled flights in the itineraries or not:

$$(td_{IT(p,2)}/(ta_{IT(p,1)} + u))-1 \geq -y_p \quad (td_{IT(p,2)}/(ta_{IT(p,1)} + u))-1 \leq 1-y_p \quad \forall p \in P \tag{11}$$

$$y_p \geq z_f \quad \forall p \in P, \quad \forall f \in IT(p) \tag{12}$$

Constraints in (13) to (16) reassign disrupted passengers. Constraints in (13) ensure that if itinerary p is disrupted, its passengers are served on different itineraries from those originally planned:

$$N_p(1-y_p) = it_p^p \quad \forall p \in P \tag{13}$$

Constraints in (14) ensure that no passengers are served on disrupted itineraries:

$$\sum_{p\in P} it_p^r \leq \sum_{p\in P} N_p(1-y_r) \quad \forall r \in R(P) \tag{14}$$

Constraints in (15) ensure that all passengers are transported to their destinations:

$$\sum_{r\in R(p)} it_p^r + trn_p = N_p y_p \quad \forall p \in P \tag{15}$$

Constraints in (16) limit the number of passengers transported on each flight leg which are not canceled to the capacity of that leg:

$$\sum_{p\in P}\sum_{r\in R(p)} (1-\delta_f^p)\delta_f^r it_p^r \leq CAP_f(1-z_f) \quad \forall f \in R(p) \tag{16}$$

Finally, Constraints in (17) ensure that the decision variables x, z and y are binary variables, the flight departure and arrival times (td_f, ta_f) are real, number of reassigned passengers it_p^P, it_p^r and trn_p are integers:

$$x_{rf},\ z_f,\ y_p = \{0, 1\}, \quad \textit{and } td_f,\ ta_f \textit{ are REAL and } it_p^p,\ it_p^r,\ trn_p \textit{ are intiger} \tag{17}$$

The model is a multiprocessor scheduling problem. This problem is categorized as SS8 by Garey and Johnson [23] and known to be NP-complete. Although our suggested mathematical model has been solved using LINGO at the size of our real data set, but solving the model becomes difficult as the size of the problem increases.

4. Methodology and model prerequisites

If the airline schedule is subjected to any source of irregularity at one or more airports, which results in delaying/canceling some flights, information on these delayed/canceled flights is made available to project all potential downline aircraft disruptions in the scope due to the introduced delays/cancellations. If an aircraft disruption is projected, remaining affected flights in the route of this aircraft are considered as disrupted flights.

Once the list of disrupted flights is projected, the list of disrupted rotations is determined. For each disrupted aircraft the earliest disrupted flight and its departure airport is considered. The disrupted flight and the next flights which turn back the aircraft to this airport are included in the aircraft rotation. Fig. 3 presents three aircraft rotations. In rotation 1, flight f1 which departs airport AR, is disrupted. The next flight of this aircraft is flight f2 which arrive at airport AR. Hence, f1 and f2 form rotation 1 for a disrupted aircraft. In rotation 2, an aircraft departs airport AR and returns to it again after having 4 flights, f10, f11, f12 and f13. Sometimes a disrupted flight and its subsequent flights will not turn the aircraft back to the first departure airport. It means making rotation from the disrupted flight point is impossible. Then the rotation of this aircraft before the disrupted flight point must be made.

In Fig. 3, rotation3 shows this situation. Aircraft and flight f16 are disrupted but it is impossible to make a rotation because flight f16 is the last flight of this aircraft and does not return to the departure airport, AR. Hence flight f16 cannot be recovered. By considering the rotation from AR before the disrupted flight point (f16), this flight will have the chance to get out of disruption through rescheduling rotation 3 (f14 and f15) and f16 flies as initial schedule.

In addition to the disrupted rotations, some undisrupted rotations (rotations with no aircraft disruptions) could be included to check the possibility of swapping their aircrafts with the aircrafts of disrupted rotations. If an undisrupted rotation is included, it is considered as one of the disrupted rotations. The originally assigned aircrafts to all rotations in the scope are considered to be used in the recovery process. These aircrafts include disrupted or affected aircrafts that cannot complete their original assignments and

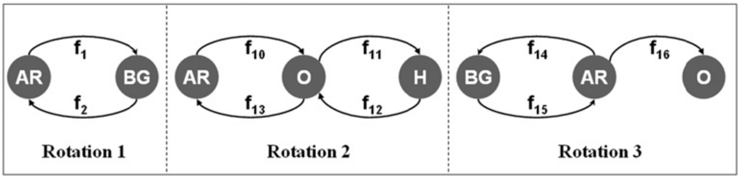

Fig. 3. Aircraft rotations.

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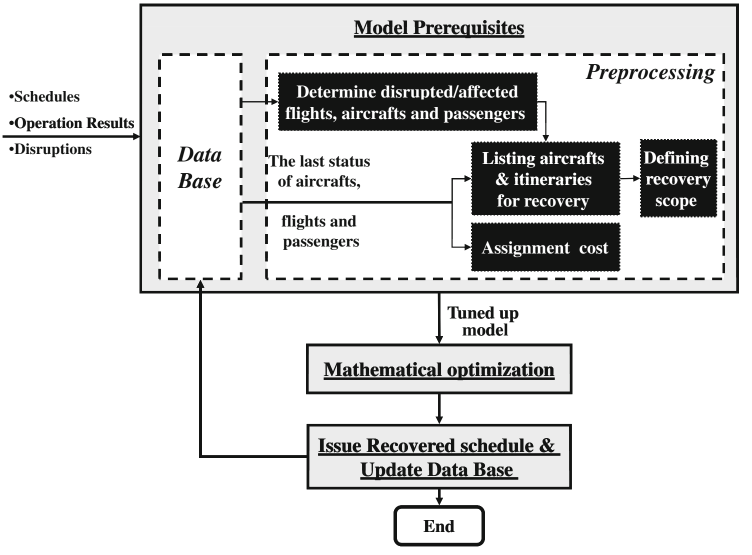

Fig. 4. Simultaneous aircraft and passengers recovery model framework.

good aircrafts that are still able to fly their assignments. The reason to consider the non-disrupted or non-affected aircrafts of the disrupted rotations is to be able to reassign these aircrafts to other rotations if their disrupted rotations are canceled.

Modeling based on rotations instead of flights helps to implicitly consider aircraft balance constraint at each airport and prevent new disruptions as the result of recovery decision. This is due to the fact that aircrafts will be returned to the same airport where their schedules were diverted from. Therefore at the end of recovery scope aircrafts are available at the planned airport. Framework of simultaneous aircraft and passenger recovery model is presented in Fig. 4.

Because of wide aspects of the problem and large variety and amount of data needed, the proposed model have to be tuned up based on the latest system state. Schedules (flights, aircrafts, and passengers), operation results, and the disruptions which have occurred are the entry data to the model framework. These data are seated in the database and after processing data, the last status of aircrafts, flights, and passengers will be determined. Therefore disrupted/affected aircrafts and recovery resource options, disrupted itineraries and recovery itineraries are concluded. After defining recovery scope and assigning cost to aircrafts, the mathematical model can be tuned up. Running the model, the resulted decisions are checked in the schedule, recovered schedule is issued and database will be updated. Model prerequisites step involves two main actions: making/having access to data of system state and preprocessing.

4.1. *Access to system state — database*

In order to make effective decision for schedule recovery, it is necessary for operations controllers, at any time t of the day of operations, to have knowledge of (1) flight schedule and their passengers; (2) station of aircrafts (reserved or planned), their assigned routes and their future maintenance requirements; (3) passengers itineraries. We refer to this information collectively as the *Airline System State* at time t.

4.2. Preprocessing

Four preprocessing steps are conducted before running mathematical model to determine the following:

– The set of disrupted flights (rotations), aircrafts, and their downline affects as well as disrupted passengers.
– The set of aircrafts and itineraries to be candidate for recovery of the disrupted flights (rotations) and disrupted passengers.
– The set of aircraft rotations to create recovery scope.
– The cost associated with the assignment of a given aircraft to a rotation.

4.2.1. Disrupted/affected flights (rotations), aircrafts, and passengers (itineraries)

Based on the information on delayed/canceled flights or disrupted aircrafts all potential down line flight and aircraft disruptions will be projected. Aircraft and next affected flights of the disrupted flight as well as affected flights in the route of disrupted aircrafts are considered as disrupted. Thereafter disrupted rotations are defined. Then passengers who cannot reach to their destination are classified as disrupted. Because one or more of the flights in their scheduled itineraries are canceled; or they will not have enough time between consecutive flights in their scheduled itineraries to get out off one flight to catch to the next flight due to re-timing disrupted flights.

4.2.2. Aircrafts and itineraries candidate for recovery

In addition to disrupted flights (rotations), some undisrupted rotations could be included to check the possibility of swapping their aircrafts with the aircrafts of disrupted rotations in the set. If an undisrupted rotation is included, it is considered as one of the disrupted rotations in the set. In order to determine the undisrupted rotations to include in the scope, all rotations that their first flights depart within 60 min from the same airport of each disrupted rotation are included in the set. We call these aircrafts departure options. In

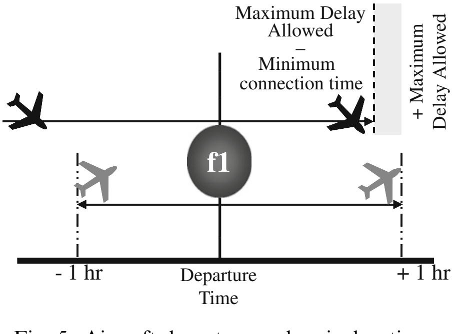

Fig. 5. Aircraft departure and arrival options.

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the current paper 60 min is chosen because the test data involve short flights.

Besides, aircrafts which arrive to the same airport of each disrupted rotation before maximum delay allowed time minus turnaround time can be options to be used. We call these aircrafts arrival options. These options are shown in Fig. 5. The originally assigned aircrafts to disrupted rotations, disrupted aircrafts and both departure options and arrival options, moreover ferried and reserved aircrafts are added to the database of aircrafts that is used in the recovery process.

Although for the disrupted passengers, some candidate itineraries which can take these passengers to their destinations from the airport that disruption has occurred and depart after this time are determined among the initial scheduled flights and itineraries.

4.2.3. Recovery scope

Guo [24] says the length of the recovery period is not deterministic. It denotes the horizon to recover from a disruption. In other words, the recovery horizon lasts until all changes caused by the disruption have been carried out. Recovery horizon starts at the same time or earlier than the departure time of the first updated flight and ends with or later than the new arrival time of the last updated flight.

In this model, all aircrafts which can be used for the recovery are pairwised comparison to check how long these changes last, in the case of exchanging their rotations. Finishing the comparison, flights and rotations which form the recovery scope are determined. Fig. 6 presents how to define recovery scope. Part (I) of Fig. 6 shows flights assigned to aircrafts

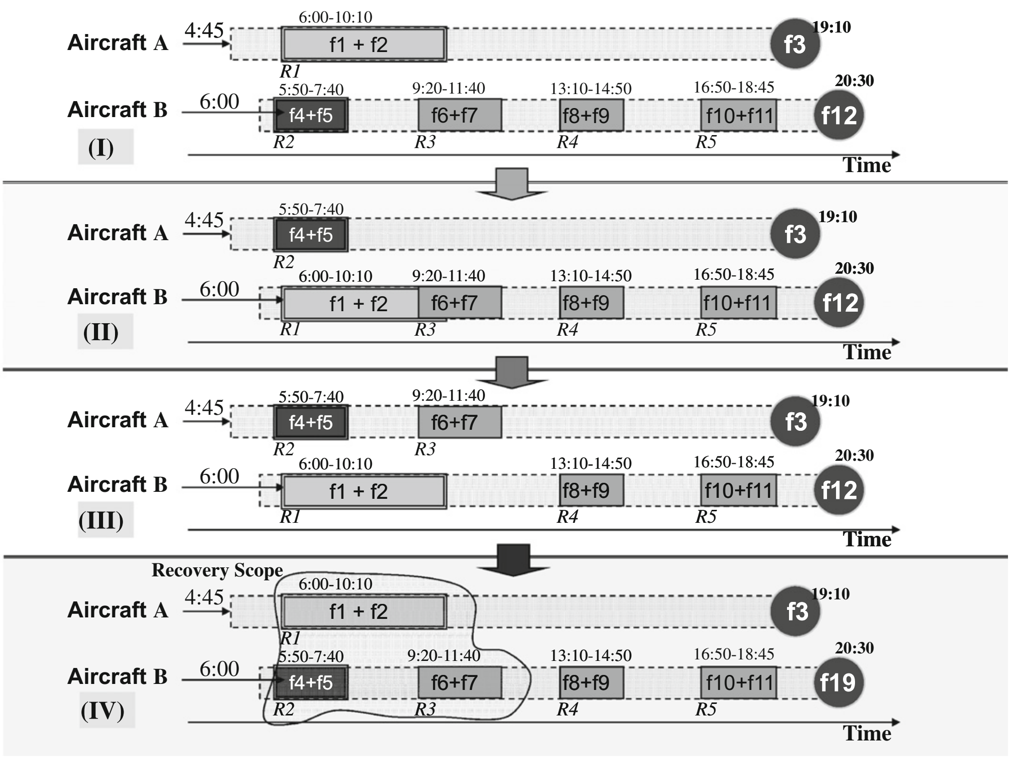

Fig. 6. Example of defining recovery scope.

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A and B. Flight f4 is disrupted because it was initially scheduled to flight at 5:50 but aircraft B can be ready at 6:00. As our model is based on rotations so flights f4 and f5 which form rotation R2 are assumed disrupted. Aircraft A is candidate for swapping so we should do pairwised comparison between rotations of aircraft A and aircraft B.

In Fig. 6 part (II) rotations R1 and R2 are exchanged. There will be no problem for next flights of aircraft A but rotation R3 of aircraft B will be disrupted. Because flight f6 was initially scheduled to fly at 9:20 while as a result of new exchange, its aircraft will be ready after 10:10 which is arrival time of flight f2. Thus R3 must be reassigned to aircraft A too, as part (III) Fig. 6. The remaining flights and rotations of aircrafts A and B will not be disrupted because of this swapping. Hence, just R1, R2, and R3 will be included in the recovery scope, part (IV) Fig. 6. In the case that there are more than one disruption, after determining recovery scope for each of them, if there are no any common areas in the scopes, it is possible to solve them separately and simultaneously. Otherwise those with common areas are merged.

4.2.4. Assignment cost

There are different options to assign a given aircraft to a rotation (some flights) because of different operation conditions and reassigning disrupted passengers because of flight capacity. Consequently, the assignment/reassignment cost in each option will be different. Modeling assignment cost based on the airline policies will result recovery solution which meets airline policies.

5. Computational results

Data set $S1$ is used to evaluate the modeling and solution strategies. Data is obtained from Andersson and Varbrand [10]. The data set contains short flights, between 15 and 125 min and is perturbed in two different ways, *a* and *b*. *a* is an aircraft breakdown, it means an aircraft is unavailable for some hours, and in *b* some flights are imposed with delays. Some passengers' itineraries are extracted from data set $S1$ to be able to cover simultaneous aircraft and passenger recovery model in this study. Table 1 sums up the important characteristics for the data set.

The minimum connecting time is 10 min for aircrafts to turn around and be ready for the next flight and passengers to walk between the arrival and departure gates of the consecutive flights. Maximum delay allowed for a single flight is set to 60 min for all flights. Connecting passengers' itineraries contain 2 flights. But the model is able to handle more

Table 1
Data set.

Data set S1	
Number of aircrafts	13
Number of aircraft types	2
Number of flights	100
Number of airports	19
Number of passengers	2236
Number of itineraries	8
Number of connecting passengers	55

Table 2
Results for aircraft recovery for S1a and S1b.

	n	Weights				**Objective function value**	Results			
		CC	$Cswt$	Csw	CD		c	st	s	d
$S1a$	1	20	100	10	1	**880**	30	2	8	0
	2	20	1000	10	1	**960**	46	0	4	0
	3	100	1000	10	1	**4620**	32	0	0	1420
	4	100	100	10	1	**2920**	25	4	2	0
$S1b$	1	20	100	10	1	**120**	0	0	12	0
	2	20	100	100	1	**650**	0	0	4	250
	3	20	100	400	1	**1580**	0	0	0	1580

flights in connecting itineraries. Each scenarios of data set is solved with different weights. It means a dispatcher would be able to change the weights if the solution obtained does not meet the requirements. The tests are performed on a Sony Vaio Intel (R) Pentium (R) M, computer with 768 Mb of memory and 1.73 GHz processors. LINGO 8.0 is used for solving the NLP problems.

First the problems are modeled and solved as aircraft recovery problem without considering connecting passengers to show the ability of the proposed approach to suggest good solutions considering to the results of Andersson and Varbrand [10]. The results for the $S1a$ and $S1b$ are presented in Table 2. In order to be in coordinate with Andersson and Varbrand recovery policies reserve aircrafts and ferrying are not considered.

CC is the weight or cost for canceling a flight, $Cswt$ the weight for assigning a flight to an aircraft of a different type, Csw the weight for assigning a flight to an aircraft in the same fleet as originally planned, and CD is the weight for delaying a flight. c notes how many passengers are affected by a canceled flight, st and s how many swaps between aircraft types and regular swaps that are made, and finally d is the total amount of passenger delay in the solution.

Results (in Table 2) show that our proposed model is able to suggest good recovery solutions for aircraft recovery problem.

Running simultaneous aircraft and passenger recovery model, results are presented in Tables 3 and 4.

S_p is the weight or cost per disrupted passenger who are not reassigned and must be arrived to their destination by even other airlines or an alternative way of transportation. it_p^r is the number of passengers who were initially assigned to itinerary p but reassigned to itinerary r. trn_p is the number of passengers who were initially assigned to itinerary p but must be served on other airlines or other transportation mode. *Objective function value* is calculated based on the objective function of this paper model (weights multiplied by results in Tables 3 and 4).

Models which just focus on aircraft recovery, like Andersson and Varbrand [10], cause disruptions for passengers with connecting itineraries. Therefore they impose some cost to the problem but this cost is not modeled.

Our (*Jafari and Zegordi*) model which integrates passenger recovery with aircraft recovery can handle disruption for passengers with connecting itineraries. We show that by

Table 3
Results for simultaneous aircraft and passenger recovery for S1a.

No.	Weights					Model	Objective function value	Results					
	CC	*Cswt*	*Csw*	*CD*	S_P			*c*	*st*	*S*	*d*	it_p^r	trn_p
1-1	20	100	10	1	10	Jafari and Zegordi	**1080**	30	2	8	0	0	20
						Andersson and Varbrand	**1280**	50	2	8	0	0	0
1-2	20	100	10	1	20	Jafari and Zegordi	**1280**	30	2	8	0	0	20
						Andersson and Varbrand	**1280**	50	2	8	0	0	0
1-3	23	100	10	1	23	Jafari and Zegordi	**1425**	30	2	8	225	0	10
						Andersson and Varbrand	**1430**	50	2	8	0	0	0
2-1	20	1000	10	1	10	Jafari and Zegordi	**1160**	46	0	4	0	0	20
						Andersson and Varbrand	**1360**	66	0	4	0	0	0
2-2	20	1000	10	1	20	Jafari and Zegordi	**1360**	46	0	4	0	0	20
						Andersson and Varbrand	**1360**	66	0	4	0	0	0
2-3	23	1000	10	1	23	Jafari and Zegordi	**1553**	46	0	4	225	0	10
						Andersson and Varbrand	**1558**	66	0	4	0	0	0
3-1	100	1000	10	1	10	Jafari and Zegordi	**4820**	32	0	0	1420	0	20
						Andersson and Varbrand	**6620**	52	0	0	1420	0	0
3-2	100	1000	10	1	100	Jafari and Zegordi	**5845**	32	0	0	1645	0	10
						Andersson and Varbrand	**6620**	52	0	0	1420	0	0
4-1	100	100	10	1	10	Jafari and Zegordi	**3120**	25	4	2	0	0	20
						Andersson and Varbrand	**4920**	45	4	2	0	0	0
4-2	100	100	10	1	100	Jafari and Zegordi	**4145**	25	4	2	225	0	10
						Andersson and Varbrand	**4920**	45	4	2	0	0	0

Table 4
Results for simultaneous aircraft and passenger recovery for *S*1*b*.

No	Weights					Model	Objective function value	Results					
	CC	*Cswt*	*Csw*	*CD*	S_P			*c*	*st*	*s*	*d*	it_p^r	trn_p
1-1	20	100	10	1	10	Jafari and Zegordi	**270**	0	0	12	0	0	15
						Andersson and Varbrand	**420**	15	0	12	0	0	0
1-2	20	100	10	1	20	Jafari and Zegordi	**420**	0	0	12	0	0	15
						Andersson and Varbrand	**420**	15	0	12	0	0	0
1-3	23	100	10	1	23	Jafari and Zegordi	**460**	0	0	12	225	0	5
						Andersson and Varbrand	**465**	15	0	12	0	0	0
2-1	20	100	100	1	10	Jafari and Zegordi	**800**	0	0	4	250	0	15
						Andersson and Varbrand	**950**	15	0	4	250	0	0
2-2	20	100	100	1	20	Jafari and Zegordi	**950**	0	0	4	250	0	15
						Andersson and Varbrand	**950**	15	0	4	250	0	0
2-3	23	100	100	1	23	Jafari and Zegordi	**990**	0	0	4	475	0	5
						Andersson and Varbrand	**995**	15	0	4	250	0	0
3-1	20	100	400	1	10	Jafari and Zegordi	**1730**	0	0	0	1580	0	15
						Andersson and Varbrand	**1880**	15	0	0	1580	0	0
3-2	20	100	400	1	20	Jafari and Zegordi	**1880**	0	0	0	1580	0	15
						Andersson and Varbrand	**1880**	15	0	0	1580	0	0
3-3	23	100	400	1	23	Jafari and Zegordi	**1920**	0	0	0	1805	0	5
						Andersson and Varbrand	**1925**	15	0	0	1580	0	0

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managing cost of disrupted passengers the total cost of problem is reduced. In $S1a$ and $S1b$ our model caused 12.2% and 6.8% reductions in total cost, respectively.

6. Conclusion

While reviewing other related papers and researches in recovery planning in airline industry, in this paper a mathematical model is developed to recover aircraft and passengers simultaneously. The computational results show that the proposed method for modeling and solving aircraft recovery problem including disrupted passengers is efficient and can provide a flight dispatcher with a number of different suggestions. The users can state their preferences in the form of weights, which are used to calculate the costs in the model.

Canceling a flight or delaying the departure of a flight will directly affect the passengers on that particular flight. But it may also, indirectly, affect the passengers on the next flight in the route for the aircraft in question. Our model focuses on this indirect affect and gives solution for it. Moreover defining recovery scope, problem size is reduced and solution is suggested in a very short time. Using rotation instead of flights helps to limit scope of disruption and is useful to return to initial schedule as soon as possible.

Several extensions are considered for this research work. The model can be extended through considering crew constraints or slot times as other resources in airline scheduling. Furthermore, developing solution techniques for large scale problems is another extension which authors are now working on.

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