Model for Recovery of Multi-type Aircrafts' Flights Considering Delay Time of Passengers

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Abstract. This paper focuses on solving the problem of abnormal flight recovery, which is a hot topic of airline. In the background of an exception occurring at an airport under multi-airport conditions, this paper analyses multi-type flight recovery problem, taking multi-type aircraft capacity, passenger seat allocation, interline flights of passengers and airport capacity into account. And a multi-type flight recovery model is constructed with the objective of minimizing the total delay time of passengers. The improved GRASP algorithm based on the path relinking algorithm is designed to solve the model. Finally, the correctness of the model and the effectiveness of the algorithm are verified by the case.

1. Introduction

According to the FlightStats website, the flight punctuality rate of most airlines in the world is low in February 2017. The flight delay problem brings serious economic loss to the airline and the decline of passenger satisfaction. Therefore, the airlines is trying to search appropriate model and algorithm to solve the problem. Based on this, this paper constructs a model based on the minimum passenger total delay time from the perspective of passengers, and discusses the problem of flight recovery.

In recent years, domestic and foreign scholars have done a lot of research on improving the quality of flight services and improving the utilization efficiency of aviation resources. On the issue of flight recovery, the emphasis of different scholars' research contents is different. Tang X.W [1] studied the problem of abnormal flight recovery under the cooperative decision-making mechanism, introduced the concept of aircraft ready time, and took aircraft flow imbalance into consideration. Petersen, J.D [2] divided the airline integrated recovery problem integration into schedule recovery, aircraft recovery, crew recovery and passenger recovery. The Bender's decomposition and column generation algorithm was designed to solve it. Apart from the emphasis of research contents, there are some differences in modeling methods adopted by different scholars. Jarrah A.I.Z [8] analyzed the shortest path method. Based on the resource assignment model, the flight delay model and flight cancellation model were constructed respectively. In the abnormal situation of the shortage of aircraft resources and the closure of the airport, Bai F [9] constructed a flight recovery model based on flight delay, aircraft replacement, flight cancellation and dispatching strategy, and used a column generation algorithm to solve the problem. Zhao X.L [10] studied the three sub problems of flight cancellation, aircraft recovery and crew recovery respectively. The integrated recovery model of flight plan was constructed through space-time network.

In order to facilitate the description of the problem, some definitions are introduced first. Flight bunch refers to a series of flight collections with the following characteristics: the arrival airport of the previous flight is the same as the take-off airport of the latter flight, and the difference between the take-off time of the latter flight and the arrival time of the previous flight is not less than the minimum time limit. Aircraft route refers to an aircraft and flight bunches executed by the aircraft. There are usually three basic adjustment strategies for flight recovery issues as follows.

1.1. Flight delay and cancellation

Some flights may be delayed because the airport is closed or other reasons. As shown in Figure 1, flight 1, flight 2 and flight 3 belong to the same flight bunch. If flight 1 is delayed, other flights whose flight bunch is the same as flight 1' may be delayed. The time interval between two neighbouring flights should not be less than the minimum interval. If a flight does not meet the relevant constraints after delaying, it will be cancelled.

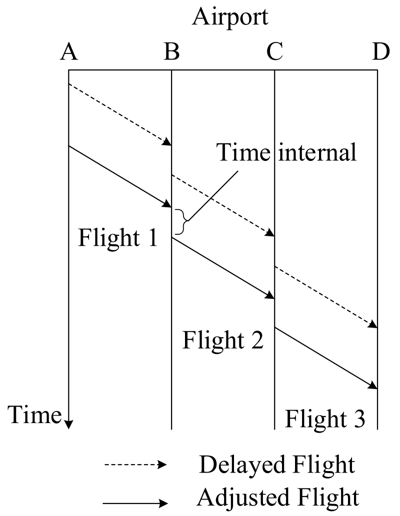

Figure 1. Flight delay.

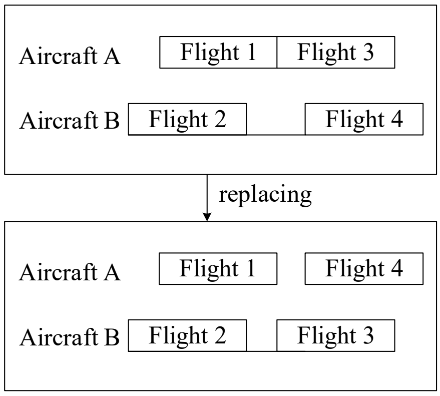

Figure 2. Aircraft replacement.

1.2. Aircraft replacement

Aircraft replacement is to arrange flights to other aircraft which is different from the original aircraft. As shown in Figure 2, the original scheduled flight 1 and flight 3 are to be executed by the aircraft A, and the flight 2 and the flight 4 are to be executed by the aircraft B. However, the aircraft A did not have enough time to execute flight 1 after executing flight 3. So the dispatcher will arrange flight 3 with aircraft B and flight 4 will aircraft A. Aircraft replacement can be carried out between different aircrafts.

2. Model

2.1. Hypothetical condition

- All flights can only be delayed and not be advanced
- The earliest take-off time cannot be earlier than the planned take-off time.

2.2. Model building

The set, parameters and decision variables used in the model are shown in Table 1.

Table 1. Model parameter

Symbol	Symbolic interpretation
P	Set of passenger numbers that represents all passengers.
P_1	Set of passenger numbers that represents the passengers cannot reach the destination because of the cancellation of any flight of interline flights.
P_2	Set of passenger numbers that represents the passengers cannot reach the destination because there is not enough time between the neighbouring flights.

P_3	Set of passenger numbers that represents the passengers cannot reach the destination because of the chances of aircraft's type.
S	Set of aircraft routes.
F	Set of flights.
PL	Set of aircrafts.
A	Set of airports.
F^{I}_{a,t_1,t_2}	Set of airport a's arrival flights in time (t_1, t_2).
C_p	Number of passengers whose passenger number is p.
C_{pl}	Capacity of aircraft pl.
x^{f}_{p}	Whether the passenger p takes the flight f.
arr^{old}_{f}	The planned arrival time of the flight f.
dep^{old}_{f}	The planned take-off time of the flight f.
PCC_p	The time cost of a passenger not reaching his destination.
N_s	Flight number of aircraft route s.
x^{s}_{f}	Whether the aircraft route s contains flight f.
d^{I}_{a}	Take-off capacity of the airport a.
d^{O}_{a}	Landing capacity of the airport a.
$a^{dep}_{s,i}$	The take-off airport of the ith flight of aircraft route s.
$a^{arr}_{s,i}$	The arrival airport of the ith flight of aircraft route s.
$f_{s,i}$	The ith flight of aircraft route s.
T_s	The minimum time interval between the neighbouring flights of aircraft route s.
$t^{earliest}_{pl}$	The earliest available time of aircraft pl.
t^{latest}_{pl}	The latest available time of aircraft pl.
arr^{new}_{f}	Decision variable, the actual arrival time of flight f.
dep^{new}_{f}	Decision variable, the actual take-off time of flight f.
$Cancel_f$	Decision variable, whether flight f is cancelled.
x^{s}_{pl}	Decision variable, whether the aircraft pl is assigned to the aircraft route s.

The aims of this paper are to reschedule flight plan, make the planned flights not be cancelled as far as possible and ensure the shortest total passenger delay cost. In order to quantify the passenger delay cost, the model divides the state of passenger delay into two kinds. First one is to arrive at airport behind schedule (arriving at airport on time can be seen as a special case that the delay cost is 0), the other is that passengers cannot reach the destination. So the total passenger delay cost includes two parts. For the passengers that take direct flights, the reason that they cannot reach the destination is the cancellation of the flight; for the passengers that take interline flights, the number of the reason that they cannot reach the destination airport is three. Firstly, any flight of interline flights is cancelled. Secondly, there is not enough time between the neighbouring flights. Thirdly, some passengers cannot take flights because that the aircrafts that execute the flights are replaced by smaller aircrafts. As a result, a mathematical model can be established as follows.

$$\min \sum_{p\in P_1\cup P_2\cup P_3} C_p PCC_p + \sum_{p\in P-(P_1\cup P_2\cup P_3)} \sum_{f\in F} C_p(1-Cancel_f)x_p^f(arr_f^{new}-arr_f^{old})$$

(1)

$$s.t. \quad \sum_{pl\in PL}\sum_{s\in S} x_f^s x_{pl}^s + Cancel_f = 1, \forall f\in F$$

(2)

$$d_a^I \geq \sum_{pl\in PL}\sum_{s\in S}\sum_{f\in F_{a,t_1,t_2}^I} x_f^s x_{pl}^s, \forall \mathrm{a}\in \mathrm{A}$$

(3)

$$d_a^O \geq \sum_{pl\in PL}\sum_{s\in S}\sum_{f\in F_{a,t_1,t_2}^O} x_f^s x_{pl}^s, \forall \mathrm{a}\in \mathrm{A}$$

(4)

$$a_{s,i}^{arr} = a_{s,i+1}^{dep}, \forall \mathrm{s}\in \mathrm{S}$$

(5)

$$arr_{f_{s,i}}^{new} + T_s = dep_{f_{s,i+1}}^{new}, \forall s\in S, i\in\{1,2,3\cdots N_s\}$$

(6)

$$dep_{f_{s,i}}^{new} \geq \sum_{pl\in PL} t_{pl}^{earliest} x_{pl}^s, \forall \mathrm{s}\in \mathrm{S} \tag{7}$$

$$arr_{f_{s,N_s}}^{new} \leq \sum_{pl\in PL} t_{pl}^{latest} x_{pl}^s, \forall \mathrm{s}\in \mathrm{S} \tag{8}$$

$$\sum_{p\in P} x_p^f C_p \leq \sum_{s\in S}\sum_{pl\in PL} x_{pl}^s x_f^s C_{pl}, \forall f\in F \tag{9}$$

(1) is the objective function to minimize the total passenger delay cost, including the flight delay cost and the delay cost for the cancellation of flights. (2) is the flight coverage constraint, which ensures that each flight belongs to a aircraft bunch and is arranged for an aircraft to execute, or is cancelled. (3) is the take-off capacity constraint of an airport. (4) is the landing capacity constraint of an airport. (5) - (8) is the time and space constraints of the aircraft route. (5) is the consistency constraint that the arrival airport of the front flight of two neighbouring flights is the same as the take-off airport of the latter flight in aircraft route. (6) is the constraint the minimum time interval between two neighbouring flights is met. (7) is the constraint the take-off time of the first flight cannot be earlier than the earliest available time of the aircraft. (8) is the constraint the arrival time of the last flight of flight bunch cannot be later than the latest available time of the aircraft. (9) is the passenger flow constraint that the number of passengers on any flight should be less than capacity of aircraft.

3. Algorithm

Flight recovery is a combinatorial optimization problem, and GRASP is a multiple-start local search algorithm to solve combinatorial optimization problems. It has been widely used in frontier fields such as artificial intelligence. On the basis of GRASP, this paper improves the original algorithm by adding path relinking to improve the efficiency of the whole solution. The basic algorithm framework is shown in Figure 3.

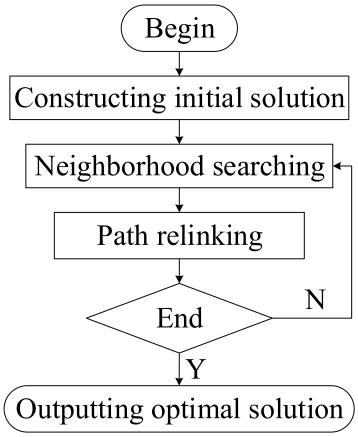

Figure 3. Basic algorithm framework.

3.1. Constructing initial solution
Firstly, the directly affected flights are extracted, and the departure or arrival time of them is put off. Secondly, the departure or arrival time of the rest flights is adjusted according to the directly affected flights. Then we obtained a flight schedule which is taken as the initial feasible solution to form the search starting point of the GRASP algorithm. By constructing a better search starting point, the restored flight should try not to deviate from the original plan, and improve the quality of the final solution.

3.2. Neighborhood searching
The operation unit of the algorithm to generate the neighborhood solution is the aircraft route. The method of the GRASP algorithm to generate the neighborhood solution is as follows. At First, two affected aircraft routes are selected randomly. Then the sub-flight bunch of one aircraft route is inserted into another aircraft route, or the sub-flight bunches of the two aircraft routes are swapped, or one of the sub-flight bunches of the aircraft routes are canceled. In order to improve the quality of the neighborhood solution and the efficiency of algorithm execution, some measures are taken to eliminate the infeasible neighborhood solution when the neighborhood solution is generated. First, the space connection of the aircraft route is considered. If all stopping airports in two aircraft routes are different, they will not be operated. Second, the time connection of the aircraft route is considered. If the landing time of the last flight of the aircraft route is greater than the latest available time of the aircraft in the generated neighborhood solution, the neighborhood solution is not feasible. Third, the exchanging aircraft types of sub-flight branches are considered. If the target value after exchanging is increased, the operation is not performed. Fourth, the merger of aircraft routes is considered. If two aircraft routes can be connected in time and space, they will be merged directly, or some flights of one of the aircraft routes must be cancelled before they are merged.

3.3. Path Relinking
Path relinking[13] is a decentralized population algorithm that local search strategy are embedded in. The main idea is to select two solutions in the population, find a path from one solution to another, obtain a series of solutions through the path, and replace the poor solution in the population with the optimal solution on the path. Among them, "path" means a series of steps to adjust a flight recovery plan to another flight recovery plan.

In order to facilitate the description of the differences between the solutions, the "Hamming distance" is introduced. The "Hamming distance" is expressed in the data transmission error control code as the number of different codes in the same position of two binary codes of the same length. And $D(x_1 + x_2)$ is expressed as the number of different aircraft routes in the two flight plans. Let the generated neighborhood solution be x and the current preferred solution set which is generated by neighbor searching be ES. The path relinking steps are as follows. Firstly, the solution in the ES is iterated over and calculated its Hamming distance with x, and the solution with largest Hamming distance is taken as the target solution x_{goal} for path relinking. Secondly, x and x_{goal} is compared and their different aircraft route set $s_{diff}(s_{diff} \in x_{goal})$ is gotten. Thirdly, if s_{diff} is empty, the path relinking ends. Otherwise, according to the above adjustment strategies, x is adjusted towards x_{goal} along the direction where target value becomes smaller. Then a new neighborhood solution is formed. Fourthly, if the target value of the neighborhood solution is smaller than the optimal target value in the ES, the neighborhood solution is added to the ES, and the solution with the worst target value in the ES is eliminated. if the target value of the neighborhood solution is greater than the optimal value in the ES and smaller than the target value of the worst solution in the ES, and the neighborhood solution is significantly different from the solution in the ES, the neighborhood solution will be added to the ES, and the solution with the smallest Hamming distance from the x in the ES is removed. Return to second step.

4. Case analysis

4.1. Basic Data

The basic data of the case includes 119 airports, 144 aircraft, 557 flights, and 36,626 passengers, including 31,237 passengers that take interline flights and 5,389 passengers that take direct flights. Some data is shown in Table 2-5. PPC_{p} is 1440 minutes; T_s is 45 minutes. The take-off time, arrival time, earliest available time, latest available time, closing start time and closing end time are all in unix format. Due to the large amount of data in the study, only part of the data is listed here.

The case's interference scenario is that airport OVS will be closed between 18:00, June 22, 2016 and 21:00, June 22, 2016 due to weather conditions. During this period, any flights cannot land or take off on the airport. And all flights are normal before the period or after the period. Therefore, all flights scheduled to take off and land between 18:00 and 21:00 (excluding 18:00 and 21:00) on the same day will need to be rescheduled and may affect subsequent flights. Under the runway restriction, 5 aircraft can take off every 5 minutes on the airport OVS, and 5 aircraft can land in the same time. For example, between 21:00 and 21:05 (excluding the 21:05 time point), there are up to 5 take-off flights and 5 landing flights. The take-off and landing times are calculated at 21:00. There are up to 5 take-off flights and 5 landing flights between 21:05-21:10 (excluding the 21:10 time point), and the take-off and landing times are calculated at 21:05. Other airports do not need to consider runway restrictions.

Table 2. Some flights

Flight Number	Take-off time	Arrival time	Take-off airport	Arrival airport	Aircraft type	Aircraft Number
174774150	1461341700	1461348120	OVS	LEH	9	41098
174774124	1461351000	1461356760	LEH	OVS	9	41098
174773927	1461326400	1461336600	GEB	OVS	73H	DCBPV
174774456	1461321660	1461334680	OCF	OVS	321	CDBPV

Table 3. Some aircrafts

Aircraft number	Aircraft type	Earliest available time	Latest available time	Starting airport	Seating
41098	9	1461333600	1461426000	OVS	87
DCBPV	73H	1461326400	1461440100	GEB	158
CDBPV	321	1461321660	1461424500	OCF	170

If a passenger number corresponds to multiple records, it means that passengers of the passenger number are takes interline flights. For example, passenger number 1 takes flight 174777880 and flight 174781120. If a passenger number corresponds to only one record, it means that the passenger number only takes direct flight.

Table 4. Some passengers

Passenger Number	Flight Number	Number of passengers
1	174777880	14
1	174781120	14
3	174778406	10

Table 5. Airport closed time

Airport	Closing start time	Closing end time
OVS	1461348000	1461358800

4.2. Test Results

The test environment is Windows10 64-bit operating system, the CPU is Intel Core i5-7300HQ, the installed memory is 8.00G, and the case is solved by Matlab2016b. The solution results are shown in Table 6.

Table 6. Result comparison

Algorithm	Total delay time of the passengers /(min)	Number of cancel flights	Number of delay flights	Running time/(s)
Delay scheme	1777098	1	293	10.9
Traditional GRASP	1335921	0	208	93
Improved GRASP	1296509	0	193	117

The total delay time of the passengers in the delay scheme is 1777098 min. The total delay time of passengers caused by flight delays is 1610058 min. The total delay time of passengers caused by passengers unable to reach the destination is 167040 min, and the number of cancelling flights is 1. The flight was cancelled because landing time of a flight was less than the latest available time of the aircraft responsible for the flight after flights delaying. The total delay time of passengers of the traditional GRASP algorithm is 1335921 min. In the optimization, the flight landing time is less than the latest available time of the aircraft responsible for the flight is avoided by flights replacement, so the number of cancellation flights is zero. Compared with the delay scheme, the result of the traditional GRASP algorithm reduces by 441177 min, which is 24.8% lower than the delay scheme. The total delay time of the passengers obtained by the GRASP algorithm with path relinking is 1296509 min, which is 39,912 min less than the result obtained by the traditional GRASP algorithm, which is reduced by 3.0%, mainly because the path relinking improves the ability of jumping out of the local optimal solution and the quality of the solution.

In summary, the improvement of the algorithm by path relinking is analysed by comparing the solution results before and after the adding path relinking. According to the results, the solving speed of the GRASP algorithm based on path relinking is slightly slower than the traditional GRASP algorithm, but the solution quality is higher.

5. Conclusion

Based on the results of the existing flight recovery research, this paper considers the passenger's interline flight, multi-type aircraft capacity and other factors, transforms the cost that passengers cannot reach the destination into delay time of passengers, and builds the model with the minimum passenger delay time as the goal. The traditional GRASP algorithm and the GRASP algorithm based on path relinking are designed to solve the model, compared and analyzed, and the abnormal flight recovery scheme is obtained. Finally, the example is verified. However, this paper minimizes the total delay time of passengers from the perspective of passengers when abnormal flights occur, and does not consider the factors of airlines' flight recovery cost. It will be considered in future research. Meanwhile, other important part of flight recovery, such as crew recovery and passenger recovery, and airline integrated recovery will be taken into account.

Acknowledgments
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