[EN-A- 069] Integrated Arrival & Departure Aircraft Sequencing under the Influence of Sequential Flights

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Abstract: An integrated arrival and departure sequencing model and algorithm were presented in this paper to enhance the runway capacity, improve the efficiency of arrival and departure and mitigate the accumulation and propagation of delays. First, an integrated arrival and departure sequencing model was constructed based on the multi-runway operating modes, wake separation, release separation and the operational characteristics of sequential flights. Second, a multi-objective simulated annealing algorithm using Pareto-domination based acceptance criterion (PDMOSA) was employed solve the integrated arrival and departure sequencing problem with two objectives - maximizing runway operating capacity and minimizing delays of sequential flights. In this algorithm, the arrival priority strategy of sequential flights was introduced into the neighborhood search process. Finally, a large domestic airport was chosen to design simulation scenarios and arrival and departure flights in rush hours were taken as examples to carry out the simulation validation. And the results not only indicate the effectiveness of the proposed model and algorithm, but also show the arrival and departure delay of sequential flights are reduced when taking the influence of sequential flights into consideration.

Keywords: air transportation; integrated arrival and departure sequencing; multi-objective optimization; simulated annealing; sequential flights

1. INTRODUCTION

In recent years, the ever increasing air traffic flow results in increased pressure on air transportation system. Such pressure could even result in traffic jams and flight delays. Therefore, there is great interest in more efficiently managing the arrival and departure operations to guarantee the flight safety and enhance the runway capacity. Therefore, integrated arrival and departure aircraft sequencing is becoming current research focus in the Air Traffic Management (ATM) filed [1].

In past years, in order to improve efficiency of terminal area (TMA) operations, many models and algorithms were developed. Tyagi [2] solved the integrated arrival and departure aircraft sequencing problem by a mixed integer programming model and obtained the optimized time of taking off and landing by using CPLEX. Ghoniem [3] transformed the integrated arrival and departure aircraft sequencing problem into Asymmetric Traveling Salesman problem, which is tackled through pre-treatment mechanism. Hancerliogullari [4] turned to Machine Scheduling Problem for help and proposed greedy heuristic and metaheuristic algorithms to obtain solutions in reasonable computation times. Xue [5] provided a fast time algorithm formulation using a non-dominated sorting

genetic algorithm to solve the arrival and departure sequencing problem. According to the actual operation of the airport and the case that cargo flights can land or take off on a fixed runway only, Wang [6] studied the optimization of sequencing and the assignment of runways for arrival and departing flights. Sölveling [7] proposed a solution methodology based on the stochastic branch and bound algorithm to find optimal, or close to optimal, solutions to the stochastic airport runway scheduling problem. Chandrasekar [8] presented a framework to compute with computational efficiency, the optimal runway assignment, and sequencing of arrival and departure operations at an airport with any number, layout and configuration of runways.

However, the above mentioned researches ignored the influence of integrated arrival and departure sequencing affected by the sequential flights. Each aircraft needs to complete flight task continually every day. The arrival time of the pre-order flight has direct influence on the take-off time of the sequential flight. Therefore the time slot allocation for the arrivals and departures plays an important role in the arrival and departure sequencing problem. Furthermore, the reasonable and efficient time slot allocation should make full use of information sharing strategy. However, the current researches only focused on

the analysis of flight delay propagation and accumulation, and how to mitigate such flight delay propagation and accumulation during the cruise phase. For example: Hsu [9] studied the flight delay propagation and accumulation methods from the perspective of managing the turnaround time of sequential flights; Takeichi [10] tried to reduce the flight delay propagation and accumulation through optimizing the fly time; and Ivanov [11] minimized the propagated delay and improved airport slot adherence based on the air traffic flow management slot allocation. And there are few researches mitigating or preventing the flight delays through taking the integrated arrival and departure sequencing into consideration.

This paper has proposed an integrated arrival and departure sequencing method under the influence of sequential flights. The proposed method is able to not only optimize the arrival and departure sequencing problem simultaneously, but also mitigate and prevent the flight delays. All these appeals are satisfied based on the prompt information sharing strategy and efficient integrated arrival and departure sequencing method.

The remainder of this paper is organized as follows. The integrated arrival and departure sequencing problem is defined in Section 2. Section 3 presents the integrated sequencing model. The multi-objective simulated annealing algorithm is presented in Section 4. The validation results are reported in Section 5. Finally, some concluding remarks are provided in Section 6.

2. PROBLEM FORMULATION

The airlines always schedule one particular aircraft to fulfill several flights every day to increase the profit. The preorder flight will be the subsequent flight after the turnaround process. And such flight is viewed as sequential flight. Figure 1 presents the macro process of arrival and departure operation, in which flight f_1 is the arrival flight without subsequent task, flight f_3 is the departure flight without preorder task, and flight f_2 is the sequential flight.
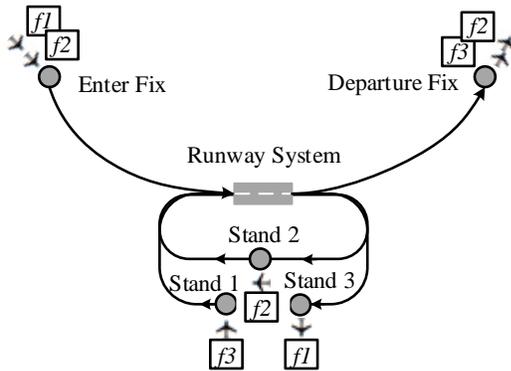

Figure 1 Macro process of arrival and departure operation

According to the real operations in one domestic airport, there are 1120 arrival and departure flights in a particular day. The sequential flights account for 53%, the departure flights without preorder is tasks 23%, while the arrival flights without subsequent tasks is 24%. Therefore, it's necessary to take the influence of sequential flights into consideration when solving the integrated arrival and departure aircraft sequencing problem.

Comparing with the arrival and departure sequencing without the influence of sequential flights, the key contribution of this work is to make full use of information sharing strategy, which means the influences of the preorder flights exerting on the preorder flights.

With regard to the arrival flights without subsequent tasks, the sequencing is completed from the entry fix to the runway threshold. With regard to the departure flights without preorder tasks, the sequencing is finished from the runway threshold to the departure fix. With regard to the sequential flights, the sequencing task contains the sequencing from the entry fix to the runway threshold and the sequencing from the gate to the threshold, i.e. the influences of the preorder flights exerting on the preorder flights. In brief, under the consideration of the influences of the sequential flights, the integrated arrival and departure sequencing should give priority to the delayed arrival flights with subsequent tasks.

3. SEQUENCING MODEL

3.1 Variables Definition
We use the following symbols and parameters to construct the integrated arrival and departure sequencing mode.

R : runway set, $R = \{1, 2, \cdots, m\}$;

J : arrival and departure flights set, $J = \{1, 2, \cdots, n\}$;

J^A : arrival flights set;

J^D : departure flight set;

e_j : estimated operation time of flight j, $\forall j \in J$;

r_j : earliest take-off or landing time of flight j, $\forall j \in J$;

d_j : latest take-off or landing time of flight j, $\forall j \in J$;

p_{ij} : minimum separation time between flight i and j that operate in the same runway, $\forall i, j \in J$, $i \neq j$;

q_{ij} : minimum separation time between flight i and j that operate in the different runway, $\forall i, j \in J$, $i \neq j$;

s_{ij} : represent whether flight i and j are sequential flights, if $s_{ij} = 1$ indicates the sequential flights, $s_{ij} = 0$ otherwise;

T_j^{TR} : turnaround time on the apron of sequential flight j;

T_j^{in} : taxi-in time of landing flight j, $\forall j \in J^A$;

T_j^{out} : taxi-out time of take-off flight i, $\forall j \in J^D$;

T_i^{rot} : runway occupied time of flight i, $\forall i \in J$;

$t_j^{S \cdot off}$: updated off blocks time of sequential flight j, $s_{ij} = 1$;

r_j^S : the updated the earliest take-off time of sequential flight j, $s_{ij} = 1$, $\forall j \in J^D$;

T_{ij}^{Delay} : the delay time of sequential flight, $\forall i \in J^A$, $\forall j \in J^D$,

$T_{ij}^{Delay} = s_{ij} \cdot [\max\{t_i - e_i, 0\} + \max\{t_j - e_j, 0\}]$.

The decision variables are:

t_j : The optimized arrival or departure time of flight j;

x_{ij} : The operation sequence of the same runway, $x_{ij} = 1$ means flight i is previous to flight j, $x_{ij} = 0$ means the other case, $\forall i, j \in J$, $i \neq j$.

y_{ij} : The operation sequence of the different runway, $y_{ij} = 1$ means flight i is previous to flight j, $y_{ij} = 0$ otherwise, $\forall i, j \in J$, $i \neq j$.

For the single runway operation, p_{ij} is related to the wake turbulence categories and operational types (arrival or departure) of the preorder and subsequent aircraft.

For the multiple runways operation, $p_{A \to D}$ and $p_{D \to A}$ are both zero in the condition of the segregated parallel operation. The lateral radar separation between flights landing on different runway should be taken into consideration in the condition of the dependent parallel approach operation.

3.2 Objectives and Constraints
In this paper, the runway capability maximization (Equation (1)) and the delay of sequential flights minimization (Equation (2)) are chosen as the objectives, the integrated arrival and departure sequencing model is constructed when considering the following constraints.

$$\min \quad \max(t_j) \tag{1}$$

$$\min \quad \sum T_{ij}^{Delay} \tag{2}$$

$$\text{s.t.} \quad r_j - t_j \leq 0 \tag{3}$$

$$t_j - d_j \leq 0 \tag{4}$$

$$t_j \geq t_i + p_{ij} - (1 - x_{ij})(d_i - r_j + p_{ij}) \tag{5}$$

$$t_j \geq t_i + q_{ij} - (1 - y_{ij})(d_i - r_j + q_{ij}) \tag{6}$$

$$x_{ij} + x_{ji} \leq 1 \tag{7}$$

$$y_{ij} + y_{ji} \leq 1 \tag{8}$$

$$x_{ij} \in \{0,1\}, \ y_{ij} \in \{0,1\} \tag{9}$$

$$t_j^{S \cdot off} \geq t_i + T_i^{rot} + T_i^{in} + T_j^{TR} \tag{10}$$

$$t_j^{S \cdot off} \geq e_j - T_j^{out} \tag{11}$$

$$r_j^S \geq r_j \tag{12}$$

$$r_j^S \geq t_j^{S \cdot off} + T_j^{out} \tag{13}$$

$$t_j^S \geq t_j^{S \cdot off} + T_j^{out} \tag{14}$$

Equation (3) and Equation (4) define the time window constrains of take-off or landing. Equation (5) provides the wake separation between the leading and succeeding aircrafts in the same runway. Equation (6) provides the separation between the leading and succeeding aircrafts in the different runway. Equation (7), (8) and (9) determine that every flight occupies only one place in sequence. Equation (10) and (11) give the time restrictions for updating (Estimated Off-Block Time) EOBT. Equation (12), (13) and (14) give the time restrictions for the taking-off time of the subsequent flight.

4. SEQUENCING ALGORITHM

4.1 Priority Strategy for Sequential Flights
For the sequential flights, the preorder landing flight will exert great influence on the subsequent taking-off flight. Therefore, in this paper, in order to mitigate the influence of the preorder landing flight, the priority strategy for sequential flights is proposed.

The off-block time of the subsequent taking-off flight is restricted by Equation (10) and (11). On the one hand, the EOBT is equal to $e_j - T_j^{out}$. On the other hand, the updated EOBT is equal to $t_i + T_i^{rot} + T_i^{in} + T_j^{TR}$.

A variable b_i is introduced to denote the deviation between the EOBT and the updated EOBT, as shown in Equation (15). A bigger value of such variable means the lower influence which is exerting on the subsequent taking-off flight from the preorder landing flight. When the value is negative, it means the delay from pre-order landing flight will definitely cause the delay of the subsequent taking-off flight, that is also to say the delay is propagating and accumulating. Therefore, the priority for the sequential flights is determined by the value of b_i.

$$b_i = s_{i,j} \left[\left(e_j - T_j^{out} \right) - \left(t_i + T_i^{rot} + T_i^{in} + T_j^{TR} \right) \right] \tag{15}$$

4.2 Multi-Objective Simulated Annealing Algorithm
A Pareto-domination based acceptance criterion multi-objective simulated annealing algorithm (PDMOSA) proposed by Suman [12] is adopted in this paper for solving the model of integrated arrival and departure sequencing problem under the influence of sequential flights (Equation (1) to (14)).

In this section, in order to promote local research near the Pareto optimal solution, the acceptance criterion is adopted by using fitness value based on the Pareto-domination. Meanwhile, the high priority to the preorder delayed landing flight is adopted to mitigate the delay propagation and accumulation.

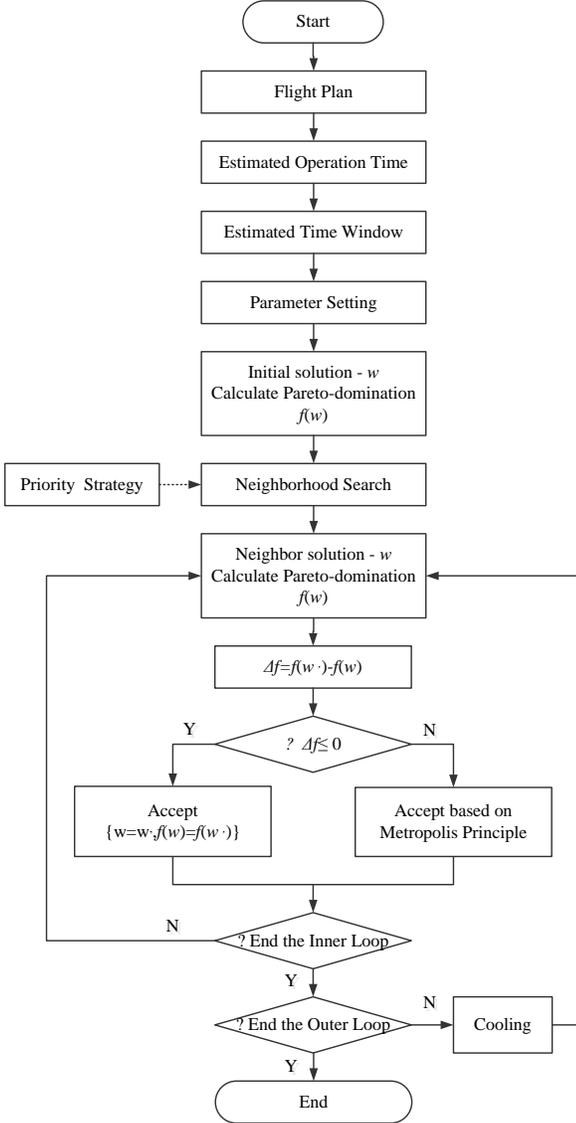The flowchart of PDMOSA algorithm is presented in Figure 2.

Table 1 Separation for wake turbulence (s)

Preceding aircraft	Following aircraft		
	Heavy	Medium	Light
Heavy	99	133	196
Medium	74	107	131
Light	74	80	98

The parameter settings for PDMOSA algorithm include: max iteration of outer loop (c_{max}=500), max iteration of inner loop (i_{max}=20), initial temperature (k=1000), cooling factor (α=0.85).

First, we obtain the distribution of Pareto optimized sets by PDMOSA from the perspective of the runway capability and the delay of sequential flights. Due to the large difference in target values, the ratio of the target value with FCFS strategy is adopted, as shown in Figure 3.
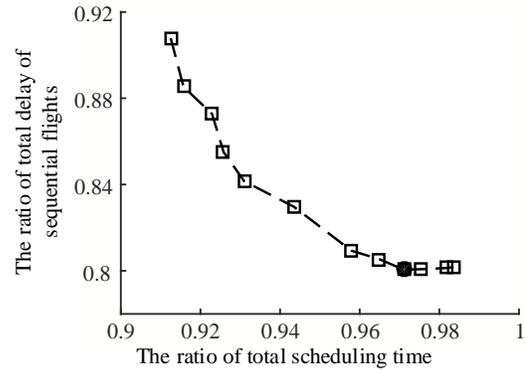
Figure 3 Pareto front for Multi-objective optimization

In the Figure 3, the x axis denotes the ratio of total runway scheduling time with the total runway scheduling time in FCFS strategy, while the y axis is the ratio of total delay of sequential flights with the total delay under FCFS strategy. The dotted line means the Pareto optimal solution set front of double-target function. Obviously the total runway scheduling time and total delay of sequential affect each other. Consolidate the above two objective, the ratio of 20% total delay reduction and the ratio of 3% total scheduling time reduction are selected as a best solution (shown as the solid circle in Figure 3).

Next, the sequencing result of arrival and departure flights affected by sequential flights is compared with the sequencing result in FCFS strategy, as shown in Table 2.

Table 2 Objectives of Integrated Arrival and Departure Scheduling (s)

Optimized strategy	Total delay time	Total scheduling time	Total delay of sequential flights
FCFS	54 312	8 653	20 125
PDMOSA	38 177	8 403	16 096

Figure 2 Flowchart of PDMOSA algorithm

5. SIMULATION AND DISCUSSION

The arrival and departure flights from one large domestic airport during the rush hour from 9:00 am to 11:30 am are chosen to verify the feasibility of model and the efficiency of the algorithm. The amount of sequential flights accounts for 25%. According to the operation standard of Civil Aviation Administration of China, the wake turbulence separations for arrivals, as shown in Table 1, are adopted in this simulation. For departures, we adopt 180 seconds for the same departure directions and 120 seconds for the different directions. And the runway occupied time is 60 seconds, while the taxi-in and taxi-out time is 20 minutes. The turnaround time for aircraft below 150 seats is 60 minutes and 70 minutes for those above 150 seats.

The total delay of arrival and departure flights is reduced by 29.7%, the total delay of sequential flights is reduced by 20.02%, while the total scheduling time is only reduced by 250 s due to the departure flights could not be released in advance.

Figure 4 presents the delay of preorder flights and the subsequent flights based on PDMOSA algorithm. The total delay of the preorder flights is reduced by 62.62%. The total delay of the subsequent flights is reduced by 14.28%. The reason are the priority is given to the aircraft in the air and the releasing limit to subsequent departure flights.
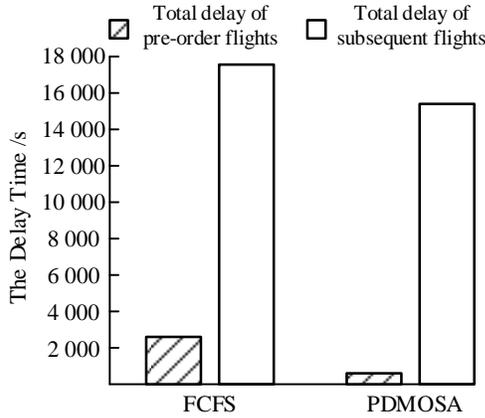

Figure 4 Total delays of preorder and subsequent flights

Finally, we compare the results of whether we consider the influence of sequential flights or not. Without considering the impact of sequential flights, the total delay of sequential flights is 18 311 s. With considering the impact of sequential flights, the total delay of sequential flights is 16 096 s, which is reduced by 12.09%. Meanwhile, when considering the impact of sequential flights, there are 24 arrival or departure flights operating in advance than the real operation, it accounts for 85.71% of the total number of sequential flights.
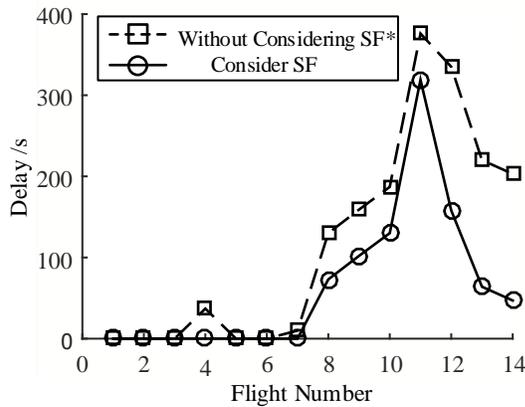
(a) Pre-order flights chart
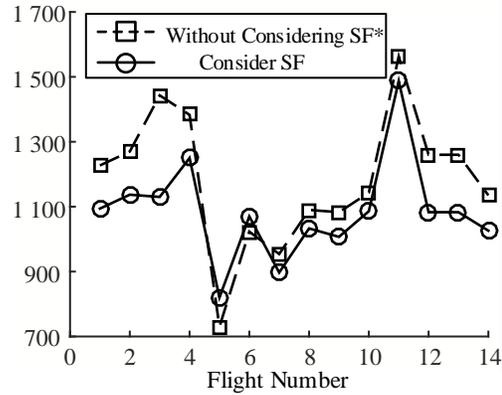
(b) Subsequent flights chart

Figure 5 Comparison of results with Sequential Flights

Figure 5 provides the contrast about the delay of the preorder flights and the subsequent flights in the condition of whether we consider the influence of sequential flights or not. From the Figure 5(a), when taking the sequential flights into account, the delay rate is reduced by 46.2% due to the priority strategy for the sequential flights. From Figure 5(b), there is a fluctuation in the delay of subsequent flights, and the delay rate is only reduced by 8.2%, as there is information sharing process between the preorder and subsequent flights.

6. CONCLUSION

This paper began with the analysis of the influence of the preorder flights exerting to the subsequent flights. Then an integrated arrival and departure sequencing model under the influence of sequential flights was constructed. Then a multi-objective simulated annealing algorithm was employed solve the problem. Finally the simulation was carried out to validate the proposed method.

As the uncertainty of taxiing time and turnaround time will affect the integrated sequencing solution, which provides a main direction for the future research.

7. ACKNOWLEDGMENTS

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