MULTI-OBJECTIVE INTEGRATED ARRIVAL & DEPARTURE AIRCRAFT SEQUENCING UNDER THE INFLUENCE OF SEQUENTIAL FLIGHTS

Junfeng Zhang, Zhixiang Zheng, Pengli Zhao, Rong Hu

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing, China

Abstract

A multi-objective integrated arrival and departure aircraft sequencing model and algorithm were presented in this paper to enhance the runway capacity, improve the operational efficiency and mitigate the accumulation and propagation of flight delays. Firstly, an integrated arrival and departure sequencing model was constructed based on the multiple runway operating modes, wake separation, release separation and the sequential flights. Secondly, a multi-objective simulated annealing algorithm using Pareto-domination based acceptance criterion (PDMOSA) was employed to solve the integrated arrival and departure aircraft sequencing problem with two objectives - maximizing runway operational capacity and minimizing flight delays of the sequential flights. In this algorithm, the arrival priority strategy of sequential flights was introduced into the neighborhood search process. Finally, Shanghai Pudong International 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.

Introduction

In recent years, the rapid growth of air traffic flow has imposed on increased pressure on air transportation system. Such pressure could even result in airport congestion problems with substantial effects on flight delays. The primary cause of these problems is a serious mismatch between growing air traffic demand and scarce airport resource supply. The supply side solution, demand management and arrival/departure management are the potential measures.

The pure supply side solution, like runway capacity expansion, is capital intensive and time consuming. The pure demand management, ranging from administrative instruments to market-based measures, may lead to quick or incremental improvements in the short and medium run [1]. But it is strongly based on economic theory, hence going beyond the scope and focus of this paper. In this paper, all of the attention is paid to how to efficiently manage the arrival and departure operations, which is becoming current research focus in Air Traffic Management (ATM) filed [2].

In past years, in order to improve efficiency of arrival and departure operations in Terminal Area (TMA), many models and algorithms were developed for the different operational conditions. For the single runway case, Balakrishnan and Chandran [3] presented a class of scalable dynamic programming algorithms for arrival and departure scheduling under Constrained Position Shifting (CPS), which could address diverse and competing considerations of efficiency, safety, and equity among airlines. Ghoniem [4] took advantage of the underlying structure of an asymmetric traveling salesman problem with time-windows to address the static aircraft sequencing problem over a mixed-mode single runway. Rodríguez [5] developed a Simulated Annealing (SA) algorithm for a specific case (considering Wake Vortex separation and CPS) to deliver quick and efficient schedules. For the multiple runway case, Hancerliogullari [6] modeled the aircraft sequencing problem as a parallel machine scheduling problem and applied greedy heuristics and metaheuristics to obtain solutions in reasonable computation times. Xue and Zelinski [7] proposed a fast time algorithm formulation using a Non-dominated Sorting Genetic Algorithm (NSGA) to solve the arrival and departure sequencing problem due to its ability to handle multi-objective optimization and multiple constraints. Chandrasekar and Hwang [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. For the multi-airport terminal area or metroplex case, Taylor [9] proposed

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an operational concept to improve high-density-area departure and arrival management that specifically accounts for complications arising in metroplex operations where multiple airports are located in close proximity. Shi [10] investigated the collaborative arrival and departure aircraft sequencing problem for multi-airport terminal area based on the improved SA algorithm. Ma studied the problem of arrival and departure traffic flow collaborative scheduling in multi-airport terminal area and designed the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) to search for Pareto optimal solutions.

The above mentioned research did reconcile the situation of mismatch between growing air traffic demand and scarce airport resource supply. However, the current research ignored the influence of the sequential flights imposed on arrival and departure management. For sequential flights, the arrival time of the pre-order flight has direct influence on the take-off time of the subsequent flight. Therefore the time slot allocation for the sequential flights plays an important role in the arrival and departure aircraft sequencing problem. Furthermore, the reasonable and efficient time slot allocation for the sequential flights should make full use of the information sharing strategy. Unfortunately, the current research only focused on the analysis of flight delay propagation and accumulation, and how to mitigate such delay propagation and accumulation during the ground or cruise phase. For example: Hsu [11] studied the flight delay propagation and accumulation methods through managing the turnaround time of sequential flights; Takeichi [12] tried to reduce the flight delay propagation and accumulation by optimizing the fly time; and Ivanov [13] minimized the propagated delay and improved airport slot adherence based on the air traffic flow management slot allocation. Therefore, there is little research about mitigating or preventing the flight delays from the perspective of integrated arrival and departure aircraft sequencing.

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

The remainder of this paper is organized as follows. The integrated arrival and departure aircraft sequencing problem is defined and the integrated sequencing model is presented. Next, the multi-objective simulated annealing algorithm is proposed and the validation results are reported. Finally, some concluding remarks are provided.

Problem Formulation

The airlines always schedule one particular aircraft to fulfill several tasks every day. The pre-order 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 f_1 is the arrival flight without subsequent task, f_3 is the departure flight without pre-order task, and f_2 is the sequential flight.

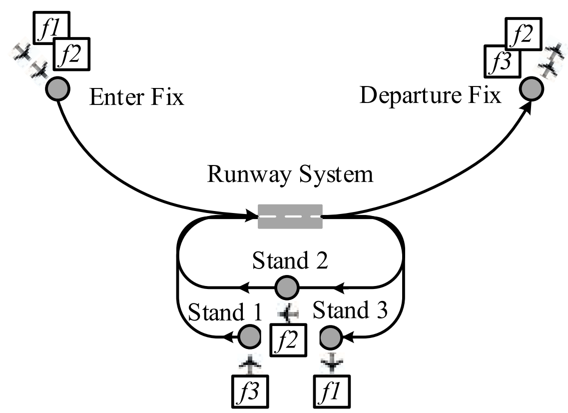


Figure 1. Process of Arrival & Departure

According to the real operations in Shanghai Pudong International Airport (ZSPD) on a particular day, the sequential flights account for 53%, the departure flights without pre-order tasks are 23%, while the arrival flights without subsequent tasks are 24%. Furthermore, an example is taken into account. An Airbus 320 aircraft with tail number B2213 executed total six tasks one day, as shown in Figure 2. Due to the delay occurred from ZLLL to ZLXY, the flight delay of subsequent tasks is propagated and accumulated. Therefore, it's necessary to take the influence of sequential flights into consideration when solving the integrated arrival and departure aircraft sequencing problem.

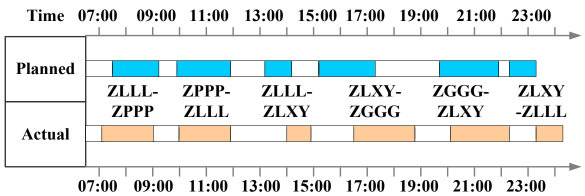


Figure 2. Sequence Diagram of Aircraft B2213

Figure 3 presents the micro process of arrival and departure operation in the TMA and on the apron under the influence of sequential flights based on the operational characteristics of arrival and departure flights. 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 pre-order flights exerting on the pre-order 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 pre-order 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 pre-order flights exerting on the pre-order 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 should be fulfilled in near future.

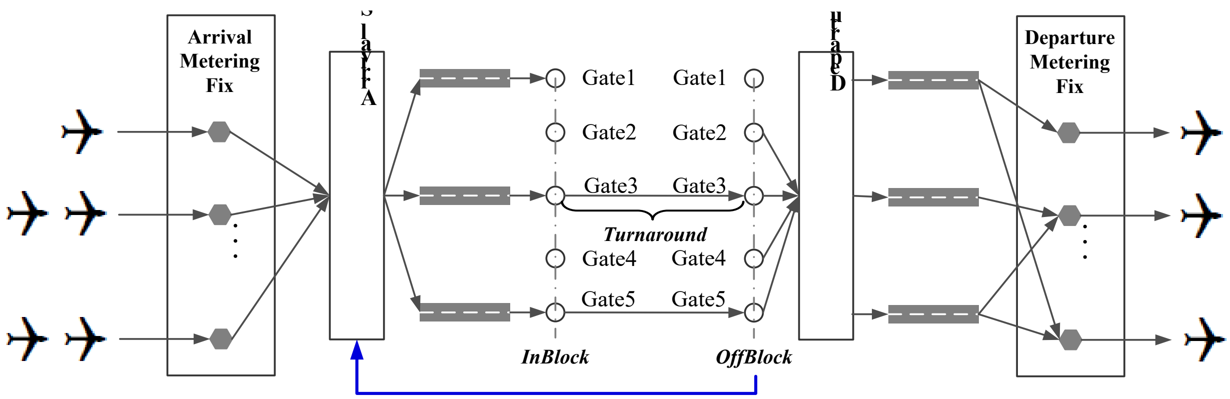


Figure 3. Detailed Process of Arrival and Departure Operation

Sequencing Model

Variables Definition

The following symbols and parameters are used to construct the integrated arrival and departure aircraft sequencing model.

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

J : arrival/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 between flight i and j that operate in the same runway, $\forall i, j \in J$, $i \neq j$;

q_{ij} : minimum separation 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, $s_{ij}=1$ 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 j, $\forall j \in J^D$;

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/departure time of 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 of the pre-order and subsequent flight.

For the multiple runways operation, $p_{\mathrm{A}\to\mathrm{D}}$ and $p_{\mathrm{D}\to\mathrm{A}}$ 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.

Objectives and Constraints

In this paper, maximizing the runway operational capability (Equation (1)) and the delay of sequential flights minimization (Equation (2)) are chosen as the objectives. The first objective takes all the sequential flights and only departure or arrival flights into consideration, while the second objective focuses on the sequential flights.

The integrated arrival and departure sequencing model is constructed as above when considering the following constraints. Equation (3) and Equation (4) define the time window constraints of take-off or landing. For the arrival aircraft, the earliest and latest time of landing could be obtained through trajectory prediction [14, 15]. Equation (5) provides the wake separation between the preceding and following aircrafts in the same runway. Equation (6) provides the separation between the preceding and following aircraft in the different runway. Equation (7), (8) and (9) determine that every flight occupies only one place in the established sequence. Equation (10) and (11) give the time restrictions for the updated Estimated Off-Block Time (EOBT). Equation (12), (13) and (14) give the time restrictions for the taking-off times for the subsequent flights.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Sequencing Algorithm

Priority Strategy for Sequential Flights

For the sequential flights, the pre-order landing flight will exert great influence on the subsequent taking-off flight. Therefore, in this paper, in order to mitigate the influence of the pre-order landing flight, the priority strategy for sequential flights is adopted.

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 pre-order 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 will be propagating and accumulating. Therefore, the priority for the sequential flights is determined by the value of b_i.

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

Multi-Objective SA Algorithm

A Pareto-domination based multi-objective simulated annealing (PDMOSA) algorithm proposed by Suman [16] is adopted in this paper for solving the model of multi-objective integrated arrival and departure aircraft sequencing problem under the influence of sequential flights (Equation (1) to (14)).

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 pre-order delayed landing flight is adopted to mitigate the delay propagation and accumulation. The flowchart of PDMOSA algorithm is presented in Figure 4.

Simulation and Discussion

The arrival and departure flights from Shanghai Pudong International Airport (ZSPD) during the rush hour from 9:00am to 11:30am are chosen to verify the feasibility of model and the efficiency of the algorithm. There are 28 sequential flights, accounting for 25%, in which there are 14 pre-order arrival flights and 14 subsequent departure flights.

According to the operation standard of Civil Aviation Administration of China (CAAC), the following parameters are pre-defined. The wake turbulence separations for arrivals, as shown in Table 1, are adopted in this simulation. For departures, we adopt 180 seconds as required separation for the same direction and 120 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.

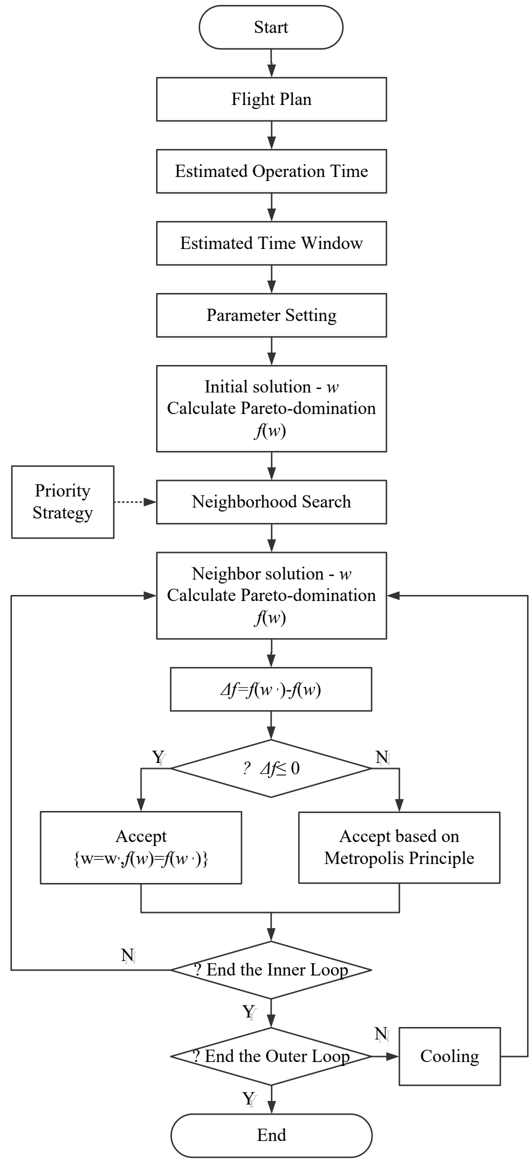


Figure 4. Flowchart of PDMOSA Algorithm

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).

Firstly, we obtain the distribution of Pareto optimized sets by PDMOSA algorithm from the multiple objectives of the runway capability and the delay of sequential flights. Due to the large difference between the two kinds of values, the ratio of the target value with FCFS strategy is adopted, as shown in Figure 5.

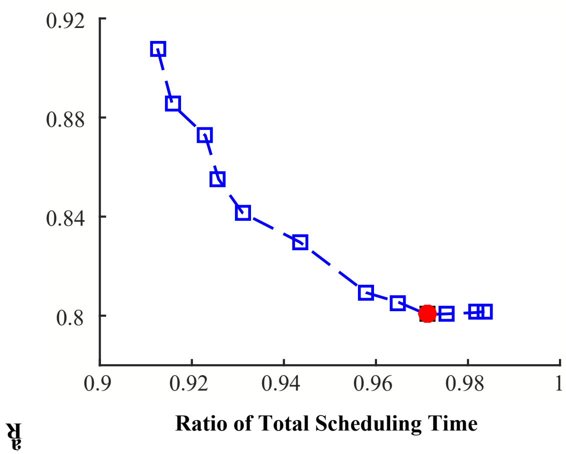


Figure 5. Pareto Front for Multi-Objective Optimization

In the Figure 5, 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 multi-objective function. Obviously the total runway scheduling time and total delay of sequential affect each other. Consolidate the above two objectives, 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).

Secondly, the sequencing result of arrival and departure flights under the influence of the sequential flights are compared with the sequencing results in FCFS strategy, as shown in Table 2.

Table 2. Objectives of Integrated Arr. & Dep. Scheduling (s)

Strategy	Total delays	Total scheduling time	Total delays of seq.
FCFS	54 312	8 653	20 125
PDMOSA	38 177	8 403	16 096

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 6 presents the delay of pre-order flights and the subsequent flights based on PDMOSA algorithm. The total delay of the pre-order flights is reduced by 62.62% due to the priority is given to the aircraft in the air. The total delay of the subsequent flights is reduced by 14.28% due to the releasing limit to subsequent departure flights.

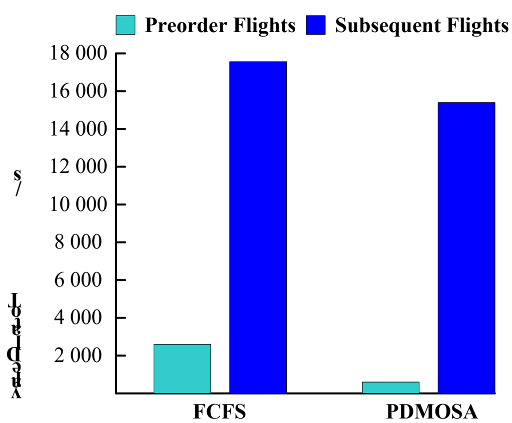


Figure 6. Total Delays of Pre-Order and Subsequent Flights

Finally, we compare the total delay results of arrival and departure aircraft sequencing whether we consider the influence of sequential flights or not, as shown in Table 3 (ETA and ETD denote the Estimated Time of Arrival and Departure, while STA and STD denote the Scheduled Time of Arrival and Departure). In Table 3, the situation of the STAs or STDs of different flights being close means those flights use the different runways.

Without considering the influence of sequential flights, the total delay of sequential flights is 18 311 s. With considering the influence of sequential flights, the total delay of sequential flights is 16 096 s, which is reduced by 12.09%. Meanwhile, when taking the influence of sequential flights into consideration, there are 24 arrival or departure flights (total number of sequential flights) operating in advance than the real operation, it accounts for 85.71% of the total number of sequential flights.

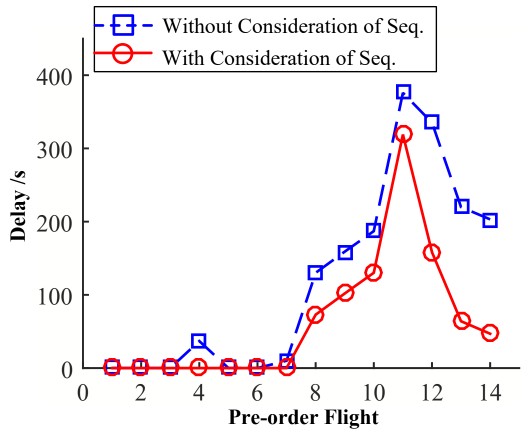
Table 3. Results of Integrated Arrival and Departure Scheduling

Tail Number	Pre-order Flight			Subsequent Flight		
	ETA	NOT Considering Seq.	Considering Seq.	ETD	NOT Considering Seq.	Considering Seq.
		STA	STA		STD	STD
B1858	09:00:00	08:58:40	08:58:40	10:35:00	10:55:27	10:53:14
B1865	09:04:00	09:03:40	09:01:30	10:29:00	10:50:10	10:47:57
B1871	09:04:47	09:04:40	09:03:27	10:41:00	11:05:03	10:59:50
B1893	09:06:03	09:06:40	09:04:43	10:45:00	11:08:03	11:05:50
B1927	09:13:15	09:10:45	09:12:40	10:50:00	11:02:10	11:03:40
B1987	09:15:03	09:14:40	09:13:43	10:45:00	11:02:03	11:02:50
B2005	09:15:44	09:15:54	09:14:57	10:51:00	11:06:54	11:05:57
B2060	09:17:00	09:19:10	09:18:13	10:42:00	11:00:10	10:59:13
B2207	09:17:45	09:20:24	09:19:27	10:55:00	11:13:03	11:11:47
B2281	09:18:56	09:22:03	09:21:06	10:54:00	11:13:03	11:12:06
B2346	09:19:03	09:25:19	09:24:22	10:44:00	11:10:03	11:08:47
B2420	09:23:25	09:29:00	09:26:03	10:59:00	11:20:00	11:17:03
B2577	09:26:59	09:30:39	09:28:03	11:02:00	11:23:00	11:20:03
B3205	09:32:32	09:35:55	09:33:19	10:58:00	11:16:55	11:15:06

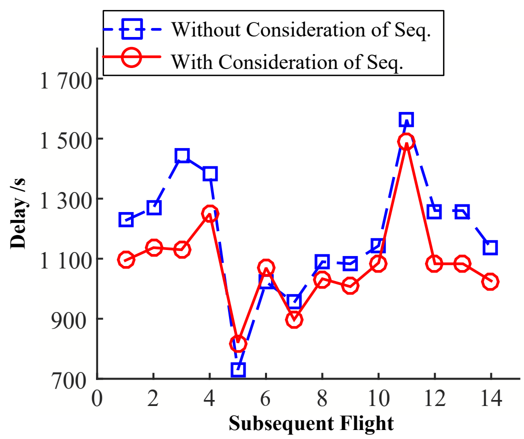
Figure 7 provides the contrast about the flight delays of the pre-order flights and subsequent flights in the condition of with or without considering the influence of sequential flights.

It should be noted that the delays of the pre-order arrivals are deviations between STAs and ETAs, obtained from trajectory prediction, not planned times of arrivals from flight schedule, while the flights delays of the subsequent departures are the deviations between STDs and ETDs, obtained from the flight scheduling.

From Figure 7(a), we could find that, 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 7(b), we could find that, 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 pre-order and subsequent flights.



(a) Pre-Order Flights Chart



(B) Subsequent Flights Chart

Figure 7. Comparison of Results with Sequential Flights

Conclusions

An integrated arrival and departure sequencing model and a multi-objective simulated annealing algorithm were proposed in this paper. As the uncertainty of taxiing time and turnaround time will impose great effects on the integrated sequencing solution, which provides a main direction for the future research.

References

[1] Zografos K G, Madas M A, Androutsopoulos K N. Increasing Airport Capacity Utilization Through Optimum Slot Scheduling: Review of Current Developments and Identification of Future Needs [J]. Journal of Scheduling, 2017, 20(1): pp.3-24.

[2] Bennell J A, Mesgarpour M, Potts C N. Airport Runway Scheduling [J]. Annals of Operations Research, 2013, 204(1): pp.204-249.

[3] Balakrishnan H, Chandran B G. Algorithms for Scheduling Runway Operations Under Constrained Position Shifting [J]. Operations Research, 2010, 58(6): pp.1650-1665.

[4] Ghoniem A, Sherali H D, Baik H. Enhanced Models for a Mixed Arrival-Departure Aircraft Sequencing Problem [J]. INFORMS Journal on Computing, 2014, 26(3): pp.514-530.

[5] Rodríguez-Díaz A, Adenso-Díaz B, González-Torre P L. Minimizing Deviation from Scheduled Times in a Single Mixed-Operation Runway [J]. Computers and Operations Research, 2017, 78: pp. 193-202.

[6] Hancerliogullari G, Rabadi G, Al-Salem A, et al. Greedy Algorithms and Metaheuristic for a Multiple Runway Combined Arrival-Departure Aircraft Sequencing Problem [J]. Journal of Air Transport Management, 2013, 32(1): pp. 39-48.

[7] Xue M, Zelinski S. Optimal Integration of Departures and Arrivals in Terminal Airspace [J]. Journal of Guidance, Control and Dynamics. 2014, 37 (1): pp. 207-213.

[8] Chandrasekar S, Hwang I. Algorithm for Optimal Arrival and Departure Sequencing and Runway Assignment [J]. Journal of Guidance, Control and Dynamics, 2015, 38 (4): pp.601-613.

[9] Taylor C, Masek T, Bateman H. Framework for High-Density-Area Departure and Arrival Traffic Management [J]. Journal of Guidance, Control and Dynamics, 2013, 36(4): pp.1134-1149.

[10] Shi M T, Zhang J F, Ge T T, et al. A Combined Arrival and Departure Scheduling for Multi-Airport System [J]. Transaction of Nanjing University of Aeronautics and Astronautics, 2017, 34(5): pp. 578-585.

[11] Hsu C I, Hsu C C, Li H C. Flight Delay Propagation, Allowing for Behavioral Response [J]. International Journal of Critical Infrastructures, 2007, 3(3): pp.301 -326.

[12] Takeichi N. Nominal Flight Time Optimization for Arrival Time Scheduling Through Estimation/ Resolution of Delay Accumulation [J]. Transportation Research Part C, 2017, 77(1): pp. 433-443.

[13] Ivanov N, Netjasov F, Jovanovic R, et. al. Air Traffic Flow Management Slot Allocation to Minimize Propagated Delay and Improve Airport Slot Adherence [J]. Transportation Research Part A, 2017, 95(1): pp. 183-197.

[14] Zhang J F, Jiang H H, Wu X G. 4D Trajectory Prediction Based on BADA and Aircraft Intent [J]. Journal of Southwest of Jiaotong University, 2014, 49(3): pp. 553-558.

[15] Zhang J F, Ge T T, Chen Q, et al. 4D trajectory prediction and uncertainty analysis for departure aircraft [J]. Journal of Southwest of Jiaotong University, 2016, 51(4): pp. 800-806.

[16] Suman B. Simulated Annealing Based Multi-Objective Algorithms and Their Application for System Reliability [J]. Engineering Optimization, 2003, 35(4): pp.391-416.

Acknowledgements

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