A Combined Arrival and Departure Scheduling for Multi-airport System

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Abstract: A combined arrival and departure scheduling problem is investigated for multi-airport system to alleviate the problem of airspace congestion and flight delay. Firstly, the combined scheduling problem for multi-airport system is defined through in-depth analysis of the characteristics of arrival and departure operations. Then, several constraints are taken into account, such as wake vortex separation, transfer separation, release separation, and separation in different runway operational modes. Furthermore, the scheduling model is constructed and simulated annealing algorithm is proposed by minimizing the total delay. Finally, Shanghai multi-airport system is chosen to conduct the simulation and validation. And the simulation results indicate that the proposed method is able to effectively improve the efficiency of arrival and departure operations for multi-airport system.

Key words: air traffic management; scheduling; multi-airport system; simulated annealing; arrival and departure

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0 Introduction

With the sustained growth of air traffic and the tremendous development of national economy, multi-airport terminal phenomenon emerges and becomes a new trend. Flight operations for multi-airport system share the same air routes and arrival/departure metering fixes(MFs), leading to spatio-temporal resource competition. An inevitable consequence is flight delays and economic losses. Given that, ICAO, FAA and EUROCONTROL have advocated that the combined arrival and departure scheduling[1-3] is the most effective way to tackle the problem of airspace congestion and flight delays.

On the subject of scheduling problem, lots of researchers have achieved progress. Ochieng et al.[4] proposed a temporally invariant ATM(Air traffic management) functional model based on the changes in the concept of operations over the years. Clarke et al.[5] put forward the multi-airport operational assessment framework through analyzing different operation modes. McClain et al.[6] presented an algorithm for determining the arrival time at MF for multi-airport system which minimized the vectoring within the terminal area. Saraf et al.[7] proposed an optimal scheduling algorithm through a hierarchical scheduling structure by means of an Eulerian model-based optimization scheme. On the basis of the above researches, Saraf et al.[8] discussed three candidate arrival scheduling algorithms that aiming at improving the efficiency and the coordination between arrival operations in a multi-airport environment. Hu et al.[9] studied the scheduling problem of arrival traffic flow at complex terminal area to improve the spatio-temporal resource availability and operational efficiency. Capps et al.[10] designed departure scheduling algorithm under the impact of multi-airport based on the constrained resource at runway and departure MFs. Wieland et al.[11] transformed multi-airport problem to single airport problem from actual operational perspective. On one hand, the scheduling prob-

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lem was divided into combined arrival departure scheduler (CADS) and airport surface manager (ASM). On the other hand, every airport coordinated with each other to compose the multi-airport scheduler model. Wang et al.[12] established combined arrival and departure scheduling model for multi-airport terminal area and designed a heuristic genetic algorithm based on multivariate restrictions.

The above-mentioned researches have indeed achieved some fruitful results, but there still exist some shortcomings: (1) Previous researches have focused on arrival scheduling or departure scheduling[10] separately. Thus, arrival and departure collaborative optimization is not realized. (2) Most of researches have not taken runway operational modes into consideration[11-12]. Thereupon, such methods cannot meet the demand of actual operation. (3)Few researches treat the problem from the macroscopic view, which should focus on both MFs scheduling and runway scheduling. Therefore, we pay close attention to the demand of collaborative terminal area management, and take the whole multi-airport system as the research object. Furthermore, the combined scheduling strategy is adopted and an simulated annealing algorithm is designed in this paper.

1 Problem Description

Flight operations in multi-airport system share the same resources, such as arrival metering fixes (AMFs), departure metering fixes (DMFs), routes, and runway etc. The combined arrival and departure scheduling for multi-airport system can be modeled as the problem of how to reasonably allocate shared resources for those inbound or outbound flights. From macro perspective, the multi-airport system can be treated as a service system, and the air traffic flow entering into the terminal area is viewed as an input.

In this paper, the concept of "outside air traffic flow" is introduced. The arrival flights from AMFs, and departure flights off block from gates, are those "outside air traffic flow", which are all going to enter into multi-airport system. They are shown as the periphery of big circle in Fig. 1. There are three main advantages through the above definition: To enhance combined management of arrival and departure flights, help the definition of constraints and objectives for combined arrival and departure scheduling, and link scheduling problem with future air traffic flow management (ATFM) seamlessly.

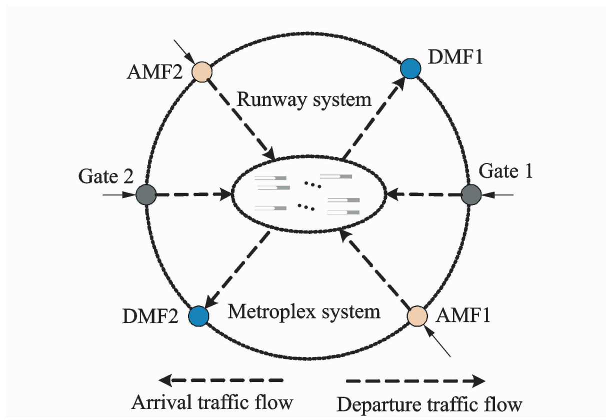

Fig. 1 Macro process of arrival and departure operation in multi-airport system

According to the airspace structure and operational characteristics, micro process of arrival and departure operation is given in Fig. 2 for multi-airport system. Compared with single airport operation, shared resources (arrival and departure MFs) are the key factors of multi-airport operation. Therefore, combined scheduling problem for multi-airport contains two parts: MFs scheduling and runway scheduling. The former is scheduled from MF to runway while the later is from runway to MF. Departure delays are transferred from air vectoring to ground holding. Arrival and departure MFs scheduling mainly consid-

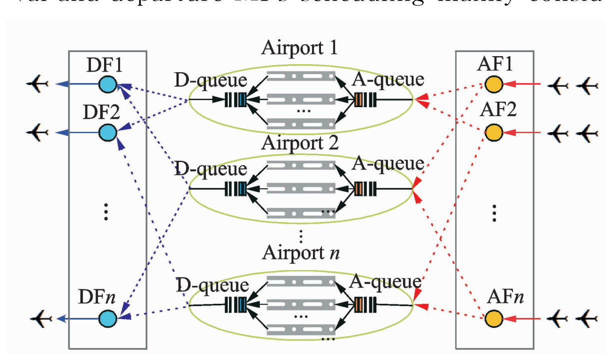

Fig. 2 Micro process of arrival and departure operation in multi-airport system

ers the constraints of wake turbulence and transfer separation, while runway scheduling mainly considers consecutive departures (D) and arrivals (A) safety separation (including AA, AD, DD and DA) in different runway operational modes.

2 Model

2.1 Symbols and parameters

There are some symbols and parameters in this paper.

M: Set of airports;

R_i: Set of runways in airport i;

P: Set of MFs (arrival and departure);

$F_{i,j}$: Set of flights that using the jth runway in the ith airport;

$F^{a}_{i,j}$ / $F^{d}_{i,j}$:Set of arrivals/departures that using the jth runway in the ith airport;

$et_{i,j,f}$/ $st_{i,j,f}$: Estimated/scheduled time of arrival flight f at runway using the jth runway in the ith airport;

$met_{i,j,f}$: Estimated time of flight f entering into terminal area using the jth runway in the ith airport (namely, estimated time of arrival at MF of arrival and estimated off-block time of departure);

$mst_{i,j,f}$: Estimated time of flight f entering into terminal area system using the jth runway in the ith airport;

$mstd_{i,j,f}$: Estimated time of flight f arrival at DMF using the jth runway in the ith airport;

$rot_{i,j,f}$: Runway occupancy time of arrival flight f using the jth runway in the ith airport;

ω_{i,j,f_1,f_2}: Required wake vortex separation between arrival flights f_1 and f_2 that using the jth runway in the ith airport;

$\alpha_{i,j_1,f_1,j_2,f_2}$: Required relative approach slant distance between arrival flight f_1 that using the j_1th runway and arrival flight f_2 that using the j_2th runway in the ith airport;

$\beta_{i,j_1,f_1,j_2,f_2}$: Required tower control separation between departure flight f_1 that using the j_1th runway and arrival flight f_2 that using the j_2th runway in the ith airport;

τ_p: Required transfer separation at MF p;

γ_{i,j,f_1,f_2}: Required release separation between departure flights f_1 and f_2 that using the jth runway in the ith airport;

$\xi_{i,j,f}$: Lower limit of feasible time window of flight f that using the jth runway in the ith airport. Namely, for arrivals, it is the earliest arrival time, and for departures, $\xi_{i,j,f}=met_{i,j,f}$.

$\eta_{i,j,f}$: Upper limit of feasible time window of flight f that using the jth runway in the ith airport. Namely, for arrivals, it is the latest arrival time, and for departures, the latest off-block time.

ε_{i,j_1,j_2}: If the operation mode between the j_1th runway and the j_2th runway is dependent parallel approach, set ε_{i,j_1,j_2} to 1. Otherwise, set it to 0 (such as independent parallel approach).

υ_{i,j_1,j_2}: If the j_1th runway and the j_2th runway in the ith airport form the close-spaced parallel runways (including the case of the j_1th $=$ j_2th which can be used not only for arrivals but also departures), set υ_{i,j_1,j_2} to 1. Otherwise, set it to 0 (such as independent parallel approach).

x_{i,j_1,f_1,j_2,f_2}: If flight f_1 that using the j_1th runway in the ith airport is prior to flight f_2 that using the j_2th runway, set $x_{i,j_1,f1,j_2,f2}$ to 1. Otherwise, set it to 0.

Ψ_{i,j,f_1,f_2}: If arrival flight f_1 that using the jth runway in the ith airport is prior to departure flight f_2 that using the same runway, set Ψ_{i,j,f_1,f_2} to 1. Otherwise, set it to 0.

y_{p,f_1,f_2}: If flight f_1 and f_2 through pass MF p, and flight f_1 is prior to flight f_2, set $y_{p,f1,f2}$ to 1. Otherwise, set it to 0.

$n_{f,j}$: If flight uses the jth runway to arrival and departure, set $n_{f,j}$ to 1. Otherwise, set it to 0.

$m_{f,p}$: If f passes MF p, set it to 1. Otherwise, set it to 0.

$d_{i,j,f}$: Delay time of flight f that using the jth runway in the ith airport is $|st_{i,j,f}-et_{i,j,f}|$, and flights advance and late are regarded as general delay.

2.2 Collaborative scheduling model

For combined scheduling for multi-airport system, the scheduling model is established based on the above symbols and parameters. i represents airport, j represents runways, and $\forall i \in M$, $\forall j \in R_i$. The decision variable are $\alpha_{i,j_1,f_1,j_2,f_2}$, $\beta_{i,j_1,f_1,j_2,f_2}$, γ_{i,j,f_1,f_2}, ε_{i,j_1,j_2}, υ_{i,j_1,j_2}, x_{i,j_1,f_1,j_2,f_2}, Ψ_{i,j,f_1,f_2}, y_{p,f_1,f_2}, $n_{f,j}$ and $m_{f,p}$.

$$\min \sum_{i \in M} \sum_{j \in R_i} \sum_{f \in F_{i,j}} d_{i,j,f} \quad (1)$$

$$st_{i,j,f_2} \geqslant x_{i,j,f_1,j,f_2}(\omega_{i,j,f_1,f_2} + st_{i,j,f_1}) \quad \forall f_1, f_2 \in F^{a}_{i,j} \quad (2)$$

$$st_{i,j_2,f_2} \geqslant x_{i,j_1,f_1,j_2,f_2} \varepsilon_{i,j_1,j_2}(\alpha_{i,j_1,f_1,j_2,f_2} + st_{i,j_1,f_1}) \quad \forall j_1 \neq j_2, \forall f_1 \in F^{a}_{i,j_1}, f_2 \in F^{a}_{i,j_2} \quad (3)$$

$$mst_{i,j_2,f_2} \geqslant y_{p,f_1,f_2}(\tau_p + mst_{i,j_1,f_1}) \quad \forall f_1 \in F^{a}_{i,j_1}, f_2 \in F^{a}_{i,j_2}, \forall p \in P \quad (4)$$

$$mstd_{i,j_2,f_2} \geqslant y_{p,f_1,f_2}(\tau_p + mstd_{i,j_1,f_1}) \quad \forall f_1 \in F^{d}_{i,j_1}, f_2 \in F^{d}_{i,j_2}, \forall p \in P \quad (5)$$

$$st_{i,j,f_2} \geqslant x_{i,j,f_1,j,f_2}(\gamma_{i,j,f_1,f_2} + st_{i,j,f_1}) \quad \forall f_1, f_2 \in F^{d}_{i,j} \quad (6)$$

$$st_{i,j_2,f_2} \geqslant x_{i,j_1,f_1,j_2 f_2} \upsilon_{i,j_1,j_2}(\beta_{i,j_1,f_1,j_2 f_2} + st_{i,j_1,f_1}) \quad \forall f_1 \in F^{d}_{i,j_1}, \forall f_2 \in F^{a}_{i,j_2} \quad (7)$$

$$st_{i,j,f_2} \geqslant \psi_{i,j,f_1,f_2}(rot_{i,j,f_1} + st_{i,j,f_1}) \quad \forall f_1 \in F^{a}_{i,j}, \forall f_2 \in F^{d}_{i,j} \quad (8)$$

$$\xi_{i,j,f} \leqslant st_{i,j,f} \leqslant \eta_{i,j,f} \quad \forall f \in F_{i,j} \quad (9)$$

$$\sum\nolimits_{j \in R} n_{f,j} = 1 \quad \forall f \in F \quad (10)$$

$$\sum\nolimits_{p \in P} m_{f,p} = 1 \quad \forall f \in F \quad (11)$$

where Eq. (1) represents the optimization objective, which minimizes the general overall delay; constraint (2) the required wake vortex separation between any two arrivals; constraint(3) the required relative slant distance between two successive arrival aircraft under dependent parallel approach mode; constraint(4) the required safety separation among aircraft that appeared at AMF; constraint(5) the required safety separation among aircrafts that appeared at DMF; constraint (6) the required releasing separation between any two departure aircraft; constraint(7) the required safety separation between arrivals and departures; constraint(8) the runway occupying time; constraint(9) the time window restriction of every flight entering into terminal area. Constraints (10) and (11) represent the constraints that every flight can use only one runway and only one AMF or DMF.

3 Algorithm Design

The combined scheduling model is constructed by Eqs. (1)—(11), and this is an NP hard problem[13]. Therefore, the simulated annealing (SA) algorithm is proposed to meet the real-time demand of combined arrival and departure scheduling for multi-airport system.

3.1 Searching space

For SA algorithm or other meta-heuristic algorithms, searching space (state space) plays a great role of finding a optimal solution. In this paper, any landing and take-off sequence represent a feasible solution, and the set of sequences form the searching space of the problem.

For every flight, its position is determined by the time of entering into terminal area ($mst_{i,j,f}$), and $mst_{i,j,f}$ is determined by time window $[\xi_{i,j,f}, \eta_{i,j,f}]$. In this paper, $mst_{i,j,f}$ is given by

$$mst_{i,j,f} = c_{i,j,f}\xi_{i,j,f} + (1 - c_{i,j,f})\eta_{i,j,f} \quad (12)$$

where $0 \leqslant c_{i,j,f} \leqslant 1$ represents the linear interpolation coefficient for every flight f that using the jth runway in the ith airport. In previous practice, the scheduled times are determined according to the sequence and separations. But in current practice, the advantage of neighborhood solution generation mechanism (Eq. (12)) is two aspects:

(1) The scheduled time of flights can be obtained within feasible time window;

(2) All kinds of the arrival and departure sequences can be successfully traversed.

3.2 Parameter setting

Parameter setting is very important to the SA algorithm. The parameters need to be set include: Acceptance criteria, annealing mode and initial temperature.

(1) Acceptance criteria: Receiving the current solution or not is based on Metropolis rule

$$P\{\text{Receive } s'\} = \begin{cases} \exp^{-\frac{(f(s') - f(s))}{t_k}} & f(s') - f(s) > 0 \\ 1 & f(s') - f(s) \leqslant 0 \end{cases} \quad (13)$$

where $f(\cdot)$ represents the objective function; t_k

the temperature of the kth iteration and $t_k > 0$, $\forall k$.

(2) Annealing mode: Rapid SA cooling mode is chosen in this paper $T(t) = T_0/(1+t)$.

(3) Initial temperature: A group of states are generated randomly, and the maximum errors of the objective value between any two states are acquired. Then, initial temperature T_0 is calculated by $T_0 = |\Delta \max| / p_0$, where p_0 represents initial acceptance probability.

3.3 Algorithm

When implementing the proposed algorithm, there are several steps should be followed:

Step 1 Calculate the estimated time of "outside air traffic flow" entering into multi-airport system, while taking the flight plans, airspace structure and runway operational modes into consideration.

Step 2 Determine the feasible time window according to the entering time from Step 1.

Step 3 Estimate the transit time of arrival and departure based on trajectory prediction[14], and estimate the arrival time at runway.

Step 4 Create the searching space, and determine the initial temperature of SA and generate the initial solution.

Step 5 Produce the neighborhood solution based on Eq. (12) under current temperature. Then, calculate the objective function.

Step 6 Determine whether the neighborhood solution is accepted or not. If the objective value is better, the neighborhood solution is accepted. If not, accepting the neighborhood solution according to Metropolis rule (Eq. (13)). If the neighborhood solution is accepted, current solution is updated.

Step 7 Determine whether the inner loop terminating condition is reached. If not, turn to Step 5.

Step 8 Determine whether the outer loop terminating condition is reached. If true, terminate the algorithm; If not, decrease temperature and turn to Step 5.

4 Simulation and Analysis

4.1 Simulation scenario

Shanghai terminal is selected to construct simulation scenarios which is a case in point of multi-airport system (Pudong and Hongqiao airport), and includes AMFs of VMB, BK, MATNU, DUMET, DMFs of LAMEN, PIKAS, HSN, ODULO, NXD.

In north-bound operation, major landing runways are: RWY34/35L (ZSPD), RWY36R (ZSSS); takeoff runways are: RWY34/35R (ZSPD), RWY36L(ZSSS). Among them, RWY 34/35L are employed in dependent parallel approach mode, while RWY34/35R are independent parallel departure mode.

In Shanghai terminal, the transfer separation of arrival and departure MFs is 20 km; slant distance of dependent parallel approach is 4 km; *rot* is 60 s; wake turbulence of flights are given by Table 1. In Table 1, H, M and L denote the heavy, medium and light aircraft. For departures, releasing separation is 180 s of the same direction (like the former is taking-off to NXD, the later is NXD, too), and 120 s of the different direction. Airbus A380 has its own regulation. Variable taxiing time(VTT), which means the time of departure flight driving from apron to runway is set to 20 min. And all the distance based separations are conversed into time separations according to the flight speed.

Table 1 Separation standard for wake turbulence

s

Former	Later		
	H	M	L
H	99	133	196
M	74	107	131
L	74	80	98

4.2 Result analysis

In Fig. 3, the objective value decreases gradually until near the optimal solution during a predetermined period. The waveform of Fig. 3 represents the current (local) optimal solution. Then, the current (local) optimal solution is given up to

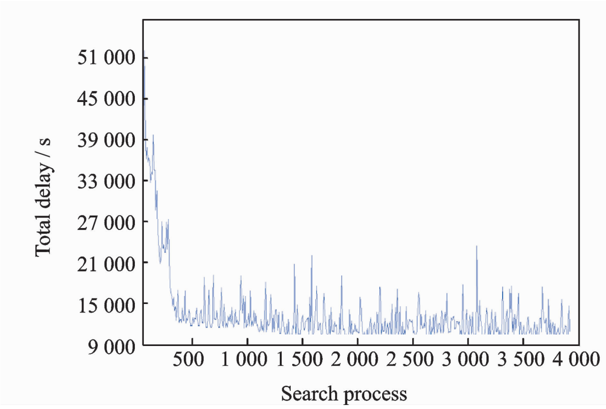

Fig. 3 Searching process of simulated annealing algorithm

better solution until the searching process ends.

To evaluate the optimization effect of the SA algorithm, the traditional FCFS(First come first service) strategy is chosen as a candidate opponent in 40 min time period. The total delay by FCFS strategy is 33 934 s, while 9 209 s through the proposed algorithm. The total delay is reduced by 72.86%, which indicates that the proposed algorithm can reduce flight delays significantly.

Fig. 4 shows the scheduling results based on different strategies for multi-airport system: (1) The proposed method speeds up the air traffic flow entering into terminal area and produces a significant improvement on airport throughput; (2) small perturbations of outside air traffic flow will cause great impact on inner operation of terminal area.

Fig. 5 shows the relationship between acceptable delay level based on the different strategies. The "normal flight (NF)" (y-axis) represents the flights that delay time is shorter than or equal to

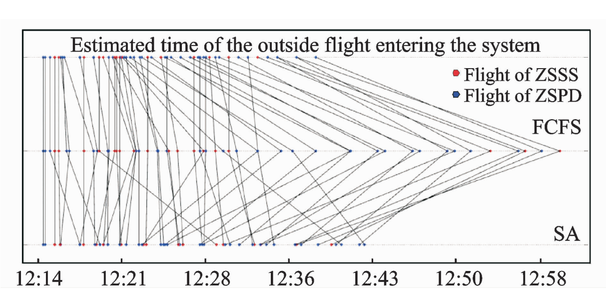

Fig. 4 Scheduling result of air traffic flow with different strategies

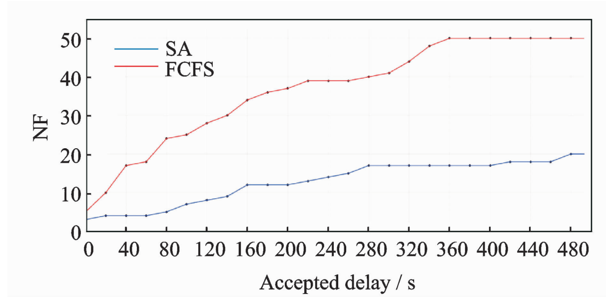

Fig. 5 Relationship between total delay and normal flight quantity

acceptable delay level (x-axis). The results indicate that the number of punctual flight of optimized strategy is larger than that of FCFS strategy under different acceptable delay level. If acceptable delay level is 360 s, the number of punctual flight of FCFS strategy and optimized strategy is 36 and 3, respectively.

Figs. 6, 7 show the comparison of MFs and runway scheduling results by different strategies. From Figs. 6, 7, it can be found that: (1) Compared with FCFS, the proposed strategy not only satisfies safety separation, but also allocates the space resources reasonable; (2) compared with arrival flights, sequence of departure flights changes greatly, which illustrates that the proposed strategy decreases total delays by sacrificing the target off-block time of departure as the arrivals' priority principle is adopted; (3) compared with FCFS strategy, the MFs and runway time resource distribution under the proposed strategy is more even, which illustrates that can reasonable assign terminal area resources.

However, the above researches have been conducted based on the fixed VTT and *rot*, which is not the case in real operation. Thus, disturbances are added to VTT and *rot* and the corresponding fluctuations are shown in Figs. 8, 9.

In Fig. 8, it can be learned that changes of *rot* are less sensitive, because: (1) *rot* is small. (2) RWY35L and 35R are close-spaced parallel runways, which means that aircraft can take off from RWY35R once aircraft lands in RWY35L. (3) Wake vortex separation and release separation are much longer than *rot*, so the impact of *rot* can

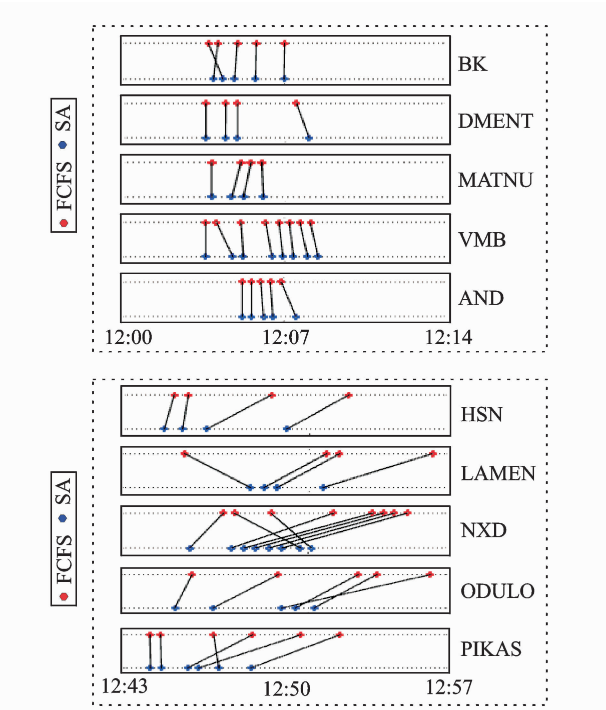

Fig. 6 Comparison of arrival and departure fix sequencing

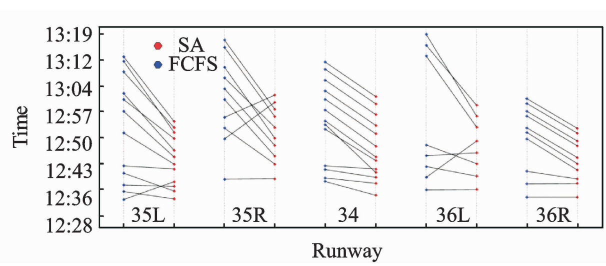

Fig. 7 Comparison of runway sequencing

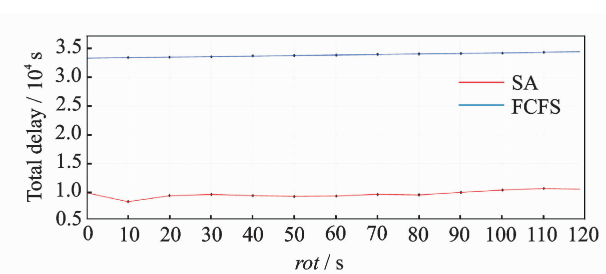

Fig. 8 Distribution of rot impact on total delay time

be absorbed partly. Meanwhile, Fig. 9 shows that VTT has a significant impact, so overall delay time can be reduced if controller can reasonably arrange VTT.

Finally, in order to test the feasibility of the proposed strategy, another simulation is carried out with various number of aircraft within 40 min. Just as Fig. 10 shows, x-axis(n) represents the number of flights and y-axis represents

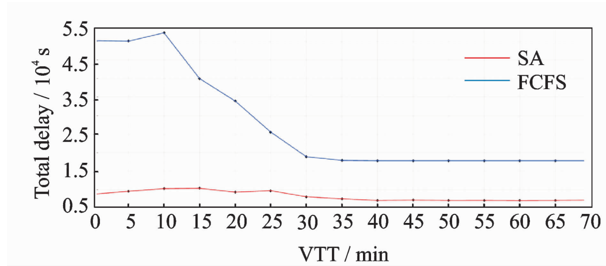

Fig. 9 Distribution of VTT impact on total delay time

the according differences of total delay between FCFS and the proposed strategies. The curve tendency shows that: (1) When the number of aircraft is smaller than 30, the optimization result is similar. (2) As the number of aircraft increases, the proposed strategy has great advantage.

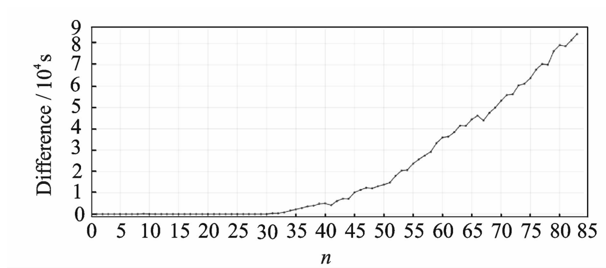

Fig. 10 Relationship between total delay and the number of flights

5 Conclusions

The concept of "outside air traffic flow" is introduced to establish the model of combined arrival and departure scheduling for multi-airport system. This model takes both the AMF and DMF constraints and the runway operation modes into consideration simultaneously.

Then, a simulated annealing algorithm based on new neighborhood solution generation mechanism is proposed to solve the combined arrival and departure scheduling problem. The simulation results indicate that the proposed algorithm represents great optimization effect in rush hour.

Finally, some disturbances are added to VTT and *rot* to study the model fluctuations under uncertainties. It can be learned that changes of *rot* are less sensitive than VTT and the total delay can be reduced if controller can reasonably arrange VTT to avoid rush hour and achieve better scheduled off-block time.

In the future, the airport surface management should be paid more attention and some more efficient algorithms should be attempted to tackle the combined scheduling problem.

Acknowledgments

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