PERGAMON

Transportation Research Part E 38 (2002) 265–277

TRANSPORTATION
RESEARCH
PART E

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Modelling of aircraft rotation in a multiple airport environment

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Abstract

The objective of this paper is to develop a simulation model to simulate aircraft rotation in a multiple airport environment. The developed aircraft rotation model (AR model) consists of two sub-models, namely the aircraft turnaround model, which describes the operation of aircraft turnaround activities at an airport and the Enroute model, which simulates the enroute flight time of an aircraft in the airspace between two airports. Delays due to operational disruptions from aircraft turnaround activities are modelled by stochastic variables in the aircraft turnaround model. Uncertainties from schedule punctuality are modelled by probability density functions in the Enroute model. The proposed aircraft rotation model is employed to carry out a case study by using real schedule and punctuality data from a European schedule airline. Simulation results when compared with observation data validate the effectiveness of the aircraft rotation model. The proposed model is also found suitable for airlines to serve as a schedule planning and analysis tool. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The issue of flight schedule punctuality is usually studied for a single airport so operational improvements by airlines are employed at individual airports to deliver punctual aircraft turnarounds and maintain the regularity of schedule implementation. However, it is found that the arrival/departure punctuality of an aircraft at an airport is significantly affected by up-stream flight operation through aircraft rotation between airports (Wu and Caves, 2001). Delays to a segment of an aircraft rotation might cause delays to following segments and probably result in

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PII: S1366-5545(02)00010-8

knock-on delays, i.e. the phenomenon of delay accumulation in aircraft rotation. The estimated delay-related monetary losses for an airline range from $45 per min to $150 per min according to some European airlines (Wu, 2001).

The issue of schedule punctuality of aircraft rotation becomes more important when the consequences of flight delays are investigated on a network scale. An analysis from Austrian Airlines revealed that only 22% of total costs of flight delays comes from direct delay consequences, i.e. additional airline operational costs. Among total delay costs, 24% comes from passengers' permanent disloyalty and the more significant portion of 54% comes from the deterioration of network quality of aircraft rotation due to the development of knock-on delays in aircraft rotation (Airline Business, 1999). In order to mitigate the consequences of knock-on delays, airlines tend to design more buffer time in flight schedules in order to absorb potential delays in aircraft rotation and to stabilise the adherence of aircraft rotation schedules (Sunday Times, 2000).

Therefore, the objective of this paper is to develop a model, namely the aircraft rotation model (AR model), to simulate the rotation of an aircraft in a multiple airport environment. The developed AR model consists of two sub-models, namely the aircraft turnaround model, which describes the operation of aircraft turnaround activities at an airport and the enroute model, which simulates the enroute flight time of an aircraft in the airspace between two airports.

The modelling of the aircraft turnaround process has been studied in the literature by using analytical methods as well as critical path methods (Braaksma and Shortreed, 1971; Hassounah and Steuart, 1993). However, these models have not been successful to capture the stochastic characteristics of aircraft turnaround operations such as the uncertainty from the ground service time of an aircraft and the influence of operational disruptions to aircraft turnaround operations. Hence, the Markov Chain concept is employed in the Aircraft Turnaround model to simulate the stochastic occurrence of operational disruptions to aircraft turnaround and to model the stochastic service time of turnaround activities. The major advantage of using Markovian concepts in the modelling of aircraft turnaround activities is that Markovian models can reflect the stochastic transition behaviour between normal turnaround activities and occasional disruptions in aircraft turnaround, which other models in the literature have failed to achieve. A case study is carried out in this paper to validate the effectiveness of the proposed AR model by using real schedule and punctuality data from a European schedule airline.

2. Methodology

The "rotation" of an aircraft is defined in this paper as the operational itinerary of an aircraft which is assigned to fly between airports as illustrated in Fig. 1. The rotation of the aircraft in Fig. 1 starts from Airport J. The aircraft is turned around at Airport K (the base airport in this case) after the scheduled turnaround time in which the required aircraft turnaround services, e.g. engineering checks, catering and aircraft fuelling services, are provided by ground handling agents at the airport. The complete rotation of the aircraft ends at Airport M, at which the aircraft is held over night. The "efficiency" of aircraft turnaround operation is defined as the capability of an airline to execute required aircraft turnaround services within available service time and to deliver a punctual departure flight. A "segment" of aircraft rotation is defined to start from the "on-

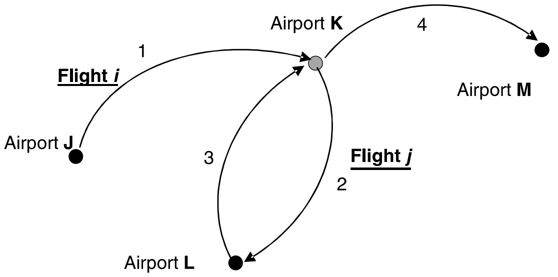

Fig. 1. Aircraft rotation in a network of airports.

chock time" of an aircraft at the gate of the origin airport to the "on-chock time" of the same aircraft at the gate of the destination airport. Hence, a segment of an aircraft rotation includes the turnaround operation of the aircraft at the origin airport and the enroute flight operation of the aircraft in the airspace between two airports. A flight is defined "punctual", if there is no schedule delay to this aircraft. Arrival/departure delays measured in this paper are based on the scheduled time of arrival/departure (denoted by STA/STD). The accumulation of delays from a segment to another is called the "knock-on delay" of aircraft rotation.

2.1. Aircraft turnaround model

The process of aircraft turnaround operation is modelled in the aircraft turnaround model by two major work flows, namely the cargo and baggage processing flow and the passenger processing and cabin cleaning flow. Service activities in the process are grouped into major states according to the purpose of service activities such as goods loading and passenger boarding. The description of states in the work flow of cargo processing and passenger processing is given in Tables 1 and 2 respectively. Operational disruptions to cargo and baggage processing are represented by State_5 to State_9 as illustrated in Fig. 2 and described in Table 1. Operational

Table 1
Cargo and baggage processing

States	State description	States	State description	IATA delay codes and description
1	Arrival			
2	Goods unloading	5	Cargo processing	22, 23, 26 Late positioning and preparation
		6	Aircraft ramp handling	32, 33 lack of loading staff, cabin load, lack of equipment, staff/operators
3	Goods loading	7	Cargo processing	22, 23, 26 late positioning and preparation
		8	Aircraft ramp handling	32, 33 lack of loading staff, special load, lack of equipment, staff/operators
		9	Passenger and baggage	11,12,18 late check-in, check-in congestion, late baggage processing
4	Departure			

Table 2
Passenger/crew/cabin cleaning process

States	State description	States	State description	IATA delay codes and description
1	Arrival			
2	Disembark passengers and crew			
3	Cabin cleaning			
4	ATC flow control			
5	Crew and passenger boarding	8	Crew	63, 94, 95 late crew boarding, awaiting crew
		9	Passengers	11, 12, 14 late acceptance, late check-in
		10	Missing passengers	15 missing check-in passengers
6	Flight operations and crew procedures	11	Flight operations	61, 62 flight plan, operational requirements
		12	Departure process	63, 89 airport facilities, ground movement
		13	Weather	71, 72 weather restriction at O/D airports, removal of snow/ice/sand
7	Departure			

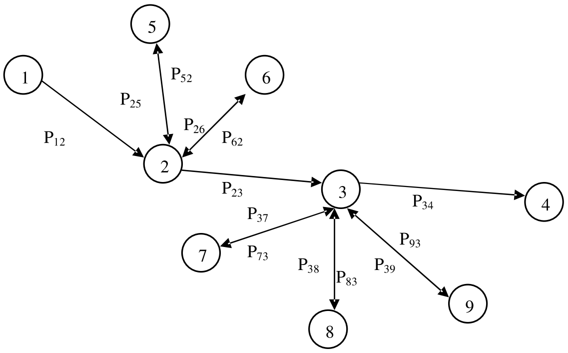

Fig. 2. Cargo and baggage processing flow in aircraft turnaround operations.

disruptions to cargo and baggage processing include equipment failure, lack of labour, late check-in cargo, late check-in passengers, late baggage and so forth. Operational disruptions to passenger and cabin cleaning process are represented by State_8 to State_13 in Fig. 3 which include missing check-in passengers, crewing problems, and flight operation delays during the departure procedure as described in Table 2.

The occurrence of operational disruptions in aircraft turnaround is simulated by Markovian transitions between normal service activities (State_1–State_4 for cargo flow and State_1–State_7 for passenger flow) and operational disruption events (State_5–State_9 for cargo flow and State_8–State_13 for passenger flow). The transition probability between disruption events and normal service activities is calculated from historical data of an airline in order to represent the operational efficiency of aircraft ground services at a specific airport. More detailed description of the aircraft turnaround model is available elsewhere (Wu and Caves, 2001).

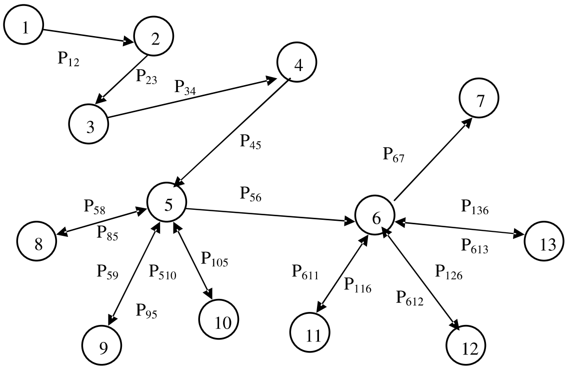

Fig. 3. Passenger and cabin cleaning processing flow in aircraft turnaround operations.

Operational disruptions may influence the departure punctuality of a turnaround aircraft only when the total duration of ground service activities exceeds the scheduled turnaround time (denoted by T_{SG}) for an aircraft. Hence, the departure delay (denoted by D_{d}) of a turnaround aircraft comes from arrival delays to the inbound aircraft (denoted by D_{a}) and operational delays due to aircraft turnaround services. Hence, the departure delay of a turnaround aircraft can be formulated by Eq. (1).

$$D_{\mathrm{d}} = \max\left\{0, \left(D_{\mathrm{a}} + \max\left\{T_{\mathrm{cgo}}, T_{\mathrm{pax}}\right\} - T_{\mathrm{SG}}\right)\right\} \quad D_{\mathrm{a}} \geqslant 0 \;\; D_{\mathrm{d}} \geqslant 0 \tag{1}$$

where T_{cgo} is the duration of cargo and baggage work flow, T_{pax} the duration of passenger processing work flow.

The objective of the AR model is to investigate the influence of aircraft turnaround efficiency on the schedule punctuality of aircraft rotations. Hence, the aircraft turnaround model simulates only uncertainties from turnaround operations of an aircraft and uncertainties from schedule punctuality, although other causes might also delay a turnaround aircraft.

2.2. Enroute model

The inbound delay of an aircraft when arriving at Airport K (shown in Fig. 1) is influenced by the outbound delay of the aircraft at the origin Airport J (the first segment of aircraft rotation in this case) and the enroute flight time in the airspace between Airport J and K. The enroute flight time of an aircraft is modelled by a stochastic distribution to simulate uncertainties from air traffic control and airspace congestion instead of detailed modelling of aircraft operation in the airspace. The purpose of the enroute model is linking two aircraft turnaround models developed for two individual airports in order to model aircraft rotation in a multiple airport environment.

The arrival delay (denoted by ${}_{\mathrm{K}}D_{\mathrm{a}}$) of an inbound aircraft arriving at Airport K is influenced by two factors: the departure delay (denoted by ${}_{\mathrm{J}}D_{\mathrm{d}}$) of the aircraft at the origin airport J and the enroute flight time (denoted by ${}_{\mathrm{JK}}T^{\mathrm{ER}}$) of the aircraft in the airspace between Airport J and K. The design of the enroute schedule block time (denoted by T_{JK}) of a flight between Airport J and K usually includes the mean flight time (denoted by $\mu_{\mathrm{JK}}^{\mathrm{ER}}$) and airborne buffer time (denoted by B_{JK}), which is expected to absorb potential delays at the origin airport as well as in the airspace. Hence, the arrival delay of an inbound aircraft arriving at Airport K can be formulated by Eq. (2).

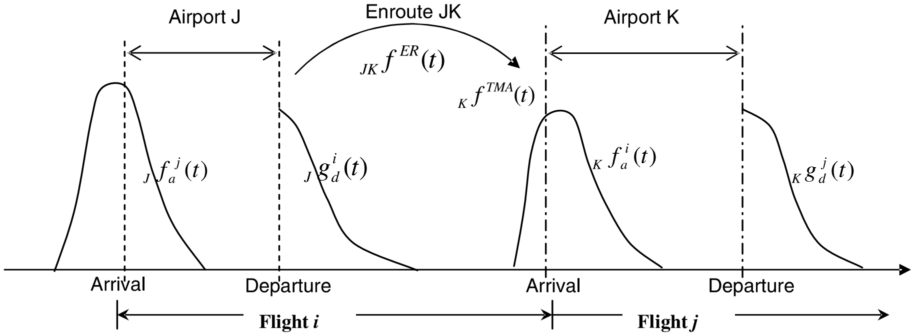

Fig. 4. Arrival and departure PDFs for turnaround aircraft between Airport J and K.

$$_{\mathrm{K}}D_{\mathrm{a}} = \max\{0, {}_{\mathrm{K}}T_{\mathrm{a}}\} \tag{2}$$

where $_{\mathrm{K}}T_{\mathrm{a}} = {}_{\mathrm{J}}D_{d} + {}_{\mathrm{JK}}T^{\mathrm{ER}} - T_{JK}$, $T_{\mathrm{JK}} = B_{\mathrm{JK}} + \mu_{\mathrm{JK}}^{\mathrm{ER}}$, T_{JK} is the schedule block time of a flight between Airport J and K, B_{JK} the airborne buffer time (if any), $\mu_{\mathrm{JK}}^{\mathrm{ER}}$ the mean flight time of an aircraft between Airport J and K (Fig. 4).

2.3. Simulation programmes

The AR model was implemented by a simulation programme in this paper. Stochastic simulation techniques were employed to simulate the turnaround time of an aircraft by using the proposed aircraft turnaround model. Monte Carlo simulation was used in the simulation programme to carry out stochastic sampling from chosen PDFs. Different model parameters were used in different aircraft turnaround models developed for different airports in the rotation network of the case study. Enroute models were calibrated for different O–D airports by using punctuality data from a European schedule airline and were used to link aircraft turnaround models to simulate aircraft rotations. Simulation programmes were coded in Fortran 90 and implemented on a Sun workstation in a Unix environment. The simulation size in the case study was 1000 rotations which are adequate to represent one-year operation of a narrow-body aircraft for a European short-haul route by the study airline company.

3. Model application

Flight schedules and punctuality data from a European schedule airline (denoted by Airline X) are employed to carry out a case study. Due to the confidentiality of research data, all identities of study schedules and punctuality data are replaced by codes. A typical aircraft rotation plan of Airline X is chosen for this study. The study aircraft rotation schedule (the winter schedule in 1999–2000) is given in Table 3. The rotation starts at 07.00 h (times are based on GMT) departing from AAA (the base airport of Airline X) and finishes at 22.00 h arriving at BBB. The scheduled turnaround time (denoted by TSG in Table 3) at CCC is 60 min. The scheduled turnaround time at AAA varies from 75 to 80 min and the scheduled turnaround time at BBB is 55 min. The

Table 3
Aircraft rotation schedule

Flight number	STD[a]	STA[b]	TSG[c]
Seg_1	07:00[d] AAA	08:15 CCC	60 min at CCC
Seg_2	09:15 CCC	10:30 AAA	80 min at AAA
Seg_3	11:50 AAA	12:55 BBB	55 min at BBB
Seg_4	13:50 BBB	15:00 AAA	75 min at AAA
Seg_5	16:15 AAA	17:20 BBB	55 min at BBB
Seg_6	18:15 BBB	19:40 AAA	80 min at AAA
Seg_7	21:00 AAA	22:00 BBB	

[a] STD stands for "scheduled time of departure".
[b] STA stands for "scheduled time of arrival".
[c] TSG stands for "scheduled turnaround time".
[d] All time shown in the table is based on GMT.

standard ground service time for this aircraft type (a narrow-body aircraft) by Airline X is 55 min at each airport.

3.1. Turnaround disruption history analysis

Punctuality data from Airline X are analysed to evaluate the turnaround efficiency of Airline X at its base airport, Airport AAA. The analysis result of the cargo and baggage processing flow is given in Table 4. It is found that there is a probability of 0.003 to encounter cargo processing problems for turnaround aircraft at AAA. There is a relatively higher probability of 0.02 for aircraft ramp handling problems to occur during aircraft turnaround operations. Delays due to cargo and baggage processing problems vary from 11 to 25 min.

According to statistical analyses of passenger processing at Airport AAA, it is found in Table 5 that there is a high probability of 0.16 to encounter delays due to departure flight operations which result from departure slot co-ordination in Europe as well as from ground movement

Table 4
Disruption probability and duration in the cargo and baggage process (at AAA)

States	State description	States	State description	Occurrence probability (P_{ij})	State time ($\Phi_{ij}(t)$)	Standard deviation
1	Arrival				μ	σ
2	Goods unloading	5	Cargo processing	0.003[a]	11[b]	9
		6	Aircraft ramp handling	0.02	25	24
3	Goods loading	7	Cargo Processing	0.003	11	9
		8	Aircraft ramp handling	0.02	25	24
		9	Passenger and baggage	0.02	15	14
4	Departure					

[a] The occurrence probability of each disruption state.
[b] The mean delay time and standard deviation of each disruption state.

Table 5
Disruption probability and duration in the passenger/crew/cabin cleaning process (at AAA)

States	State description	States	State description	Occurrence probability (p_{ij})	State time ($\Phi_{ij}(t)$)	Standard deviation
1	Arrival					
2	Disembark passengers and Crew					
3	Cabin cleaning					
4	ATC flow control				μ	σ
5	Crew and passenger boarding	8	Crew	0.04[a]	23[b]	19
		9	Passengers	0.02	15	14
		10	Missing passengers	0.02	12	12
6	Flight operations and crew procedures	11	Flight operations	0.0004	17	10
		12	Departure process	0.16	14	16
		13	Weather	0.004	45	40
7	Departure					

[a] The occurrence probability of each disruption state.

[b] The mean delay time and standard deviation of each disruption state.

congestion at Airport AAA. Delays that occur in passenger processing and cabin cleaning procedure vary from 12 to 45 min, the longer one being due to weather causes.

Turnaround efficiency analyses for Airport BBB and CCC are also carried out by using punctuality data recorded in the same period of time. Analysis results for Airport BBB and CCC are used as model parameters in individual Aircraft Turnaround models to form the required AR model.

3.2. Simulation results

The modelling performance of the AR model is validated by comparing simulation results from the AR model with observation data from Airline X through three measurements, namely the departure/arrival punctuality, the mean departure/arrival delay and the expected departure/arrival delay of segments of aircraft rotation.

It is seen in Fig. 5 that the observed departure punctuality of the study rotation varies between 30% and 75%. It is seen from observation data that the departure punctuality in the study rotation decreases from Seg_1–Seg_4, then remains under 50% until the start of the last segment, Seg_7. This is due, as shown by the rotation schedule given in Table 3, that there is less ground time scheduled for aircraft turnarounds at out station airports, i.e. Airport BBB and CCC in this case. The long turnaround time scheduled for Seg_2, Seg_4 and Seg_6 at the base airport does not successfully control the departure punctuality of the rotation. When the arrival punctuality from simulation results is compared with observations in Fig. 6, it is found that the observed arrival punctuality is slightly lower than that from simulations except Seg_1. It is seen in Fig. 6 that the observed arrival punctuality of segments in the study rotation varies between 30% and 55%.

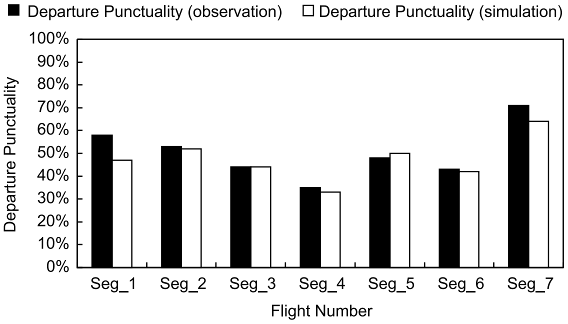

Fig. 5. Comparison of departure punctuality between simulation and observation data.

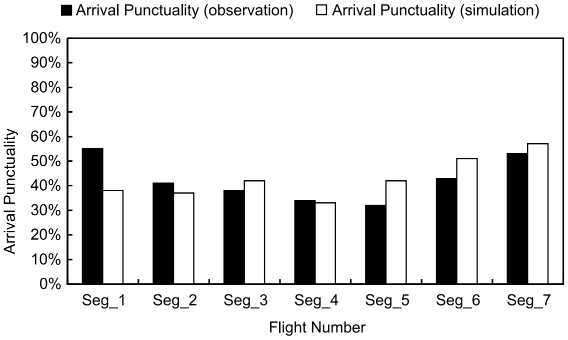

Fig. 6. Comparison of arrival punctuality between observation and simulation data.

When the observed mean departure delay of segments in the aircraft rotation is compared with simulation results, it is found in Fig. 7 that the simulation result is close to the observation data. The observed mean departure delay of segments in the study rotation varies between 5 and 15 min. Among seven rotation segments, Seg_4 and Seg_6 exhibits higher departure delay because the

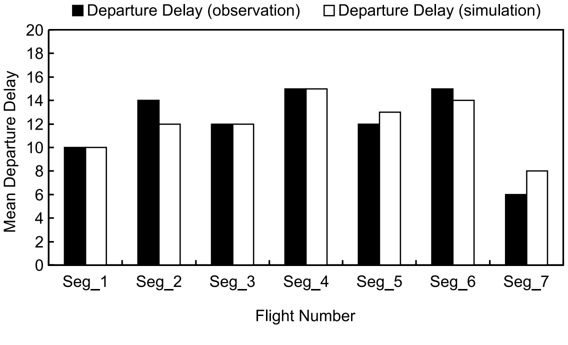

Fig. 7. Comparison of mean departure delay between simulation and observation data.

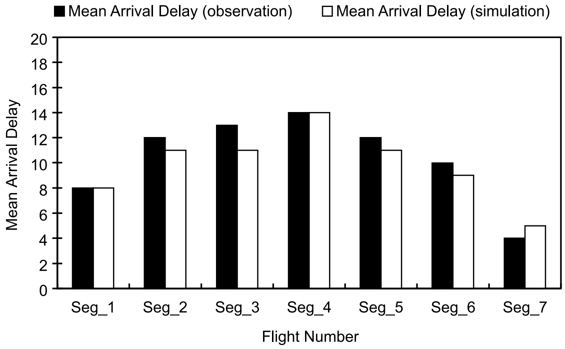

Fig. 8. Comparison of mean arrival delay between observation and simulation data.

scheduled turnaround time (55 min at Airport BBB) is just enough for standard turnaround operations required by Airline X but is not enough to absorb turnaround delays occurred at Airport BBB and knock-on delays from previous segments in the rotation. The mean arrival delay from the AR model is compared with the mean arrival delay from observation data in Fig. 8. It is found that the maximum difference between the mean arrival delay from simulation and observation is 2 min. Overall, the AR model has effectively simulated the fluctuation of delays in the study aircraft rotation.

When the expected departure delay from observation is compared with that from simulation, it is seen in Fig. 9 that only minor difference exists between the two sets of data except for the last segment of the rotation, Seg_7. The simulation performance of the AR model is relatively good for the other segments in the rotation according to Fig. 9. The high expected departure delay from simulation results for Seg_7 is due to knock-on delays accumulated in the simulation model. The comparison of the expected arrival delay is shown in Fig. 10. It is found that the expected arrival delay from simulation is close to observation data. The maximum difference between these two sets of data is 2 min.

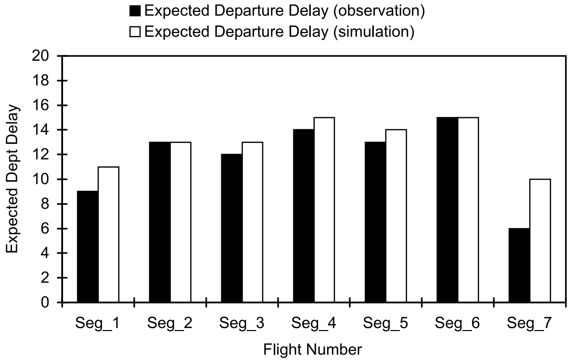

Fig. 9. Comparison of expected departure delay between simulation and observation data.

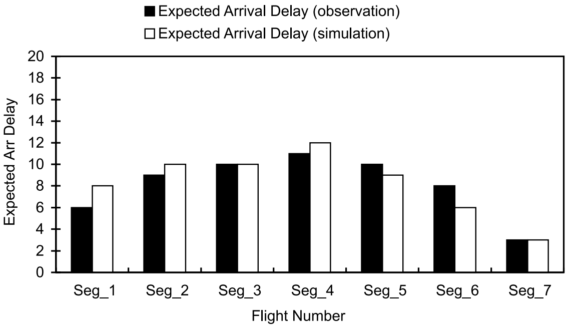

Fig. 10. Comparison of expected arrival delay between observation and simulation data.

4. Discussions

The implementation reliability of an aircraft rotation schedule relies on two factors: the design of the schedule and the managerial and operational efficiency of aircraft rotation by the airline. It is found in the case study that the scheduling policy of Airline X is to schedule short turnaround time at out stations and long turnaround time at its base airport. This scheduling policy allows more flight connection time for transfer passengers at the airline's base airport, Airport AAA. However, it is also found that the mean departure delay at out stations is usually higher than that at the base airport (as shown in Fig. 7 and Fig. 8) and consequently the arrival delay to inbound aircraft at the base airport is also higher than that at out stations. Although the scheduled turnaround time at Airport AAA is high (80 min in this case), it is usually consumed by arrival delays to inbound aircraft and therefore, the effectiveness of the control of knock-on delays by designing long turnaround time at Airport AAA is also compromised.

When the turnaround efficiency of Seg_3 at Airport AAA is compared with Seg_4 at Airport BBB, it is seen in Fig. 11 that the operational efficiency of the turnaround aircraft at two airports

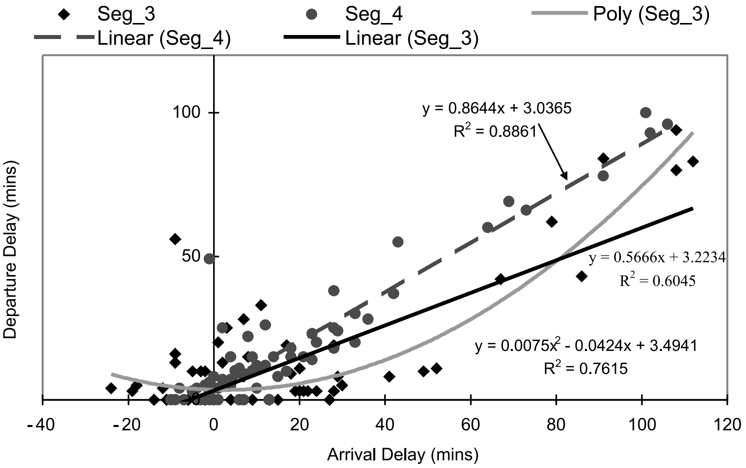

Fig. 11. Turnaround efficiency comparison between Seg_3 at AAA and Seg_4 at BBB.

differs from each other. When the relationship between the arrival delay time and the departure delay time is analysed for Seg_3, it is found that the slope of the linear regression line is <1. It implies that the arrival delay is usually absorbed by long aircraft turnaround buffer time at AAA. When quadratic functions are employed in the regression analysis for Seg_3, it is found that the quadratic function fits observation data better. This implies that the departure delay of the turnaround aircraft at Airport AAA might increase significantly when the arrival delay of inbound aircraft gets higher. When the regression result of Seg_4 is compared with that of Seg_3 in Fig. 11, it is found that the departure delay of the turnaround aircraft at Airport BBB is highly correlated to the arrival delay of its inbound flight. This implies firstly, that the turnaround efficiency of Seg_4 at BBB is high. Secondly, the scheduled turnaround time for Seg_4 is just enough for the study aircraft to complete turnaround operations. As a consequence, arrival delays due to late inbound aircraft are not likely to be absorbed by ground operations at BBB and it is more likely that the arrival delay influences turnaround operations and results in equivalent or higher departure delay to departure aircraft. Although the designed turnaround time for Seg_3 at Airport AAA is 80 min, i.e. 25 min buffer time, it is seen in Fig. 11 that the punctuality data of Seg_3 is more scattered than Seg_4. This suggests that the management of aircraft turnaround operations by Airline X at Airport AAA needs to be improved in order to manage the punctuality of aircraft rotations.

5. Conclusions

A simulation model (the AR model) was developed in this paper to simulate aircraft rotation in a multiple airport environment. A case study was carried out by using real data from a European schedule airline to validate the modelling performance of the AR model. The comparison between simulation results and observation data showed that the modelling performance of the AR model was good in terms of three measurements: the departure/arrival punctuality, the mean departure/arrival delay and the expected departure/arrival delay of segments in the rotation schedule. It was found from the case study that the punctuality of aircraft rotation relies on both the design of aircraft rotation schedules and the operational efficiency of aircraft turnarounds. The proposed AR model was suggested to be applied by airlines to evaluate the impact of changes to aircraft rotation schedules, particularly for low-cost airlines which employ short-turnaround-time policy in scheduling aircraft rotations.

Acknowledgements

The provision of flight schedules and punctuality data by a European airline, which wishes to remain anonymous, is highly appreciated by the authors. The work of the first author is partially sponsored by the Overseas Research Scholarship Award (ORSA) from the Committee of Vice Chancellors and Principals (CVCP) of the Universities of the United Kingdom. Valuable comments from two anonymous reviewers are highly appreciated by the authors.

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