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Journal of Air Transport Management 6 (2000) 201–208

Journal of
AIR TRANSPORT
MANAGEMENT

www.elsevier.com/locate/jairtraman

Aircraft operational costs and turnaround efficiency at airports☆

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Abstract

The aim of this paper is to investigate the relationship between flight schedule punctuality and aircraft turnaround efficiency at airports, in order to minimise system operational costs and meanwhile to maintain a required level of schedule punctuality. Investigations of aircraft operational costs, passenger delay costs and airline schedule time-opportunity costs are carried out in this paper. A mathematical model is applied to simulate aircraft turnaround operations by considering the stochastic effects of schedule punctuality as well as aircraft turnaround performance. Two numerical examples demonstrate the performance of the aircraft turnaround model. Results show the significance of a proper use of schedule buffer time in maintaining schedule punctuality performance.

Keywords: Aircraft turnaround operations; Schedule punctuality performance; Aircraft operational costs

1. Introduction

It has been argued that the lack of air transport system capacity and the consequent air traffic control (ATC) delays contribute to the majority of the deteriorating performance of flight schedule punctuality in Europe. Austrian Airlines estimated that ATC-related delays cost it \$52 million dollars in 1999 (Airline Business, 1999). However, a project by London Gatwick Airport showed that the delay due to aircraft/airline ground operations was the second largest contributor to flight delays after ATC-related delays (European Civil Aviation Conference, 1996). ATC-related delays were responsible for 30% of total delays during the Gatwick survey, while aircraft/airline ground services accounted for 25% of delays.

While the focus has been put on the improvement of airspace congestion, aircraft ground delays have not relatively received enough attention. An estimate from Austrian Airlines revealed that only 22% of the total costs of flight delays comes from direct consequences, i.e. additional airline operational costs; 24% of the total costs comes from passengers' permanent disloyalty (Airline Business, 1999). Research concerning the relationship between airline market shares and airline performance (in terms of schedule punctuality, service availability and safety records) showed the significance of passengers switching between airlines, once they experience unsatisfactory services from an airline (Suzuki, 2000). It has also been found that the significance of turnaround serviceability is not only essential to the improvement of schedule punctuality while turning around aircraft, but also essential to the maintenance of aircraft linkages and aircraft rotation stability (Chinn, 1996; Eilstrup, 2000).

The turnaround time for a short-haul flight is defined as the time for an aircraft to complete full off-loading, loading and where required, catering and cabin cleaning procedures (International Air Transport Association, 1997). For long-haul flights, the time including comprehensive technical and cabin services should be considered instead. Due to the variance of schedule punctuality, it is hypothesised in this paper that the proper use of schedule buffer time in the ground time of a turnaround aircraft would be able to optimise the schedule punctuality performance under the trade-off between schedule punctuality and aircraft turnaround time.

Therefore, the aim of this paper is to investigate how the trade-off situation between the ground time of a turnaround aircraft and schedule punctuality performance varies with the buffer time allocated to the schedule. The scheduled ground time of a turnaround aircraft is defined as consisting of two portions, namely the standard ground service time and schedule buffer time (if any). A mathematical model is proposed to simulate aircraft

☆Paper presented at the 32nd annual conference of the Universities of Transport Studies Group (UTSG) on the 5th January 2000, Liverpool England.

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0969-6997/00/\$ - see front matter
PII: S0969-6997(00)00014-4

turnaround performance by taking into account stochastic effects of schedule punctuality and delay absorption effects of schedule buffer time.

This paper consists of five sections including this introductory section. Section 2 describes the investigation of system costs, which include aircraft delay costs, passenger delay costs, and schedule time costs of an airline. The description of the turnaround model is provided in Section 3, which is followed by Section 4, Numerical Analyses. Conclusions of this paper are drawn in Section 5.

Table 1
Aircraft Classification

Aircraft classification[a]	Maximum take-off weight (MTOW, lb)	Average seat capacity
Medium Aircraft (narrow-body jets)	MTOW $\leqslant$ 300,000	150
Large aircraft (wide-body jets)	300,000 $<$ MTOW $\leqslant$ 600,000	250
Heavy aircraft (jumbo jets)	600,000 $<$ MTOW	400

[a]Classification with respect to maximum take-off weight (MTOW) and seat capacity.

2. System costs

System costs considered in this paper include aircraft departure delay costs, passenger delay costs and schedule time costs of an airline. Due to the unavailability of detailed financial information of airlines, cost values are calculated approximately from published financial data for the purpose of the demonstration of the turnaround model proposed in this paper, rather than precisely reflecting cost values of any specific airline in the industry. However, this simplification in cost calculation does not impair the potential of the proposed turnaround model, as proper parameter values can be developed by potential users to implement this model, when more detailed cost information is available for analysis.

2.1. Aircraft delay costs (C_{AC})

Various values of aircraft delay costs have been used in literature. Unit ground delay costs for European airlines used in relevant literature were \$1330, \$2007 and \$3022 per hour for medium, large and heavy jets, respectively (Janic, 1997). The estimates of unit delay cost of an aircraft in the US were \$430, \$1300, and \$2225 per hour with respect to small, medium and large aircraft (Richetta and Odoni, 1993). Although aircraft delay cost values like these can be easily found from the literature, a further study of aircraft delay cost is provided in this paper to meet specific analytical needs of the proposed mathematical model.

When an aircraft is delayed at a gate either with engines off or on, the airline not only incurs operational costs but also has to forego revenue. The aircraft delay cost, denoted by C_{AC} hereafter, is defined as "the hourly fixed operating cost per aircraft" and the loss of revenue being considered later as schedule time cost, C_{AL}. Aircraft delay costs depend on aircraft types and sizes. For the purpose of this paper, aircraft sizes are classified into three categories, namely medium, large, and heavy aircraft, as shown in Table 1.

Aircraft operating costs of major airlines are calculated and listed in Table 2 by using published financial data from International Civil Aviation Organisation (ICAO) (ICAO, 1997a, b). Aircraft operating costs are found to differ among air carriers, one of the reasons being the difference of the fleet structure. For instance, British Airways operates 32% of heavy aircraft for long-haul intercontinental flights (as shown in Fig. 1) and consequently has a high average operating cost of \$4498. KLM operates proportionately more large jets than Lufthansa, so KLM has a higher average aircraft operating cost of \$4757. Lufthansa has a similar aircraft fleet structure to United Airlines, but exhibits a higher operating cost of \$3407. American Airlines mainly operates large and medium aircraft and few heavy ones, so a lower operating cost of \$2207 is reasonable. On the other hand, British Midland uses mainly narrow body jets and exhibits an hourly aircraft operating cost of \$2822. Cost calculations in Table 2 are based on average aircraft operating costs due to the unavailability of detailed cost break-downs with respect to aircraft types and sizes from published information (ICAO, 1997).

2.2. Passenger delay costs (C_P)

The unit delay cost per passenger (denoted by C_P hereafter) is related to the average wage rate, flight classes, trip characteristics and delay time perception of a passenger. A survey by the Civil Aviation Authority (CAA) in the UK showed that the average wage rate was \$46 per hour for passengers using Heathrow Airport and \$42 per hour for passengers using Gatwick Airport (CAA, 1996). On the other hand, business passengers using London City Airport exhibited a higher average wage rate of \$64 per working hour. The average wage rate for leisure passengers was \$39 per hour from the same survey by CAA in 1996.

When calculating passenger delay time costs, trip purposes and passengers' characteristics are major factors believed to explain differences between users. Literature on the value of time suggests that a passenger values on-mode time at the wage rate for business flights and a quarter of wage rate for leisure flights. Waiting and delay time is valued higher, but it is not the purpose of

Table 2
Hourly aircraft operating costs with engines off at gates[a]

	British Airways (BA)	British Midland (BD)	KLM	Lufthansa (LH)	American Airlines (AA)	United Airlines (UA)
Total operating expenses[b]	11,395	866	5372	9370	14,409	16,110
Aircraft fuel and oil expenses[b]	(1150)	(50)	(580)	(1014)	(1726)	(1898)
Subtotal[c]						
Operating Expenses	10,245	816	4792	8356	12,683	14,212
Number of Aircraft	260	33	115	280	656	593
Aircraft operating costs ($/h/AC)	*4498*	*2822*	*4757*	*3407*	*2207*	*2736*

[a]Sources: Digest of Statistics, Financial Data Commercial Air Carriers, ICAO 1997. Digest of Statistics, Fleet-Personnel, ICAO 1997.
[b]Units in US $ (millions) ( ) Values of cost items.
[c]Subtotal = (Total operating expenses) − (Fuel and oil expenses).

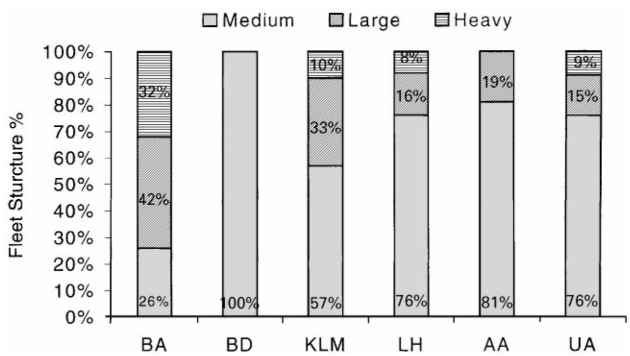

Fig. 1. Aircraft types of major airlines.

this paper to investigate precise cost figures of time value of passengers. Therefore, for simplicity, the hourly delay cost of a passenger is assumed as the average wage rate of $42 per hour for the consideration of a single class passenger during waiting time at an airport. Also, it is found worth doing sensitivity analyses in later research to investigate the influence of different considerations of passenger delay costs on flight schedules.

2.3. Schedule time costs (C_{AL})

Airlines try to minimise the turnaround time of aircraft in order to produce more revenue-making flight time (International Air Transport Association, 1997; Eilstrup, 2000). This is especially true for low-cost airlines and air carriers using intensive hubbing operations (Airports Council International, 2000; Gittell, 1995). Therefore, it is assumed in the quantification of the schedule time cost (denoted by C_{AL} hereafter) that scheduled ground time can be alternatively utilised as revenue-generating airborne block hours. In other words, the use of schedule buffer time for turnaround aircraft may reduce the expected departure delay, but incurs schedule time-opportunity costs.

It is assumed that the variation of fixed operational costs per hour due to the variation of total flight hours is insignificant compared with the change of total annual revenues. In other words, it is assumed that the change of the scheduled ground time causes only changes of revenues and variable costs due to changes of aircraft block hours. Based on this rationale, the hourly schedule time-opportunity cost is defined in this paper as "the marginal hourly operating profit of an airline". It is calculated by deducting hourly variable expenses from hourly revenues as demonstrated in Table 3.

It is observed from Table 3 that US airlines have lower average schedule time costs when compared with European air carriers, except for the similarity between British Midland and US carriers. Schedule time costs of heavy jets are logically higher than those of large and medium jets. This statement is supported by Fig. 2, in which British Airways schedule time cost is higher than all other airlines. From Fig. 2, it can be seen that British Airways operates more long-haul flights (observed from the line denoting holdings of large and heavy jets which correspond to the vertical axis on the right) and consequently it has a higher schedule time cost. Compared with British Airways, KLM operates more medium-distance flights, but KLM exhibits a higher schedule time cost than Lufthansa and two US airlines. The data in Fig. 2 suggest that schedule time costs can be categorised with respect to aircraft classes and flight range, when more detailed financial information is available.

3. Aircraft turnaround model

The trade-off situation occurs as an airline schedules turnarounds to maximise schedule punctuality while maintaining a short turnaround time for aircraft. A mathematical model is applied in this paper to simulate this trade-off situation as well as the aggregate aircraft turnaround performance. The turnaround model is

Table 3
Hourly schedule time costs of major airlines[a]

	British Airways	British Midland	KLM	Lufthansa	American Airlines	United Airlines
Revenues[b]	12,226	890	5699	9986	15,856	17335
Variable costs[b]						
Fuel and oil	(1149)	(50)	(580)	(1014)	(1726)	(1898)
Maintenance	(663)	(64)	(350)	(441)	(937)	(1049)
Station expenses	(1602)	(93)	(875)	(1434)	(2102)	(2195)
Passenger service expenses	(1637)	(139)	(535)	(1168)	(1775)	(1895)
Subtotal[c]						
(Revenues − Costs)	7172	576	3359	5929	9316	10,298
Flight hours (h)	*840,223*	*118,392*	*433,339*	*988,393*	*2,039,569*	*1,865,195*
Schedule time costs ($/h)	*8535*	*4865*	*7751*	*5998*	*4567*	*5521*

[a]Sources: Digest of Statistics, Financial Data Commercial Air Carriers, ICAO 1997. Digest of Statistics, Fleet-Personnel, ICAO 1997.
[b]Units in US $ (millions), ( ) Values of cost items.
[c]Subtotal = (Revenues) − (Costs).

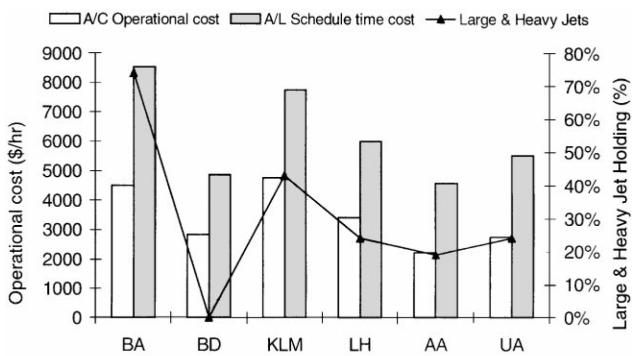

Fig. 2. Comparison of operational costs and aircraft fleet usage.

based on the formulation of uncertainties in terms of the schedule buffer time (denoted by T), the arrival punctuality of inbound turnaround aircraft (denoted by $f(t)$) and the service performance of ground handling agents (denoted by m_2). The objective of this model is to minimise total system costs (denoted by C_T) while maximising schedule punctuality. The objective function can be expressed by Eqs. (1)–(7).

To minimise C_T:

$$C_T = \alpha C_D + (1-\alpha) C_{AL}, \quad (1)$$

where

$$0 \leqslant \alpha \leqslant 1, \quad (2)$$

$$C_D = E[C_u(s)] = \int C_u(s) g(s)\, ds, \quad (3)$$

$$C_{AL}(T) = \int c^m_{AL}(T - T_A)\, dT, \quad (4)$$

$$g(s) = F[f(t), T, m_2]|J_s|, \quad (5)$$

$$s = m_1(t - T_A) \quad T_A, \leqslant t \leqslant T, \quad (6)$$

$$s = m_1(T - T_A) + m_2(t - T), \quad T < t \leqslant T_{max}, \quad (7)$$

where

$$m_1 = (m_2/T_{max} - T_A)(T_{max} - T), \quad T_A \leqslant T \leqslant T_{max}.$$

The first term of Eq. (1) calculates the expected delay cost of a delayed aircraft and on-board passengers, as in Eq. (3), by using a probabilistic departure time distribution $g(s)$ formulated in Eq. (5). The second term of Eq. (1) estimates the cost of implementing a "schedule buffer time" into a flight schedule. A weight factor α in Eq. (1) is used to explain trade-off conditions to balance the cost of delays and the cost of schedule time.

In Eq. (3), C_D stands for the expected delay cost of an aircraft and on-board passengers. The marginal delay cost of passengers and aircraft is assumed to be constant through time. Hence, the delay cost of passengers and aircraft is formulated by a linear function (denoted by $C_u(s)$ in Eq. (3)) with respect to delay duration. Although more general forms may be used when modelling delay time costs, a simplified usage of constant marginal costs still demonstrates the effects of delays on passengers and aircraft (Tosic et al., 1995). If a non-linear marginal cost function is assumed alternatively, it will be able to increase the weight of passenger delay cost in the objective function of this model and change the system optimum as well.

The airline schedule time cost $C_{AL}(T)$ in Eq. (4) is assumed to have a linear marginal cost function to account for an increasing opportunity cost when the length of schedule buffer time-increases. It is realised that schedule time–opportunity cost becomes higher when saved schedule time becomes long enough for an aircraft to carry out an additional flight to make revenue. The departure time distributions, $g(s)$ in Eq. (5), of a turnaround aircraft is modelled by the corresponding arrival time of the inbound aircraft (t in Eq. (6)), schedule buffer time (T in Eq. (6)), and performance of ground services (m_2 in Eq. (6)). The performance of the turnaround process is simulated by a stepwise linear function (as shown in Eqs. (6) and (7)) to take into account the delay absorption ability of scheduled buffer time.

4. Numerical analyses

The arrival punctuality performance of inbound aircraft is simulated by probability density functions (PDF) to account for punctuality uncertainties. Real flight data from a European airline was collected in 1999, in order to justify the use of PDFs in modelling aircraft punctuality performance. Fitted probability curves are shown in Fig. 3. Stochastic distributions were statistically tested by both *K–S test* and χ^2 *goodness-of-fit test* to ensure the power of curve fitting. Three different types of arrival punctuality patterns were found to be representative for three different routes. Domestic flights showed a quasi-normal punctuality pattern in the form of Beta (18,20). Short-haul international flight, on the other hand, exhibited a right-tailed Beta (4,14) punctuality performance. Long-haul flights showed a Beta (2,13) arrival pattern with a long right tail. Accordingly, the Beta function ($f(t)$ in Eq. (5)) is chosen to model schedule punctuality performance, because of its analytical tractability in calculations.

Three types of arrival patterns, i.e. early arrivals, late arrivals, and normal-distributed arrivals, are investigated in numerical analyses to find the influence of inbound aircraft's punctuality on departure punctuality of turnaround aircraft. For simplicity, Beta (10,3) was selected to model the arrival pattern with the majority of flights arriving within a maximum delay of twenty minutes. Beta (3,10) distribution was used to simulate late arrival patterns, and Beta (10,10) distribution was set to represent a quasi-normal arrival pattern.

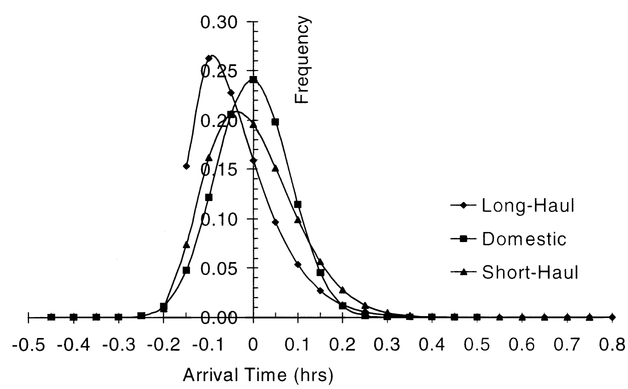

Fig. 3. Aircraft arrival PDFs from real data.

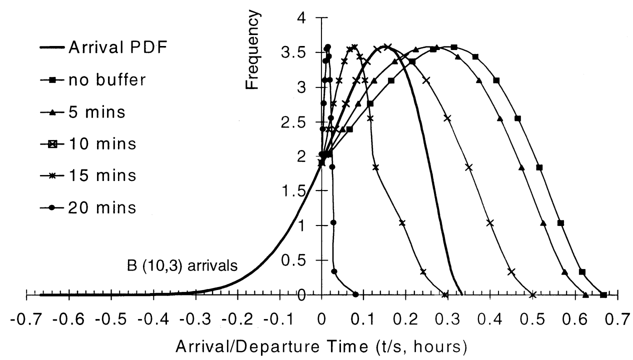

Fig. 4. Departure time distributions subject to various schedule buffer time.

4.1. Arrival Punctuality

The influence of schedule buffer time on the punctuality of a turnaround aircraft is demonstrated by Fig. 4. It illustrates the influence of different schedule buffer time on a turnaround aircraft with Beta (10,3) arrival punctuality performance. It is clearly observed from Fig. 4 that the more schedule buffer time is scheduled into the ground time of a turnaround aircraft, the more punctual departure flights will be. Two numerical examples are carried out by using published information of British Airways (BA) and British Midland (BD) from the ICAO database (ICAO, 1997). Parameter values used in numerical analyses are listed in Table 4.

When a quasi-normal arrival pattern (Beta (10,10) function in this case) is applied to the turnaround model, it is found from Fig. 5 that the optimum schedule buffer time for the BA case is ten minutes, though the system cost curve of BA (denoted by BA-CT' in Fig. 5) exhibits a rather flat concave shape. This is resulted from the use of linear cost functions in calculating passenger and aircraft delay costs. The use of linear delay cost functions is a relatively optimistic assumption in which it does not consider any increasing marginal passenger delay costs over time. If a non-linear delay cost function is used to model passenger and aircraft delay costs, the total system cost curve will become more concave and is expected to achieve a system minimum with a longer buffer time than the current case.

Therefore, when ten minutes of schedule buffer time is scheduled into the example BA route, 95% of flights are expected to arrive within ten-minute buffer time. A similar situation is observed from the BD case as shown in Fig. 5. The optimum schedule buffer time for the example BD route is also found to be ten minutes.

4.2. Airline operational strategies

While scheduling flights, several different factors are considered by an airline in order to build a feasible and profitable flight schedule. In this paper, a weight factor

Table 4
Parameter values used in numerical analyses[a]

	C_{AC} Aircraft operating costs ($/h)	C_P Passenger delay costs ($/h)	C_{AL} Airline schedule time costs ($/h)	m_2 Ground service capability
British Airways	*4500*	*5880*[b]	*8535*	*2*
British Midland	*2822*	*4100*[c]	*4865*	*2*

[a]Notes: Calculation was based on information from *ICAO Statistics 1997*.
[b]Average aircraft size for BA European flights is set to be 200 seats with an average load factor of 0.7.
[c]Average aircraft size for BD European flights is set to be 150 seats with an average load factor of 0.65 (Wu, 2000).

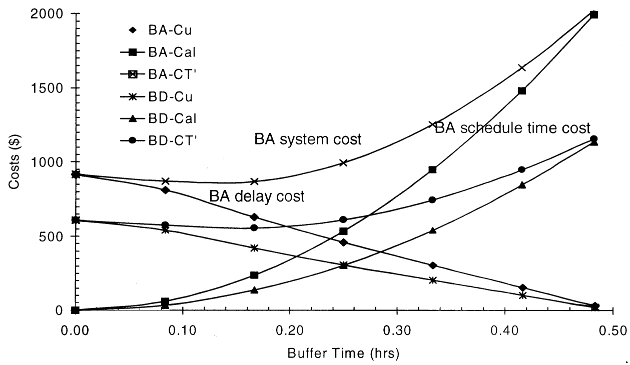

Fig. 5. System cost curves for BA and BD cases.

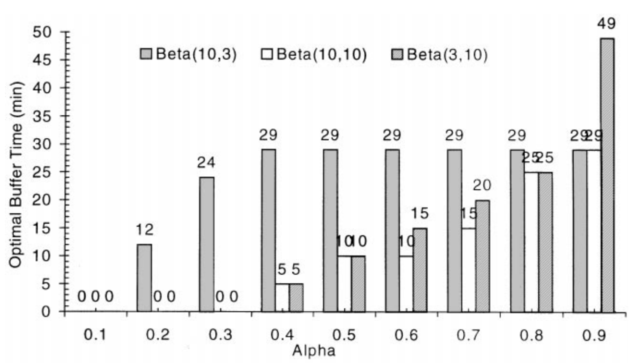

Fig. 6. Scheduling strategy influence on the use of schedule buffer time.

α is used to trade off the cost of aircraft schedule time and expected delay costs. For some routes, aircraft block time could be so valuable that an airline will try to minimise aircraft ground time in order to increase profitable block hours. Under such a circumstance, the weight factor α can be set at a value lower than 0.5 to favour a schedule with short schedule buffer time. Passengers may then suffer from a higher risk of having departure delays, and airlines may suffer from aircraft delay costs as well.

It is observed from Fig. 6 that the expected delay cost in the Beta (10,3) case, i.e. the late arrivals, is higher than the schedule time cost, so the optimum buffer time is set to be as high as 30 min. On the other hand, Beta (3,10) and Beta (10,10) cases, i.e. early and normal-distributed arrivals, show that the airline schedule time is more valuable than expected delay costs when schedule buffer time is getting longer. Therefore, it can be concluded that an airline may minimise operational costs by scheduling different schedule buffer time to its flight schedule according to individual arrival punctuality performance of inbound aircraft.

4.3. Schedule punctuality performance

Conventionally, flight schedule punctuality performance (SPP) is defined as the percentage of punctual flights or the percentage of flights departing within a period of tolerable delay, e.g. the "airline dependability statistics" defined by the Department of Transportation in the US (Luo and Yu, 1997). However, the SPP measured in this way only measures the punctuality out-turn after the implementation of a flight schedule. Hence, an alternative approach to measure SPP is proposed by using the turnaround model in this paper.

The SPP of a flight is defined as "the cumulative percentage of departing flights subject to a given turnaround time (if any schedule buffer time is included) and a departure delay tolerance". For instance, if a flight exhibits a Beta(10,3) arrival pattern, then the SPP of this flight under 10-minute schedule buffer time and fifteen-minute departure delay tolerance will be 85% as denoted by point A in Fig. 7. Accordingly, an airline can estimate the SPP of a turnaround aircraft under given arrival punctuality of inbound aircraft and the limit of tolerable delay.

Alternatively, when an SPP is set to be an operational goal of a route, the optimum schedule buffer time of turnaround aircraft for this route can also be found by the inverse application of the above methodology. For instance, if the required SPP is set to be seventy percent and the delay tolerance is 15 minutes, then the corresponding schedule buffer time for a turnaround aircraft with a Beta (10,3) arrival punctuality becomes five minutes (as shown by point B in Fig. 7).

This paper discusses whether a different use of schedule buffer time for turnaround aircraft with different

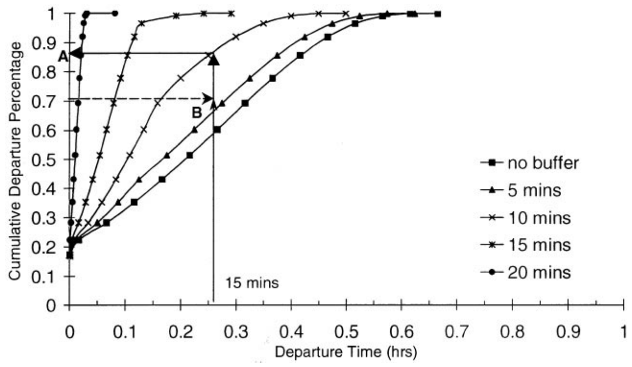

Fig. 7. Evaluation and estimation of SPP of turnround aircraft.

Table 5
Schedule Reliability with respect to Buffer Time Length

	Buffer Time					SPP		
	0 min	5 min	10 min	15 min	20 min	*70%*	*80%*	*90%*
B(10,3)	58%[a]	65%	85%	100%	100%	*6* min[b]	*8* min	*12* min
B(10,10)	90%	90%	95%	100%	100%	*0* min	*0* min	*5* min
B(3,10)	77%	80%	85%	87%	90%	*0* min	*8* min	*20* min

[a]Cumulative percentage of flight departing within 15 min.
[b]Punctuality buffer with respect to required SPP and 15-min delay tolerance.

inbound punctuality would be able to optimise the SPP. Hence, the SPP for different arrival punctuality patterns with different schedule buffer time is derived and results are given in Table 5. It is found that a longer buffer time does indeed increase the schedule punctuality performance of a turnaround aircraft, if the operating environment remains unchanged. However, the trade-off situation between the use of schedule buffer time and the expected system cost still applies. Hence, the use of schedule buffer time is still constrained by the increasing opportunity cost of schedule time.

Results in Table 5 also show that more schedule buffer time is needed to maintain a higher requirement of SPP. Applying this methodology, an airline/airport will be able to estimate the SPP in advance and monitor the SPP after the implementation of a flight schedule, if historical flight punctuality performance information is available for analyses.

5. Conclusions

The influence of schedule buffer time on the schedule punctuality performance of aircraft turnaround is demonstrated by using the proposed turnaround model. The optimum schedule buffer time is calculated by using nominal cost values derived from an investigation of aircraft operational costs. Results of numerical analyses support the argument that a proper use of schedule buffer time for different classes of turnaround aircraft can derive a system optimum by minimising system costs while maximising schedule punctuality performance. The methodology proposed to measure the SPP in this paper is found to be a suitable managerial tool for airlines and airports to estimate and evaluate the SPP both before and after the realisation of flight schedules, wherever historical flight punctuality performance and aircraft turnaround efficiency information are available for analyses.

Although punctuality uncertainties still arise from ATC operations, it is believed that a well-designed flight schedule is able to stabilise schedule punctuality performance. The proper choice of schedule buffer time for turnaround aircraft increases the reliability of flight connections at airports. As a consequence, an airline is able to optimise its aircraft rotational schedule in a flight network in order to minimise its operational costs while maintaining a good reputation of punctuality to its customers.

Acknowledgements

The provision of flight schedule and punctuality data by an air carrier, which wishes to remain anonymous, is greatly 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.

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