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Towards the optimisation of the schedule reliability of aircraft rotations

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Abstract

A cost minimisation model is developed to optimise the scheduling of aircraft rotation by balancing the use of schedule time, which is designed to control flight punctuality, and delay costs. A case study is conducted using schedule and punctuality data from a European airline. Optimisation shows that the operational performance of an aircraft rotation schedule is improved in terms of: schedule regularity, mean delays and expected delays of aircraft rotation. Although the total schedule time of the study rotation is increased by 5%, a system cost saving of some \$9.3 million/1000 aircraft rotations is gained after schedule optimisation. Three schedule reliability surrogates—mean delay time of aircraft rotation, expected delay time of aircraft rotation and schedule regularity—are employed to evaluate the reliability of aircraft rotation schedules. It is found that the reliability and robustness of schedule implementation is significantly improved after optimisation.

Keywords: Aircraft rotation; Schedule reliability; Schedule optimisation

1. Introduction

The consequences of delays in the air transport system are reductions in the productivity of air carriers as well as loss of time and loyalty of passengers. The influence of schedule punctuality of aircraft rotation becomes more significant when the consequences of flight delays are investigated on a network scale. Previous analysis by Austrian Airlines revealed that only 22% of the total costs of flight delays comes from direct delay effects—i.e. additional airline operational costs. Of total delay costs, 24% comes from a permanent loss of passengers' loyalty and 54% from induced knock-on delays in aircraft rotation schedules (Airline Business, 1999). In order to mitigate the consequences of knock-on delays, airlines tend to design more buffer time in flight schedules so as to conceal delays in aircraft rotations (Sunday Times, 2000).

The general approach to the issue of flight schedule punctuality has been to investigate the cumulative percentage of departure flights within a chosen tolerance of delay, e.g. the airline dependability statistics defined by the US Department of Transportation (Luo and Yu, 1997). This approach only measures the schedule punctuality at a single airport after the implementation of a flight schedule. However, it is found that the schedule punctuality of a flight may be influenced by the efficiency of aircraft turnaround operations on the ground as well as the arrival punctuality of inbound aircraft from out-station airports in the network of aircraft rotations (Wu, 2001). Major shortcomings of using airline dependability statistics included the fact that the measurement is an ex poste measure and it reveals only the results of schedule delays without any further investigation into determining factors such as schedule design and airline operations. The objective here is to investigate the influence of aircraft rotation schedule design on the reliability of schedule implementation in order to optimise aircraft rotation.

Major system cost items for passengers and airlines resulting from the operation of aircraft rotations are considered, including passenger delay costs, aircraft delay costs and the cost of scheduling buffer time in aircraft rotation by an airline. A trade-off situation for the airline is found between the use of buffer time in flight schedules to control schedule punctuality—resulting in lower aircraft utilisation—and delay costs

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imposed on passengers and the airline itself. Hence, the aim is to optimise the scheduling of aircraft rotation to minimise system costs by allocating a schedule time to each segment of rotation schedules.

Reliability surrogates are also developed to provide quantitative performance indices to evaluate the reliability of aircraft rotation. A case study is carried out by using schedule information from a European schedule airline to demonstrate the improvement of schedule reliability after optimisation.

2. Formulation of system costs in aircraft rotation

The rotation of an aircraft is illustrated in Fig. 1. The rotation of the aircraft in Fig. 1 starts from Airport A. The aircraft is turned around at Airport B (the base airport) after a period of scheduled turnaround time. The complete rotation of this aircraft ends at Airport D, at which the aircraft is held over night. A segment of aircraft rotation is defined to start from the on-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, the operation of a segment of aircraft rotation includes the turnaround operation of the aircraft at the origin airport and the en route operation in the airspace between two airports. Arrival/departure delays measured are based on the scheduled time of arrival/departure (STA/STD). The accumulation of delays in aircraft rotation is called the knock-on delay of aircraft rotations.

The notation used in the formulation of system costs is: B_A is the schedule buffer time for flight i at airport A; B_{AB} is the schedule buffer time for flight i en route airport A and B; C_T is the system costs from aircraft rotation; C_T^i is the operating cost of flight i; C_{AL}^A is the opportunity cost of ground schedule buffer time at airport A; ${}_dC_D^A$ is the expected departure delay costs of an aircraft at airport A; C_{AL}^{AB} is the opportunity cost of airborne schedule buffer time between airport A and B; ${}_aC_D^B$ is the expected arrival delay costs of flight i when arriving at airport B; ${}_dC_{DP}^A$ is the expected departure delay costs for passengers on-board flight i; ${}_aC_{DP}^B$ is the expected arrival delay costs for passengers on-board flight i; ${}_dC_{DA}^A$ is the expected departure delay costs for flight i at airport A; ${}_aC_{DA}^B$ is the expected arrival delay costs for flight i arriving at airport B; $f(t)$ is the delay cost of flight i as a function of delay time (t); $h(t)$ is the time value of passengers on flight i as a function of delay time (t); $k(B)$ is the schedule time opportunity cost as a function of schedule buffer time (B); α^A is the weight factor in the objective function for expected departure delay costs of flight i departing from Airport A; β^A is the weight factor in the objective function for ground schedule buffer time cost of flight i departing from airport A; α^{AB} is the weight factor in the objective function for expected arrival delay costs of flight i arriving at airport B; and β^{AB} is the weight factor in the objective function for airborne schedule buffer time cost of flight i arriving at airport B.

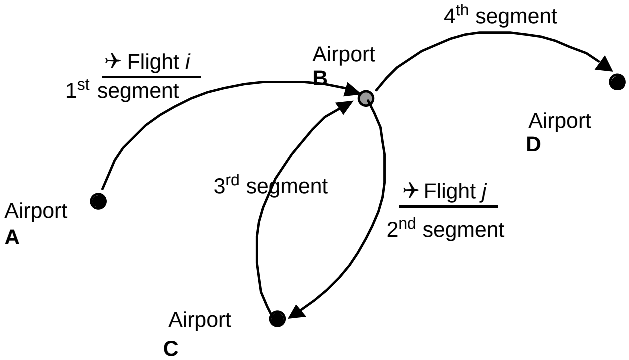

Fig. 1. Aircraft rotation between airports.

The operating cost (C_T^i) incurred by flight i (Fig. 2) comes mainly from the expected departure delay cost of on-board passengers and the aircraft at airport A, (${}_dC_D^A$), the ground schedule buffer time opportunity cost at airport A (C_{AL}^A), the expected arrival delay cost of on-board passengers and the aircraft at airport B (${}_aC_D^B$), and the airborne schedule buffer time opportunity cost in the block time between airport A and B (C_{AL}^{AB}). To simplify modelling, only cost items mentioned above are included, although other costs may influence the total costs of aircraft rotation. Hence, the operating cost of flight i can be formulated by

$$C_T^i = ({}_dC_D^A + C_{AL}^A) + ({}_aC_D^B + C_{AL}^{AB}). \quad (1)$$

Aircraft departure delay at the origin airport imposes delay costs on passengers as well as the airline itself. The expected departure delay cost for a delayed aircraft is, therefore, composed of two parts: the delay cost for on-board passengers (${}_dC_{DP}^A$) and the delay cost for the aircraft (${}_dC_{DA}^A$). Hence, the expected departure delay cost for a delayed aircraft is represented by

$${}_dC_D^A = {}_dC_{DP}^A + {}_dC_{DA}^A. \quad (2)$$

It is generally realised that there is a higher risk for passengers to miss connection flights at the destination airport when the delay time of an aircraft is getting longer. Hence, it is assumed that the time value of passengers on flight i can be modelled by a quadratic function ($h(t)$) to simulate passengers' perception of delays and the invisible loss of time value. Hence, the expected delay cost for on-board passengers can be expressed as

$${}_dC_{DP}^A = E[h^A(t)]. \quad (3)$$

It is assumed that the expected delay cost for flight i (${}_dC_{DA}^A$) can be formulated by a linear cost function

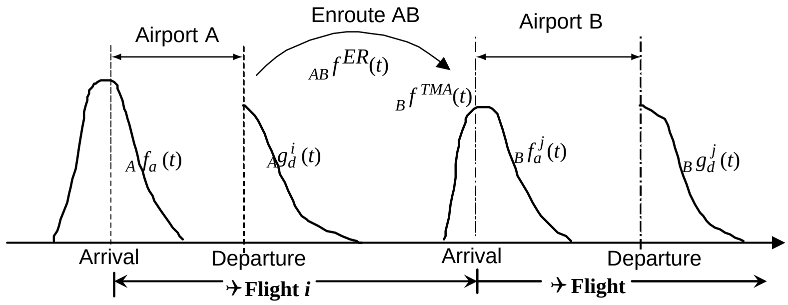

Fig. 2. Arrival and departure PDFs for turnaround aircraft between Airports A and B.

$(f(t))$ as

$$ {}_{\mathrm{d}}C_{\mathrm{DA}}^{\mathrm{A}} = E[f^{\mathrm{A}}(t)]. \tag{4}$$

Hence, the expected departure delay cost for flight i at airport A can be re-written as

$$ {}_{\mathrm{d}}C_{\mathrm{D}}^{\mathrm{A}} = {}_{\mathrm{d}}C_{\mathrm{DP}}^{\mathrm{A}} + {}_{\mathrm{d}}C_{\mathrm{DA}}^{\mathrm{A}} = E\lfloor h^{\mathrm{A}}(t)\rfloor + E\lfloor f^{\mathrm{A}}(t)\rfloor. \tag{5}$$

Similarly, the expected arrival delay cost of flight i arriving at airport B can be expressed as

$$ {}_{\mathrm{a}}C_{\mathrm{D}}^{\mathrm{B}} = {}_{\mathrm{a}}C_{\mathrm{DP}}^{\mathrm{B}} + {}_{\mathrm{a}}C_{\mathrm{DA}}^{\mathrm{B}}. \tag{6}$$

The scheduling of buffer time, if any, in aircraft rotation schedules stabilises schedule punctuality, though it reduces the utilisation of aircraft. Hence, it is assumed that the opportunity cost of scheduling buffer time (B_{A}) in the turnaround time of flight i at airport A can be formulated by a quadratic function ($k(B)$) to account for the increasing value of schedule time opportunity cost for an airline. Accordingly, the cost of scheduling buffer time in the turnaround time at airport A ($C_{\mathrm{AL}}^{\mathrm{A}}$) is formulated as Eq. (7). On the other hand, the cost of scheduling airborne buffer time ($C_{\mathrm{AL}}^{\mathrm{AB}}$) in the block time for flight i en route to airport A and B is modelled by Eq. (8):

$$ C_{\mathrm{AL}}^{\mathrm{A}} = k(B_{\mathrm{A}}), \tag{7}$$

$$ C_{\mathrm{AL}}^{\mathrm{AB}} = k(B_{\mathrm{AB}}). \tag{8}$$

Hence, the operating cost incurred to flight i (C_{T}^{i}) is as in the following equation:

$$ C_{\mathrm{T}}^{i} = \left(E\lfloor h^{\mathrm{A}}(t)\rfloor + E\lfloor f^{\mathrm{A}}(t)\rfloor\right) + k(B_{\mathrm{A}}) + \left(E\lfloor h^{\mathrm{B}}(t)\rfloor + E\lfloor f^{\mathrm{B}}(t)\rfloor\right) + k(B_{\mathrm{AB}}). \tag{9}$$

The system costs of all segments in the study rotation schedule can be modelled by Eq. (10). Weights—e.g. α^{A} and β^{A}—are used to model the trade-off situation between schedule punctuality and system costs due to flight delays. The objective is to minimise system costs (C_{T}) in aircraft rotations by optimising the allocation of schedule buffer time in aircraft rotation schedules, e.g. the schedule buffer time at airport A (B_{A}), and in the block time between airport A and B (B_{AB}). Since it is mathematically difficult to get a closed-form solution to Eq. (10), the minimisation problem is solved by numerical analyses:

$$ C_{\mathrm{T}} = \sum_{i}(C_{\mathrm{T}}^{i}) \quad \forall i \in \{1,2,3,\ldots,n\} \quad \text{for segments,} \tag{10}$$

where

$$\begin{aligned}
&C_{\mathrm{T}}^{i} = (\alpha^{\mathrm{A}}\,{}_{\mathrm{d}}C_{\mathrm{D}}^{\mathrm{A}} + \beta^{\mathrm{A}}C_{\mathrm{AL}}^{\mathrm{A}}) + (\alpha^{\mathrm{AB}}\,{}_{\mathrm{a}}C_{\mathrm{D}}^{\mathrm{B}} + \beta^{\mathrm{AB}}C_{\mathrm{AL}}^{\mathrm{AB}}),\\
&{}_{\mathrm{d}}C_{\mathrm{D}}^{\mathrm{A}} = {}_{\mathrm{d}}C_{\mathrm{DP}}^{\mathrm{A}} + {}_{\mathrm{d}}C_{\mathrm{DA}}^{\mathrm{A}} = E\lfloor h^{\mathrm{A}}(t)\rfloor + E\lfloor f^{\mathrm{A}}(t)\rfloor,\\
&C_{\mathrm{AL}}^{\mathrm{A}} = k(B_{\mathrm{A}}),\\
&{}_{\mathrm{a}}C_{\mathrm{D}}^{\mathrm{B}} = {}_{\mathrm{a}}C_{\mathrm{DP}}^{\mathrm{B}} + {}_{\mathrm{a}}C_{\mathrm{DA}}^{\mathrm{B}} = E\lfloor h^{\mathrm{B}}(t)\rfloor + E\lfloor f^{\mathrm{B}}(t)\rfloor,\\
&C_{\mathrm{AL}}^{\mathrm{AB}} = k(B_{\mathrm{AB}}),\\
&\alpha^{\mathrm{A}} + \beta^{\mathrm{A}} = 1,\\
&\alpha^{\mathrm{AB}} + \beta^{\mathrm{AB}} = 1.
\end{aligned}$$

3. Measuring the reliability of aircraft rotation schedules

The reliability or robustness of a schedule is defined as the adherence of the schedule implementation to that planned, i.e. a schedule with pre-planned timetables. The general issue of schedule reliability has been widely discussed (Adamski and Turnau, 1998; Leon et al., 1994). The robustness of scheduling job shops in a manufacturing factory was studied by Leon et al. (1994). The objective of Leon's work was to investigate the performance of a planned job shop schedule in the presence of disruptions. The measures of schedule reliability considered in Leon's work included: the weighted measure of mean service time and mean delay time, the expected delay of a schedule, the operational efficiency of manufacturers as well as the average slack time (buffer time) in a planned schedule. It was concluded that the expected delay is superior to the others as a measure for indicating reliability, though it usually takes time to calculate the measure by model simulations. Without time-consuming model simulations, the average slack time of a schedule was found to be a good surrogate to schedule robustness.

The reliability of train schedules has also been investigated because of the occurrence of occasional knock-on delays in railway schedules. The risk of a delayed arrival or departure was proposed as a surrogate for the reliability of railway schedules (Carey, 1994, 1998, 1999; Ferreira and Higgins, 1996; Higgins et al., 1995). The expected delay of a train was also used to measure schedule adherence because it accounts for both the delay time and the probability of delay (Carey, 1994, 1998, 1999; Carey and Kwiecinski, 1995; Ferreira and Higgins, 1996; Hallowell and Harker, 1998; Higgins et al., 1995). Descriptive statistics of a train schedule—e.g., the standard deviation (SD) and the variance (VAR) of schedule delay—have also been proposed as alternative measures to schedule reliability because they account for the variability in the implementation of a planned timetable (Carey, 1994; Hallowell and Harker, 1998). The concept of the aggregate schedule reliability was developed by Carey (1999) who modelled the reliability of a train trip as a whole instead of modelling the schedule reliability of a train at a single station. The aggregate reliability measure was modelled by calculating the mean probability that a train does not suffer knock-on delays.

Previous work thus suggests measures for a planned timetable including the probability of delays, the expected delay of a schedule as well as descriptive statistics of the on-time performance of a timetable. Although ex ante heuristic measures of schedule reliability have also been discussed, for these measures there is a need to build simulation models from historical schedule performance data recorded by the operator of the schedule (Carey, 1999). The function of schedule reliability measures is also not only to provide schedule operators with estimated schedule performance figures before the implementation of a schedule but additionally to help design reliable and robust schedules at the early planning stage. The aims here are to improve the stability and reliability of aircraft rotation schedules in which 'exogenous' disruptions cause the least knock-on delays to aircraft rotations and to develop suitable reliability surrogates to aircraft rotation schedules with respect to the characteristics of rotations.

A reliable schedule for an airline needs to adhere to pre-planned timetables and to maintain the implementation feasibility in the presence of operational uncertainties from daily schedule operations. Hence, three reliability surrogates of aircraft rotation are used: (i) the mean delay of aircraft rotation segments, (ii) the expected delay of aircraft rotation segments, and (iii) the regularity of aircraft rotation schedules.

3.1. Mean delay of aircraft rotation segments

The mean delay time (μ^{D}) of a schedule is the most commonly used indicator for measuring timetable reliability. The mean delay of a schedule can be calculated by statistic methods after the implementation of a schedule either as the mean arrival delay at the destination airport ($\mu_{\mathrm{a}}^{\mathrm{D}}$) or the mean departure delay at the origin airport ($\mu_{\mathrm{d}}^{\mathrm{D}}$). The mean delay of aircraft rotation segments ($\mu_{\mathrm{SEG}}^{\mathrm{D}} = \mu_{\mathrm{a}}^{\mathrm{D}} + \mu_{\mathrm{d}}^{\mathrm{D}}$) is used as the reliability measurement of aircraft rotation. It is easy to calculate from schedule punctuality data and, in some cases, the departure delay of an aircraft could be absorbed and the aircraft still arrives punctually or with only minor arrival delay, if ample airborne time is designed in the schedule. Hence, the mean delay of aircraft rotation segments is used to reflect the departure punctuality at the origin airport, the delay absorption effects of scheduled airborne time and the arrival punctuality at the destination airport.

3.2. Expected delay of aircraft rotation segments

The expected arrival delay of an aircraft ($E[t]_{\mathrm{a}}^{\mathrm{D}}$) is defined in Eq. (11) and the expected departure delay of an aircraft (denoted by $E[t]_{\mathrm{d}}^{\mathrm{D}}$) in Eq. (12):

$$E[t]_{\mathrm{a}}^{\mathrm{D}} = \int t f_{\mathrm{a}}(t)\,\mathrm{d}t, \tag{11}$$

$$E[t]_{\mathrm{d}}^{\mathrm{D}} = \int t f_{\mathrm{d}}(t)\,\mathrm{d}t, \tag{12}$$

where $f_{\mathrm{d}}(t)$ is the probability density function (PDF) of outbound aircraft and $f_{\mathrm{a}}(t)$ is the PDF of inbound aircraft

The accumulated expected delay of aircraft rotation segments ($E[t]_{\mathrm{SEG}}^{\mathrm{D}}$) is the accumulation of the expected departure delay at the origin airport and the expected arrival delay at the destination airport (Eq. (13)). The advantage of this reliability surrogate, when compared with the measure of the mean delay, is the inclusion of delay occurrence probability in the calculation of the expected delay. The expected delay of an aircraft represents the effects of both the delay duration and the occurrence probability of the delay:

$$E[t]_{\mathrm{SEG}}^{\mathrm{D}} = E[t]_{\mathrm{a}}^{\mathrm{D}} + E[t]_{\mathrm{d}}^{\mathrm{D}}. \tag{13}$$

3.3. Regularity of aircraft rotation schedules

The regularity of a flight schedule (R_{REG}) is defined as the likelihood for successful implementation of a pre-planned rotation schedule. Hence, the schedule regularity indicates the operational feasibility of the schedule as well as the robustness of the schedule design when facing daily operational uncertainties (Chinn, 1996; Leon et al., 1994). When operational disruptions are likely to result in serious delays, an airline has to make operational decisions that consider whether the disruption is going to influence the rest of the aircraft rotation schedule, and whether it is necessary to cancel flights or break aircraft rotation links to stop an escalation of knock-on delays. If the link between segments of aircraft rotation is broken it brings irregularity to the flight schedule and usually increases an airline's operating costs.

The implication of schedule irregularity is that the original schedule needs to be changed on the day of operation. On the other hand, the regularity of a schedule reflects how robust the schedule is against unforeseen disruptions as well reflecting the operational capability of an airline in managing day-to-day aircraft rotations. The calculation of schedule regularity is based on a chosen delay time threshold representing the maximum tolerable delay time for a specific route to prevent knock-on effects on following aircraft rotation segments.

4. Case studies

4.1. Schedule optimisation

Flight schedules and punctuality data from a European schedule airline (airline X) are used in a case study. For confidentiality, all identities were replaced by codes. A typical European short-haul aircraft rotation schedule of airline X was chosen. The study aircraft rotation schedule (the winter schedule in 1999–2000) is seen in Table 1 and in Fig. 3. The rotation started at 07:00 h GMT departing from AAA (the base airport of airline X) and finished at 22:00 h arriving at BBB. The scheduled turnaround time (TSG) at CCC was 60 min. The scheduled turnaround time at AAA varied from 75 to 80 min and the scheduled turnaround time at BBB was 55 min. The standard ground service time for this narrow-body aircraft type was 55 min at each airport.

Table 1
Aircraft rotation schedule (case study)

Flight number	STD[a]	STA[b]	TSG[c]
LEG_1	07:00[d] AAA	08:15 CCC	60 (at CCC)
LEG_2	09:15 CCC	10:30 AAA	80 (at AAA)
LEG_3	11:50 AAA	12:55 BBB	55 (at BBB)
LEG_4	13:50 BBB	15:00 AAA	75 (at AAA)
LEG_5	16:15 AAA	17:20 BBB	55 (at BBB)
LEG_6	18:15 BBB	19:40 AAA	80 (at AAA)
LEG_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 times shown in the table are based on GMT.

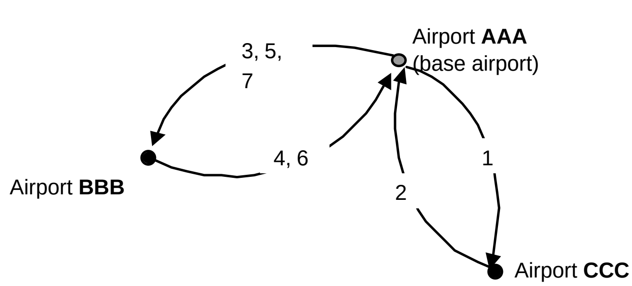

Fig. 3. Aircraft rotation schedule in the case study.

The time value of a passenger is taken as \$54/h (Wu and Caves, 2000). The value of the unit delay cost of an aircraft is estimated by the airline to be \$120/min for ground delays—equivalent to a delay cost of \$7200/h/aircraft. The opportunity cost of schedule buffer time is estimated to be \$9900/h. Equal weights for the delay cost of passengers and the airline schedule time cost in the objective function are used.

The result of a schedule optimisation is compared with data from the original schedule. It is seen from Fig. 4 that the improvement of schedule punctuality after optimisation varies from 10% to 40%. The mean departure punctuality of the study rotation is maintained above 80% after schedule optimisation. The mean departure delay of segments in the rotation, as shown in Fig. 5, is controlled to within 7 min after schedule optimisation when compared with fluctuating delays ranging from 6 to 15 min from the original schedule. It is also seen from Fig. 6 that in terms of the

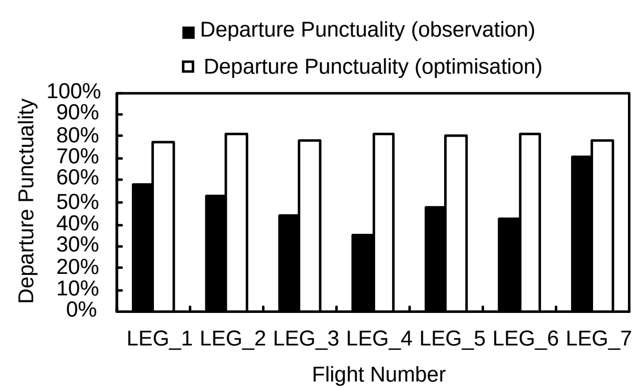

Fig. 4. Comparison of departure punctuality between optimisation and observation.

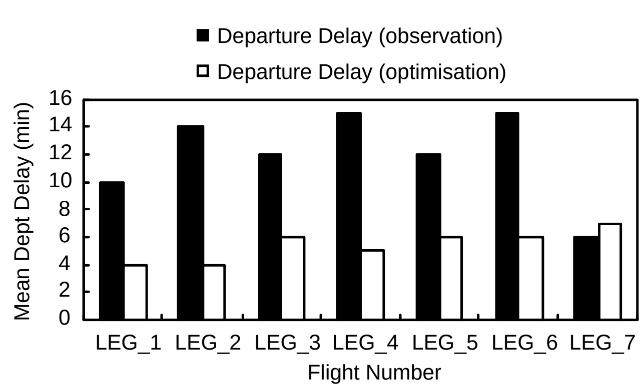

Fig. 5. Comparison of mean departure delay between optimisation and observation.

expected delay of segments in the study rotation, the optimisation significantly controls delays within 8 min.

The optimised segment time of the rotation schedule is given in Table 2 and in Fig. 7. The optimised schedule time of most segments in the rotation is slightly higher than the original schedule except the last segment, LEG_7. The total rotation time after optimisation is 1005 min which is 45 min (5%) more than the original schedule time (960 min). The optimised turnaround time of early rotation segments—i.e. LEG_1, LEG_2 and LEG_3—is slightly higher than the original schedule while the optimised turnaround time decreases for later segments. The optimisation, therefore, tends to allocate more buffer time for early segments in order to mitigate potential delay impacts resulting from early segments in the rotation. The schedule design with ample buffer time for early segments also reduces the likelihood of developing knock-on delays in aircraft rotation and hence controls the use of schedule time for later rotation segments. Optimisation results additionally validate the general understanding that good schedule adherence for early segments of aircraft rotation (‘morning readiness’) improves the reliability of aircraft rotation schedules.

When the system cost of the original schedule is compared with that after schedule optimisation (Fig. 8), the system cost of the original schedule increases significantly along with the implementation of aircraft rotation. Although the system cost of the optimised schedule also grows gradually with aircraft rotation, a significant reduction of system cost is seen from the optimisation case. A total saving of $9,305,127 (43%) per thousand aircraft rotations (which is equivalent to one and a half-year of short-haul European operation of the study aircraft) is gained after schedule optimisation. To further investigate the change of system costs before and after schedule optimisation, the breakdown of system costs for the original schedule and the optimised

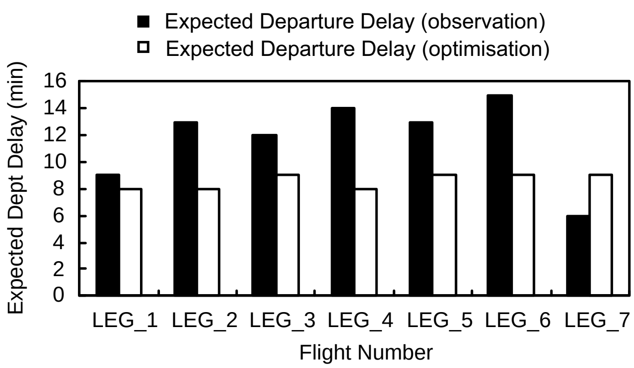

Fig. 6. Comparison of expected departure delay between optimisation and observation.

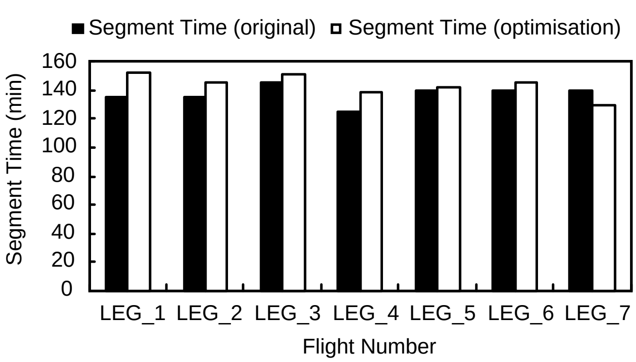

Fig. 7. Comparison of segment time in aircraft rotation schedule before and after optimisation.

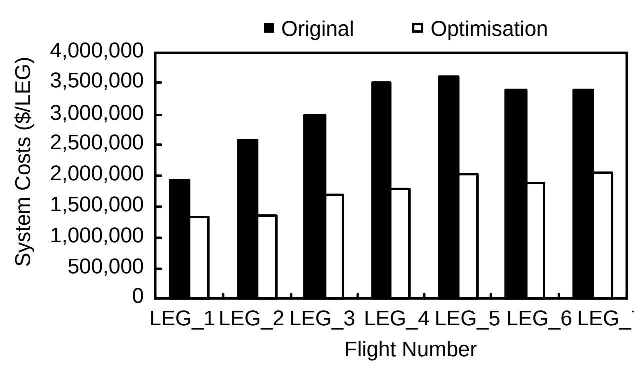

Fig. 8. Comparison of system costs for each segment before and after optimisation.

Table 2
Aircraft rotation schedule after optimisation

From	To	Flight number	TSG		Scheduled block time (T_B)		Total segment time	
			Original	Optimised	Original	Optimised	Original	Optimised
AAA	CCC	LEG_1	60	72	75	80	135	152
CCC	AAA	LEG_2	60	66	75	80	135	146
AAA	BBB	LEG_3	80	81	65	70	145	151
BBB	AAA	LEG_4	55	64	70	74	125	138
AAA	BBB	LEG_5	75	72	65	70	140	142
BBB	AAA	LEG_6	55	61	85	85	140	146
AAA	BBB	LEG_7	80	67	60	63	140	130
						Total time	960	1005

schedule is shown in Fig. 9. The share of passenger delay cost decreases by 8% and the aircraft delay cost decreases by 11%. Since the use of schedule time by the airline is increased after schedule optimisation, the share of schedule time cost is increased by 19%.

4.2. Schedule reliability

The reliability of aircraft rotation schedule is investigated by applying three schedule reliability indices to the optimised schedule as well as the original schedule. The mean delay time of segments in the study rotation after optimisation is compared with the original observations (Fig. 10). The average segment delay time for the original schedule varies from 6 to 29 min. The optimised aircraft rotation becomes more reliable than the original one because the mean delay of each segment in the optimisation case is maintained under 5 min. Hence, the schedule reliability is improved after optimisation in terms of the level of mean delay time in aircraft rotation.

The expected delay time of segments for the original schedule is compared in Fig. 11 to the expected segment delay time after schedule optimisation. The expected segment delay for the original schedule increases from 15 min at the start of the rotation to as high as 25 min in the mid-day and then decreases to 6 min by the end of the rotation. On the other hand, the expected segment delay for the optimisation case is maintained between 5 and 7 min. The schedule optimisation thus improves the reliability and stability of the aircraft rotation by effective control of the expected segment delay of the rotation schedule.

The schedule regularity of the original schedule is measured by two thresholds of schedule modification, 60 and 90 min ($R_{\mathrm{REG\_60}}$ and $R_{\mathrm{REG\_90}}$), and is compared with those for the optimised schedule (Fig. 12). The schedule regularity for the first few segments is lower for the original schedule. Then the schedule regularity increases gradually as the rotation proceeds in a day. This implies that the overall likelihood of encountering long delays exceeding 60 min is relatively high for early segments (LEG_1, LEG_2 and LEG_3) when compared with the schedule regularity for later segments. The implication is that early segments in this rotation schedule could be potential weak links that might result in knock-on delays in aircraft rotation. This finding is validated by observations of airline X's current operation.

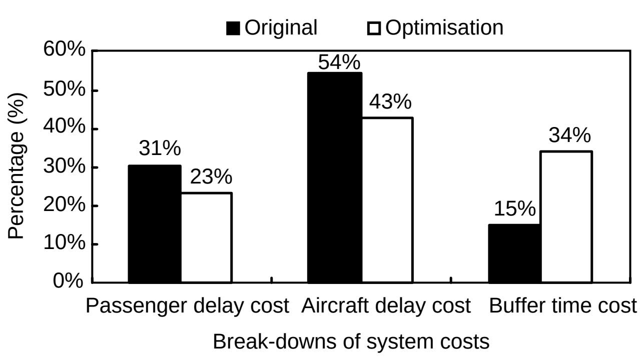

Fig. 9. Comparison of the breakdown of system costs before and after schedule optimisation.

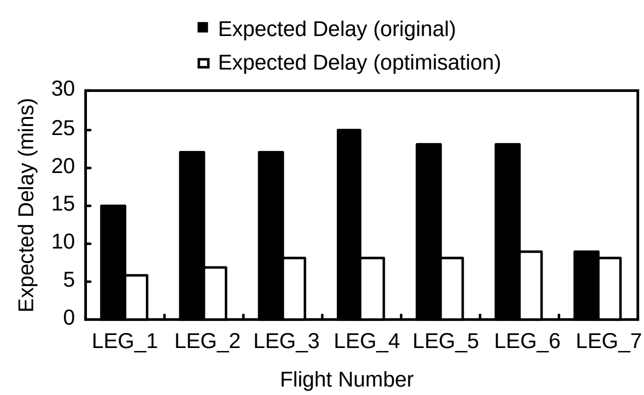

Fig. 11. Expected delay of segments in aircraft rotation (schedule reliability analysis).

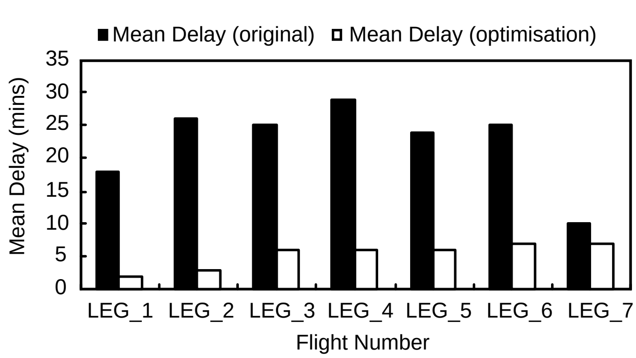

Fig. 10. Mean delay of segments in aircraft rotation (schedule reliability analysis).

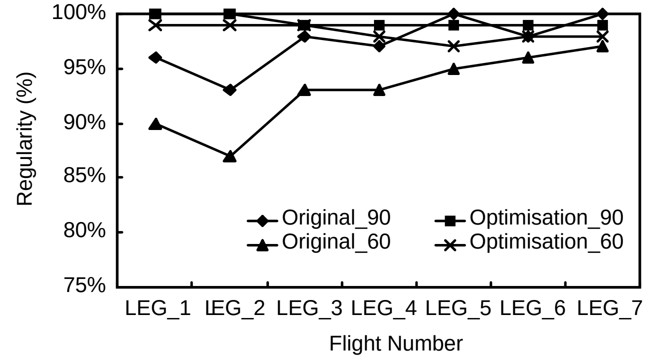

Fig. 12. Schedule regularity for aircraft rotation (schedule reliability analysis).

5. Conclusions

The results indicate that the reliability of aircraft rotation for the study route is significantly improved after schedule optimisation. The schedule reliability in terms of the mean delay time and the expected delay time shows that the operational reliability of the optimised schedule is higher and better-controlled than the original one. In addition, the regularity analysis of the optimised schedule strongly suggests that the robustness and reliability of schedule implementation is improved after optimisation. Therefore, the optimisation of the study rotation schedule by airline X improves the overall schedule punctuality as well as the reliability of schedule implementation.

In terms of reliability surrogates, the mean delay of aircraft rotation segments can be easily produced by statistical analyses. But, the index is of little help when an airline is attempting to investigate the potential bottlenecks in aircraft rotations because it only reflects a part of operational characteristics in aircraft rotations. On the other hand, the reliability measure of the expected delay of aircraft rotation has the advantage of considering stochastic effects from delay time and the probability of occurrence, although it requires sophisticated statistical computation to be reliable. From the managerial perspective, the implementation regularity of a flight schedule not only reflects how well the schedule resists operational uncertainties but also how well the daily operation of aircraft rotation is managed by the airline.

The mean delay seems suitable for preliminary investigations to the operational reliability of a flight schedule because of its ease of calculate and its ability to reveal basic information regarding schedule reliability. The expected delay, on the other hand, seems better at serving as the major reliability surrogate because it incorporates two important stochastic factors—the occurrence probability of delays and the duration of delays. The schedule regularity measure can be seen as an indicator of operational feasibility and reliability of a flight schedule because it reflects both the robustness of the schedule design and the operational feasibility of the flight schedule.

Although the schedule reliability of aircraft rotation in the case study has been improved by optimisation, the gain in reliability does not come without extra expenses from the airline. In the case study, 45 more minutes of schedule time are designed into the optimised schedule to stabilise the operation of aircraft rotation. Research results also raise another issue about the optimal use of schedule time and its operational efficiency in aircraft rotation schedules.

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