Examining Delay Propagation Mechanisms for Aircraft Rotations

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Abstract.
State-of-the-art optimization software for robust airline resource scheduling are often based on stochastic approaches for which understanding and modeling realistic delay occurrence and propagation mechanisms are essential. In this context, this paper deals with the evaluation of a theoretical delay propagation model with real-world data of a major European carrier. The results show that especially in the event of delayed departure, the turnaround process can be accelerated and thus the operational robustness is underestimated. The findings can be used to estimate delay propagation in robust aircraft scheduling and simulation closer to operational reality.

Keywords: Robust Efficiency, Airline Resource Scheduling, Propagation, Simulation

1 Introduction

In the globalized world, the rising demand for air transportation leads to increased frequencies on existing flight routes and new destination offerings by airlines. This inevitably goes along with additional complexity of resource schedules since more crews, aircraft but also airport equipment for ground operations and scares airspace must be efficiently scheduled. A wide range of sophisticated commercial optimization suites and IT solutions has been developed in recent decades from specialized providers such as Sabre, SITA, Lufthansa Systems, Jeppesen or EDS, see [1] for details.

The traditional objective of cost minimization preferably leads to the efficient usage of resources at preferably high utilization levels. Since idle times are costly, ground times between flights tend towards a minimum in cost-optimized schedules. We refer to the costs for a schedule that can be operated as planned as nominal costs. However, airlines frequently have to deal with exogenous delays during operations, caused by bad weather conditions, technical failure or congestion, to name just a few. In case of insufficient buffer times, delays may propagate further on consecutive flights, inducing additional reactionary costs for schedule recovery, resource

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reassignment or passenger rerouting. The real costs that actually emerge for airline operations can therefore substantially differ from nominal costs.

This issue is addressed by the concept of *robust efficiency* which aims at the minimization of real costs by already taking into account reactionary costs during the scheduling stage. Besides cost-efficiency, the additional objective of robustness is considered, aiming at the reduction of delay propagation effects. A stronger coupling between scheduling and operations can be achieved.

In recent decades, stochastic optimization approaches have been developed to improve either the stability [2]-[4] or flexibility [5] of resource schedules, mostly focusing on crews and aircraft. The benefit of these approaches greatly depends on realistic assumptions on occurrence probabilities of exogenous delays. Related studies can be found in [6] and [7]. In addition, the examination of realistic delay propagation mechanisms is crucial for the anticipation of potential propagated delays, allowing the realistic assessment of schedule robustness.

In this work, we address this topic by evaluating the prediction accuracy of the theoretical delay propagation model of [2] based on real-world data for four years from a major European carrier. The data set comprises 2,197,406 flight delay records for a hub-and-spoke network from March 2003 to February 2007. Findings can be used in a prototypical scheduling and simulation framework in which scheduling strategies are evaluated for practical application.

The remainder of the paper is organized as follows. In Section 2, we present the formalization of a generalized turnaround process for aircraft and the evaluated theoretical propagation model. Section 3 deals with determining essential minimum ground time values for the aircraft turnaround. Based on this, propagation mechanisms for aircraft rotations are analyzed in Section 4. Conclusions and an outlook are given in Section 5.

2 Fundamental Assumptions on the Turnaround Process and Propagation Effects

The generalized aircraft turnaround process between two consecutive flights within a rotation R is illustrated in Figure 1. Case (1) represents scheduled times in regular operations. Every flight $f \in R$ has a scheduled departure time STD_f and a scheduled arrival time STA_f.

The turnaround process starts with the aircraft arriving at the gate. The scheduled ground time $sgt_{a(f)f}$ between flight f and its aircraft predecessor $a(f)$ consists of the minimum ground time $mgt^A_{a(f)f}$ needed for the turnaround and a potential buffer time $b^A_{a(f)f} \geq 0$.

Cases (2) and (3) depict cases in which flight $a(f)$ arrives late. ATD_f and ATA_f describe the actual times of departure and arrival of flight f, respectively. d^D_f denotes the departure delay $ATD_f - STD_f$ and d^A_f the arrival delay $ATA_f - STA_f$. $agt_{a(f)f}$ is the actual ground time $ATD_f - ATA_{a(f)}$.

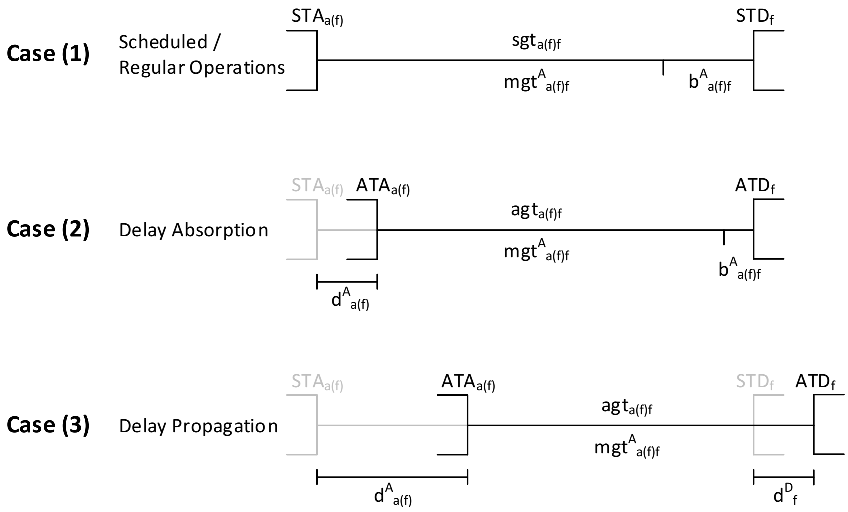

Figure 1. Delay Propagation in during the Aircraft Turnaround Process

In Case (2), the delay can be absorbed by the buffer time and it holds

$$agt_{a(f)f} \geq mgt^{A}_{a(f)f}, \tag{1}$$

$$b_{a(f)f} \geq 0. \tag{2}$$

In contrast, Case (3) implies a delay propagation to flight f with

$$agt_{a(f)f} = mgt^{A}_{a(f)f}, \tag{3}$$

$$b_{a(f)f} = 0. \tag{4}$$

Delay propagation by crew itineraries follow the same mechanisms with the respective minimum ground time $mgt^{C}_{c(f)f}$ between flight f and the crews' predecessor $c(f)$. Based on these assumptions, a basic propagation model for crews and aircraft is formulated in (5)-(9), following [2]:

$$ATA_f = \max\{STA_f, ATD_f + t_f\},\ \forall\ f \in F, \tag{5}$$

$$ATD_f = max\left\{STD_f, max\begin{Bmatrix} ATA_{a(f)} \ + mgt^{A}_{a(f)f} \\ ATA_{c(f)} + mgt^{C}_{c(f)f} \end{Bmatrix}\right\} + X_f, \forall\ f \in F. \tag{6}$$

$$d^{D}_{f} = ATD_f - STD_f, \forall\ f \in F. \tag{7}$$

$$d^{A}_{f} = ATA_f - STA_f, \forall\ f \in F. \tag{8}$$

$$s_f = d_f - X_f, \forall\ f \in F. \tag{9}$$

X_f represents a stochastic variable for exogenous delays in ground processes that can be modeled based on findings from related studies such as [6] and [7]. A block time t_f is associated to each flight f, determining the time from gate to gate, including taxi-out, flying time and taxi-in.

A flight can depart only if both crew and aircraft are available (6). Equalities (7) and (8) explicitly describe departure and arrival delays, respectively. Note that one main assumption of the model is that negative delays do not propagate, i.e. early arrivals do not imply early departures of subsequent flights. s_f depicts the amount of propagated departure delay for every flight f and therefore is the common target value concerning the evaluation of schedule robustness. Since the duration of the minimum ground time plays a central role in terms of delay propagation, its specification is discussed in further detail in the following.

3 Minimum, Scheduled and Actual Ground Times

Necessarily, minimum ground times *mgt* are determined prior to the construction of aircraft rotation based on generalized rules. It is defined as the shortest time span in which the turnaround process can be performed. Several – partly interconnected – tasks have to be carried out, leading to a fairly complex system of interactive processes. Several studies on a high granular level have been carried out on this topic, see e.g. [8] and [9]. According to [9, p.81], the *mgt* for continental fleets is 45 minutes at the main hub. It can be reduced to 40 minutes when both the inbound and outbound flights are domestic. Since *mgt* values are only available for the main hub, we derive a sufficient estimator for *mgt* values at all other airports of the flight network based on scheduled ground times *sgt*.

At first, possible influential factors that may affect the length of turnaround times are checked in a CART analysis[1]. The results confirm the expectation that fleets are the most substantial influential factor for the *sgt*, followed by O&Ds[2]. As an additional parameter we use a binary variable indicating whether the inbound and outbound flights are both domestic or not. Significant differences by seasonal attributes cannot be observed. We check the following candidates as *mgt* estimators:

- **Minimum Value** as theoretical threshold for data without outliers,
- **.01, .05, .075, .10, and .15 Quantiles** as estimators that are robust against outliers,
- **Modal Value**, based on the assumption that most turnarounds are performed in minimum time available.

[1] See https://cran.r-project.org/package=rpart for details (last visited November 9th, 2017).
[2] The Origin & Destination (O&D) of a flight is determined by its departure and arrival airport.

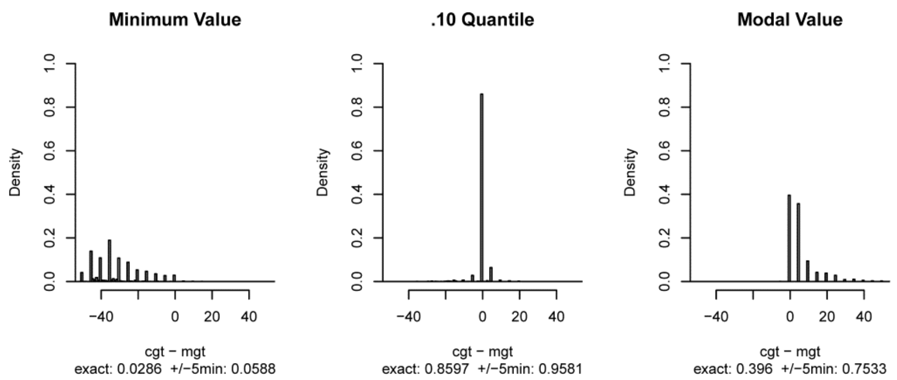

Figure 2. Selected estimators for scheduled *mgt* values

The results for the main hub are presented in Table 1. The second and third column depict the mean and standard deviation of $(cgt - mgt)$ where *cgt* is the minimum ground time computed using the respective estimator and *mgt* is the minimum ground time value given in the data set. The last two columns are the relative amount of flights for which the minimum ground time is derived exactly or within a tolerance range of ±5. It turns out that the .10-quantile suits best for retrieving mgt from sgt, leading to an exact derivation for 86% of all flights. Within the tolerance range of ±5 minutes the value increases to 95.9%.

For further illustration, Figure 2 shows the histogram for the .10-quantile in comparison to the minimum and modal values, indicating the extremes concerning under- and overestimation. In combination with figures of Table 1, we can assume that the .10-quantile is the best estimator of *mgt* values for all airports in the flight network for the scope of this analysis.

Table 1. Prediction accuracy for *mgt* value estimators

			Accuracy	
Estimator	*Mean*	*SD*	*exact*	*±5 minutes*
min	33.705	13.339	0.029	0.059
.01 quantile	20.152	11.129	0.043	0.115
.05 quantile	3.514	6.916	0.587	0.911
.075 quantile	1.734	5.765	0.832	0.951
.10 quantile	1.326	5.132	0.860	0.958
.15 quantile	1.901	4.475	0.690	0.944
mode	6.615	10.820	0.396	0.753
mean	24.436	7.565	0.000	0.001

4 Examination of Propagation Mechanisms on real-world Data

Prior to the assessment of the prediction accuracy of the propagation model, we give an introducing example of a daily rotation based at Hub H_1 that is affected by exogenous delays. Table 2 represents the daily rotation of an Airbus A321 at one representative day in summer. ΔGT indicates the difference between scheduled and actual ground time of flight f and its predecessor $a(f)$:

$$\Delta GT = (STD_f - STA_{a(f)}) - (ATD_f - ATA_{a(f)}). \tag{10}$$

Negative ΔGT values are commonly induced by the usage of buffers for the absorption of incoming delays. In case of a delayed turnaround, the actual ground time exceeds the scheduled ground time, leading to positive ΔGT values. Analogously, ΔBT describes the block time difference

$$\Delta BT = (ATA_f - ATD_f) - (STA_f - STD_f). \tag{11}$$

Concerning O&Ds, H_1 stands for a hub airport while $\{S_1, \ldots, S_4\}$ depict four spoke airports that are served by the out-and-back principle. Column *in* shows the incoming arrival delay of the predecessor flight, columns *rot* and *prim* stand for actual rotation and primary delays. The first flight has a primary departure delay of 69 minutes due to weather conditions at the destination airport (IATA Delay Code 84). Additionally, the scheduled block time is exceeded by 23 minutes, resulting in an arrival delay of 92 minutes. 24 minutes can be absorbed during the following ground time. The turnaround is performed within 46 minutes, close to the minimum ground time of 45 minutes. Nevertheless, the second flight departs 68 minutes late and again experiences an increase of the scheduled block time duration (16 minutes).

The ground time between flight 2 and 3 does not contain any buffer time and takes 7 minutes more than scheduled. The initial delay can finally be absorbed prior to departure of flight 4. The aircraft spends 165 minutes on ground rather than the originally scheduled 255 minutes. The extended ground time prior to flight 5 is a result from the early arrival of flight 4. Eventually, flight 6 is severely delayed, awaiting a crew interchange (IATA Delay Code 95, *flight deck or entire crew*). Overall, a primary delay of 69 minutes in combination with additional 39 minutes of block time delay entails accumulated propagated delays of 159 minutes.

Table 2. Exemplary one-day rotation of an Airbus A321

O&D	*STD*	*ATD*	*STA*	*ATA*	*ΔGT*	*ΔBT*	*in*	*rot*	*prim*
S_1-H_1	06:00	07:09	07:10	08:42	-	23	14	0	69
H_1-S_2	08:20	09:28	09:15	10:39	-24	16	92	68	0
S_2-H_1	09:55	11:26	11:10	12:41	7	0	84	91	0
H_1-S_3	15:25	15:25	16:35	16:25	-91	-9	91	0	0
S_3-H_1	17:25	17:22	18:55	18:42	6	-10	-9	0	0
H_1-S_4	19:55	21:17	20:40	22:01	95	-1	-13	0	0

In the following, we examine the prediction accuracy of the delay propagation and absorption estimation by the presented propagation model. The key question is if operational propagation effects are sufficiently represented or if severe over- or underestimations become apparent. The estimated rotation delay $\hat{d}_f^r$ of flight f is computed as the difference between the arrival delay of the preceding flight (denoted as $inDLY$) and the scheduled buffer time:

$$\hat{d}_f^r = \max(\max(inDLY, 0) - (sgt - mgt), 0). \tag{12}$$

We validate the accuracy of the rotation delay estimation of the model for the 28,502 daily rotations of the A321 fleet in the data set. Each rotation consists of 4.86 daily flights on average. For 58.09% of the underlying 138,662 flights, the predecessor flight in the rotation arrives late so that a rotation delay may emerge. An average of 7.30 minutes of incoming arrival delay leads to 3.30 minutes of outgoing rotation delay which is an absorption rate of 45.24%.

Table 3 shows certain figures concerning the accuracy of rotation delay estimations for flights when the predecessor flight of the aircraft arrives at least one minute late. To compare, Table 4 shows the same values for flights whose aircraft predecessor flight arrives on-time. H1 and H2 stand for the two main hub airports, respectively, while S depicts all spoke airports. Furthermore, we differentiate between domestic (index *d*) and continental flights (index *c*).

Table 3. Estimated rotation delay when the preceding flight of the aircraft arrives late

	all	all_d	all_c	$H1_d$	$H1_c$	$H2_d$	$H2_c$	S_d	S_c
avg	-0.54	-0.49	-0.57	-0.42	-0.20	-0.07	-0.15	-0.78	-0.91
SD	3.51	2.87	3.81	2.98	3.00	2.47	2.27	2.93	4.43
±0 (%)	70.80	74.91	68.64	79.03	76.54	79.21	86.30	68.96	60.47
±5 (%)	90.30	92.67	89.05	92.49	92.45	94.88	97.15	91.71	85.49
$r\Delta_{ta}$ *(%)*	13.33	13.62	13.18	7.99	6.65	8.36	3.81	21.42	19.43
$a\Delta_{ta}$	-5.18	-4.58	-5.51	-4.65	-3.91	-3.69	-3.27	-4.73	-6.00

Table 4. Estimated rotation delay when the preceding flight of the aircraft arrives on-time

	all	all_d	all_c	$H1_d$	$H1_c$	$H2_d$	$H2_c$	S_d	S_c
avg	0.02	0.02	0.02	0.02	0.01	0.06	0.04	0.00	0.02
SD	0.44	0.45	0.43	0.41	0.38	0.76	0.77	0.17	0.41
±0 (%)	99.72	99.68	99.75	99.78	99.81	99.14	99.50	99.91	99.72
±5 (%)	99.87	99.86	99.87	99.85	99.88	99.66	99.77	99.98	99.88
$r\Delta_{ta}$ *(%)*	1.02	1.41	0.78	0.35	0.24	0.61	0.14	2.78	1.39
$a\Delta_{ta}$	-2.58	-2.42	-2.78	-2.07	-2.58	-2.16	-2.00	-2.49	-2.82

In a first step, we discuss the overall prediction accuracy. The first row depicts the average deviation between estimated rotation delay $\hat{d}_f^r$ and actual rotation delay d_f^r which is given in the data set. Throughout all categories, the value is negative, indicating a general overestimation of rotation delays by the model. For continental flights departing at spokes (column S_c), rotation delays are overestimated the most, while values are closest to zero for Hub 2. The rotation delay is estimated correctly on the precise minute for 70.8% of all flights. Overestimation emerges in 19.87%, underestimation in 9.33% of all cases. Best results can be obtained at Hub 2, followed by Hub 1. Obtaining a ±5 minute threshold, results are significantly better but still in the same order for all categories. This is a direct consequence of the fact that departure and arrival times are commonly scheduled in 5 minute intervals. In addition, delay recording at many spoke airports is performed within 5 minute steps.

Table 4 shows respective values for all turnarounds without an incoming arrival delay of the preceding flight. It allows counter-checking if rotation delays occur even when they are theoretically impossible. Slightly positive values in the first row are implied by 160 flights containing rotation delay records without a preceding late aircraft arrival. Apart from these obviously inconsistent records, no systematic falsifying effects become apparent.

Concerning the rotation delay overestimation of the propagation model for turnarounds with incoming arrival delays (Table 3), there are differences between actual operational turnaround durations and generalized *mgt* values. Target *mgt* times do not necessarily determine the operational turnaround duration and may already contain certain slack times as it has already become apparent in Section 3. Referring to this, the two bottom rows of Tables 3 and 4 depict

- $\boldsymbol{r}\Delta_{\boldsymbol{ta}}$ as the relative share of turnarounds that are performed in less than the minimum ground time $(agt < mgt)$ if a late aircraft arrival is likely to postpone the following flight departure, and
- $\boldsymbol{a}\Delta_{\boldsymbol{ta}}$ as the average of the absolute difference $(agt - mgt)$ in minutes.

The actual ground time falls below the minimum ground time at spoke airports significantly more often. Assumingly, this is due to conservatively scheduled *mgt* values at spoke airports since the lack of strong presence makes it harder for an airline to perform recovery actions in case of unscheduled events.

On the one hand, spare resources like reserve crews are mostly available at hubs rather than spokes, on the other hand less possibilities for aircraft swaps exist at spokes. The importance of this effect becomes apparent when comparing the results to corresponding values in Table 4. If an aircraft arrives late for the turnaround, it is thirteen times more likely that the turnaround is performed faster than scheduled.

Going into more detail, we check this mechanism by specifically considering data for the main Hub 1. Depending on the exact arrival delay of the aircraft predecessor flight, we examine if length and frequency of turnaround speed-ups change accordingly. Finally, we check the overall operational importance in terms of the total amount of delay savings.

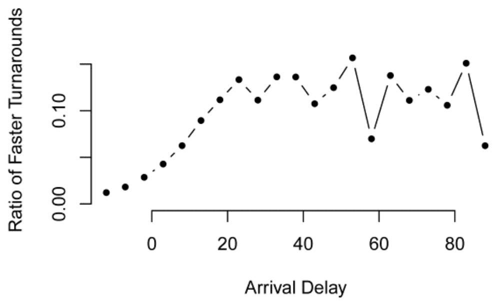

Figure 3. Ratio of turnarounds that are performed in less than minimum ground time

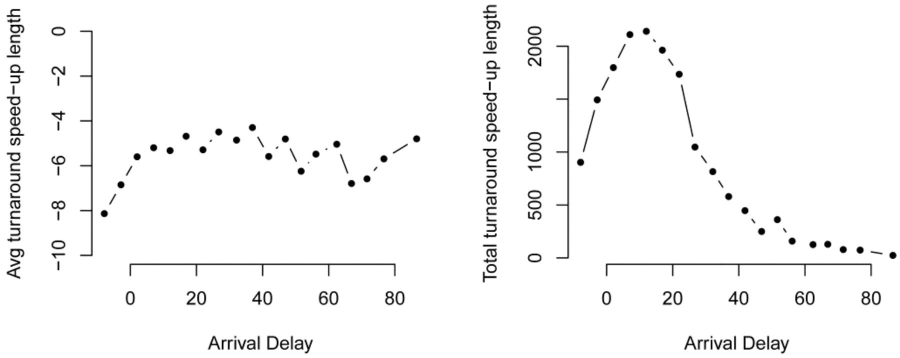

Figure 4. Operational emergence of turnarounds in less than the minimum ground time

For a start, the left panel of Figure 3 shows the ratio of turnarounds with $(agt < mgt)$ depending on the arrival delay of the aircraft predecessor flight. We use bins of 5 minutes for arrival delays up to 60 minutes. There is a substantial and steady increase of faster turnarounds until an arrival delay of 25 minutes. For larger arrival delays, inconclusive fluctuations at high levels can be observed.

In addition, the left panel of Figure 4 shows the average absolute difference $(agt - mgt)$ in minutes depending on the arrival delay. Values are in a constant interval, however, with considerable fluctuations. No relevant pattern can be observed. Finally, the right panel of Figure 4 is intended to indicate operational relevance of turnaround speed-ups. The y-axis shows the sum of absorbed arrival delay by turnaround speed-ups in minutes. It thus depends on both absolute turnaround speed-up and the occurrence frequency of certain arrival delay values. Most substantial savings are achieved for arrival delays between 0 and 25 minutes.

The dominant factor for the curve progression is that significantly large arrival delays are extremely rare and although turnarounds are performed faster in these cases, too, the operational relevance is minor in terms of a holistic assessment of rotation delays.

5 Conclusion

In the presented analysis, the assessment of the delay propagation model of [2] has been provided as a first step concerning the refinement of delay propagation mechanisms for a prototypical robust aircraft scheduling and simulation framework.

It has turned out that 70.8% of rotational delay propagation can be precisely estimated. Within a ±5 minute tolerance threshold, the estimation is correct for about 90.3% of all flights. The prediction provides best results for large hub airports with values up to 97.15% while at continental spokes only 85.49% can be reached. On average, rotation delays are overestimated by 0.54 minutes per flight. This value ranges from nearly 0 at Hub 2 to around 0.91 minutes at continental spoke airports.

A substantial responsibility for the overestimation of rotation delays lies in the fact that actual ground times sometimes fall below scheduled target minimum ground. It happens in 13.33% of all turnarounds when the aircraft arrives late. On average, 5.18 minutes of propagated delay can be saved in these cases. Deeper insight in the dependency between arrival delays and turnaround speed-ups shows that operational relevance is given for arrival delays between 1 and 25 minutes. In this range, delays are often overestimated by the propagation model in comparison to actual operations.

Future work has to deal with the incorporation of specific correction terms into the propagation model. Subsequently, the scheduling framework can be used to examine in how far refined delay propagation actually leads to an improved assessment of schedule robustness. Furthermore, it has to be evaluated if findings are comparable when crew-related propagation effects are considered additionally. Final results form the basis for the synchronization of assumptions on delay propagation in scheduling with the operational reality in practical robust resource scheduling.

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