

THE PROPAGATION OF AIR TRANSPORT DELAYS IN EUROPE

Paper based on correspondent thesis

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Abstract

This empirical study is concerned with the propagation of delays in European air traffic. The so-called 'reactionary' delays account for about 40 percent of all departure delays in Europe but, due to data limitations, most delay studies have traditionally focused on the analysis of primary delays at the departure airports. Using data collected by the Central Office for Delay Analysis (CODA), this study developed aircraft sequences in order to analyse the propagation of delays and to better understand the amplifying or mitigating factors.

Hub-and-spoke carriers tend to have a smaller level of propagation than point-to-point and low-cost carriers because they have a higher ability to absorb delay during the ground phases. On the other hand, low-cost operations absorb notably more delay in the block phase than the other operations.

Overall, the sequences of reactionary delays starting in the morning have a higher impact and magnitude than the ones starting in the afternoon as they propagate on average on more subsequent flight legs. However, the level of propagation in the afternoon appears to be higher which suggests that airline efforts to mitigate delay propagation are higher in the morning than in the afternoon. Moreover, the magnitude of sequences of reactionary delays after short delays is higher, because reactionary delays increase throughout the sequence due to further primary delays in block and ground phase.

Looking at major European hubs, it was observed that they affect daily 30 to 50 other airports, but in terms of reactionary delays they mostly affect their own operations. Aircraft returning to the hub after one flight leg arrive with up to 50 percent of the original departure delay when leaving the hub airport.

1. Introduction

Due to increasing air traffic and congested airports on-time performance of flights is challenged. Generally accepted KPIs for on-time performance are punctuality¹ and average delay minutes. Summarizing the costs of delays for airlines, two types have to be considered: Firstly, strategic costs caused by buffer time which is implemented in the schedule to absorb possible delay minutes. Secondly, tactical costs affecting airlines on the day of operation when dealing with the actual delay. The break-even point is reached where an additional buffer minute costs more than a delay minute. It is important to note that the impact on the entire network is mostly greater than the impact of the root delay itself.² The network average value of a delay of more than 15 minutes was estimated to about 77 Euros per minute.³ Considering that reactionary delays account for more than 40 percent of all departure delay minutes in Europe⁴, thus representing the “largest delay cause”⁵, it is surprising that research effort was limited in the past and mainly focused on primary delays. Consequently, it has been shown that airlines do not fully adjust their schedules to predictable delays.⁶

The aim of this study is to better understand processes of delay propagation and to identify mitigating and amplifying factors. The analysis is based on actual flight-by-flight data of 36 airlines which are classified in hub-and-spoke, point-to-point, and low-cost operations. For data consistency the geographical and temporal scope of this study is limited to the European Civil Aviation Conference (ECAC) area and two years (2007/08 IATA winter season to 2009 IATA summer season), respectively.

After a high level analysis of reactionary delays in Europe, indicators are defined to find out differences in airline business models and scheduling strategies. Following, sequences of aircraft rotations affected by reactionary delays are created and grouped by length and daytime of the root delay, and number of affected flights. Finally, delay propagation is look at from the airport point of view.

2. Data validation and processing

The data set used in this study mainly consists of the actual flight-by-flight data which is reported monthly to the Central Office for Delay Analysis (CODA) by over 100 airlines. Meanwhile data covers over 60 percent of all IFR flights in the ECAC area. The reported data include next to scheduled off- and on-block times and the actual OOOI-times⁷, the unique aircraft registration and up to five different IATA delay

¹ Proportion of flights delayed by more than 15 minutes compared to the published schedule

² Cf. Ahmad Beygi et al (2008) p.231

³ Cf. University of Westminster (2004) p. 100;

⁴ Cf. CODA (2009) p.36

⁵ Guest (2007) p.29; cf. CODA (2009) p.34

⁶ Cf. Mayer (2003) p.16

⁷ Out of the gate, Off the runway, On the runway, Into the gate

codes. This standard delay coding system was created by IATA to simplify and synchronize delay reporting and monitoring. It provides about 80 delay codes to specify the reason for a delayed departure, out of which only six are dedicated to better description of reactionary delays (Table 1).

IATA delay code	Definition
91	Awaiting load from another aircraft
92	Awaiting passengers and baggage from another aircraft
93	Late arrival of the aircraft previous flight
94	Awaiting cabin crew from another aircraft
95	Flight deck or entire crew from another flight (including Deadheading crew members)
96	Operations control: rerouting, diversion, consolidation, aircraft change for reasons other than technical

Table 1: IATA Codes for the classification of reactionary delay⁸

Delay code 93 describes the so-called rotational reactionary delays, which indicate reactionary delays on successive flights of the same aircraft (Figure 1, Aircraft 1). They are essential for the analysis of delay propagation within aircraft rotation sequences later on. All other reactionary delays are so-called non-rotational reactionary delays. Note that a non-rotational reactionary delay becomes a rotational reactionary delay when propagating to the following flight (Figure 1, Aircraft 2).

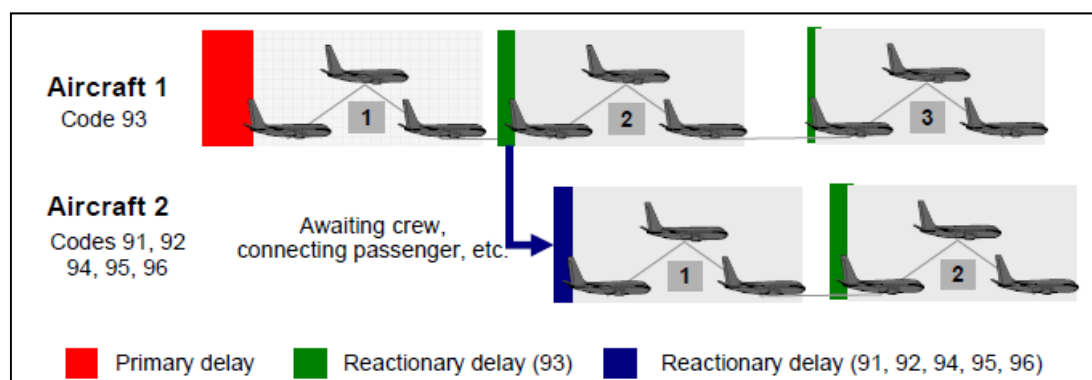


Figure 1: Delays propagating on successive flights of the same and other aircraft

The most important prerequisite of this study is the data processing and validation. The data provided by the airlines is cross-validated with data from the Central Flow Management Unit (CFMU) and the Central Route Charges Office (CRCO). This way information was double-checked, blanks filled in and errors solved.

After data validation, rotational sequences are built by linking individual flights through their unique aircraft registration over time. All flights for each unique aircraft registration are connected by date and time and by their ICAO airport designator. For

⁸ Cf. IATA Airport Handling Manual, 21st Edition (2001)

example, the arrival airport of one flight leg has to match with the departure airport on the subsequent flight leg and so on. As the sample relates to pan-European flights, most sequences start in the early morning and end at night. In the model of this study a sequence is not limited by a fixed daytime but by a pre-defined scheduled ground time⁹ (SGT) limit. Therefore the sequence of flights continues until there is either an error in the reported flight data or until the observed SGT exceeds the pre-defined, generally considered as sufficient, turn-around time. In order to account for the different aircraft sizes, the SGT limits are divided into four groups according to the median seat capacity, average observed SGT and expert judgment from EUROCONTROL staff working in this area. To include extreme cases of delay propagation, sequences do not end when a flight exceeds the SGT limit but reports a reactionary delay on the next flight leg.

3. High-level analysis

In order to get a general overview, firstly the different types of reactionary delays were looked at. It is observed that rotational reactionary delays (IATA delay code 93) account for almost 90 percent of all reactionary delays. Naturally, reactionary delays due to delay cause 91 or 92 (awaiting for load or passengers/baggage from another aircraft) as well as 94 and 95 (awaiting for crew) are mainly found in hub-and-spoke operations and almost never in low-cost operations. For the entire study daytime is grouped in “morning”, “afternoon” and “night”, lasting from 06:00 to 13:59 hours, 14:00 to 21:59 hours, and 22:00 to 05:59 hours, respectively. Most reactionary delay minutes (around 60 percent) occur irrespective of the type of operation in the afternoon, while the morning share reaches about 30 percent. During nighttime reactionary delays account for less than ten percent in hub-and-spoke and point-to-point operations, however around 20 percent in low-cost operations. The little share of non-rotational delays increase in the afternoon, indicating that airlines focus on schedule adherence in the morning and connectivity in the afternoon.

The sensitivity of airline business models (hub-and-spoke, point-to-point, low-cost) to primary delays can be measured using the reactionary/primary delay ratio.

$$Ratio = \frac{\sum \text{Reactionary delays}}{\sum \text{Primary delays}}$$

⁹ The SGT is the difference between the scheduled arrival time (STA) of the previous flight and the scheduled departure time (STD) of the subsequent flight.

The higher the ratio, the more sensitive is the operational system to primary delays and the more reactionary delay minutes are generated for each minute of primary delay. This draws a high-level picture of the impact and the importance of reactionary delays in European air traffic and reveals differences between the business models. In Figure 2 the average delay of delayed departures (ADDD) and the share of reactionary delay are illustrated by type of operation in summer 2008. The bottom part shows the percentage of delayed departures for each of the three different

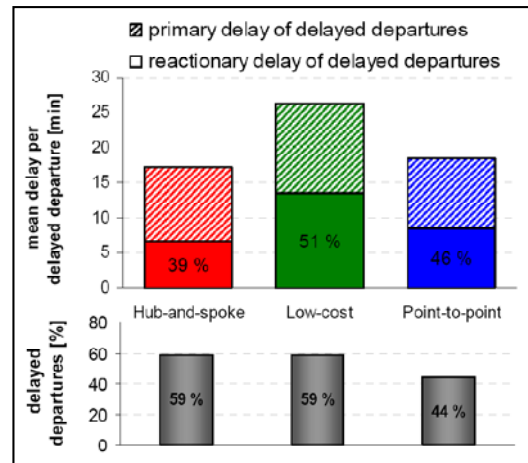


Figure 2: Share of reactionary delay by type of operation (Summer 2008)

airline business models. Note that for the purpose of this report, delays are counted from the first minute on. Of the three analysed airline business models, hub-and-spoke operations show with 17 minutes the lowest ADDD and also the lowest share of reactionary delay (7 minutes). Hence, the ratio is 39 percent. Low-cost operations have the highest ADDD (26 minutes) and also the highest share of reactionary delay (13 minutes). On average, every minute of primary delay generated more than one minute of reactionary delay for this type of business model.

The analysis of the ratio over the day revealed that reactionary delays overweigh primary delays later in the day. Thus, the ratio increases over the day and rises well above one in the afternoon.¹⁰

4. Analysing scheduling strategies

Following Key Performance Indicators (KPI) are used to measure and describe scheduling tactics concerning the propagation of delays.

Block-to-block phase related indicators

The block time is defined as the difference between the off-block (OUT) and the on-block (IN) time. A related indicator compares the actual to the scheduled block time irrespective of the flight's adherence to published schedule.

$$DDI - F = \text{actual block time} - \text{scheduled block time} \quad [\text{min}]$$

$$BTO = \frac{\text{Number of flights exceeding the scheduled block time}}{\text{Number of all flights}} \times 100 \quad [\%]$$

The **Delay Difference Indicator-Flight** (DDI-F) provides an order of magnitude of the deviation between the scheduled and the actual flown block times. The **Block**

¹⁰ Cf. also CODA (2009) p.37

Time Overshoot (BTO) is the share of flights exceeding the scheduled block time during a defined time period. It replenishes the DDI-F, so that both of them provide an overall picture of the block-to-block phase performance.

Results

A clear correlation between the two is observed. With a higher mean DDI-F, the number of flights exceeding the scheduled block time rises as well. Operational performance in the block-to-block phase varies among the analysed airlines, e.g. one hub-and-spoke carrier showed a comparatively low DDI-F of around minus 7,5 minutes and a BTO of only 17 percent while another carrier exceeded the scheduled block time by 3 minutes on average and up to 75 percent of the flights exceeded the scheduled block time.

On average low-cost airlines absorb some five minutes per flight, hub-and-spoke airlines three minutes, and point-to-point airlines only two minutes. Only a few airlines were observed actually generating delay as a result of insufficient scheduled block-to-block times.

In general, planning more block-to-block time than actually required indicates that a certain level of buffer time is included in the scheduled block-to-block times. However, the inclusion of buffer time in the block-to-block phase (DDI-F < 0) has also disadvantages as it reduces aircraft and crew efficiency. Crews are assigned to fly longer block times than they really do, which leads to additional costs due to slack time in the crew scheduling. Apart from this negative impact on airline efficiency, time buffers in scheduled block-to-block times result in a certain level of aircraft to arrive ahead of their scheduled times (“early arrivals”). This in turn may have an impact on airport operations as facilities and stands may not be readily available.

Looking at flight sequences, it was observed that carrier with no or positive DDI-F are likely to increase the number of delayed flights on arrival, or even double them during the first block phase. Whereas flights of airlines absorbing at least two minutes during the first block phase are clearly able to reduce the number of delayed flights.

Turn-around phase related indicators

The turn-around time is defined as the difference between the on-block (IN) and the off-block (OUT) time and is here also referred to as “ground time”. The indicators correspond to the ones for the block-to-block phase and are used to get a first understanding of whether an airline is able to stick to its scheduled ground time.

$$DDI - G = \text{actual ground time} - \text{scheduled ground time} \quad [min]$$

$$GTO = \frac{\text{Number of flights exceeding the scheduled ground time}}{\text{Number of all flights}} \times 100 \quad [\%]$$

The **Delay Difference Indicator – Ground** (DDI-G) provides an order of magnitude of the deviation between the scheduled and the actual observed turn-around times. The **Ground Time Overshoot** (GTO) is the share of flights exceeding the scheduled ground time during a defined time period. It is important to note that the DDI-G can

include additional time in both directions of the scheduled ground time: early arrivals are considered just like added delay during turn-around. In order to provide a deeper look at the turn-around process itself, the **Turn-around Delay Indicator (TDI)** was created. It equals the DDI-G but neutralizes early arrivals, i.e. the actual arrival time is set to the scheduled arrival in case of an early arrival. The complementary indicator is the **Turn-around Time Overshoot (TTO)**. The TDI and TTO demonstrate whether and how much delay is added during ground time in general.

However, for the analysis of the propagation of delays, the reaction following an inbound delay needs to be looked at individually. For this purpose the “**schedule padding-Ground**” (sched.pad-G) is introduced as another ‘IF-indicator’ of the DDI-G. The sched.pad.-G measures the deviation of the actual to the scheduled ground time, IF the aircraft arrived late. It seems similar to the TDI, but reveals slightly different information as it only includes delayed flights.

The **absorbed inbound delay (used buffer time)** is the last indicator for the evaluation of the performance in the ground-phase.

$$\text{Absorbed inbound delay} = \text{reported reactionary delay} - \text{inbound delay} \quad [\text{min}]$$

$$\forall \text{ inbound delay} > 0$$

This is an essential indicator because none of the previous indicators can make a distinction between reactionary and primary departure delays. Due to the reported IATA delay codes the length of the reactionary delay and the newly added primary delay during ground phase can be determined, i.e. how much of the inbound delay was absorbed during the turn-around phase.

Results

For almost all airlines the same relation is observed: the higher the DDI-G, the more flights stay longer on the ground than scheduled. It is striking that irrespective of the type of airline operation between 60 and 90 percent of all flights have a turn-around time longer than actually scheduled, e.g. around 70 percent of the hub-and-spoke operations exceed the scheduled ground time, leading to a mean DDI-G of almost plus five minutes.

However, the analysis of the TDI reveals information on early-arrival practices of airlines. It shows that between 10 and 50 percent of aircraft exceed the scheduled ground time because of new primary delay. In comparison, almost twice as many exceed the scheduled turn-around time because of a combination of an early arrival with a late departure. Considering the tight schedule of low-cost operators, it is not surprising that on average they exceed their scheduled turn-around times more often than the other types of operation, e.g. up to 46 percent of the analysed low-cost operations exceed their scheduled turn-around phase and consequently generated on average four minutes of delay. In comparison, hub-and-spoke operations add only around 1 minute.

In a next step the sched.pad-G is looked at. Following a late arrival the mean actual turn-around time varies from minus five to almost plus nine minutes from the scheduled turn-around time. Hub-and-spoke operations are on average able to reduce the inbound delay by one minute, point-to-point operators by more than two

minutes. As already indicated by the TDI, low-cost operators are not able to reduce inbound delays and even add more delay following an inbound delay.

Finally, due to the given reported reactionary delays the actual propagated reactionary delay can be identified and the absorbed inbound delay quantified. Figure 3 shows the relation between the average delay per delayed inbound (ADDI) on the horizontal axis, the mean absorbed inbound delay on the vertical axis and the mean reactionary delay of delayed departures on the subsequent flight (size of the bubbles).

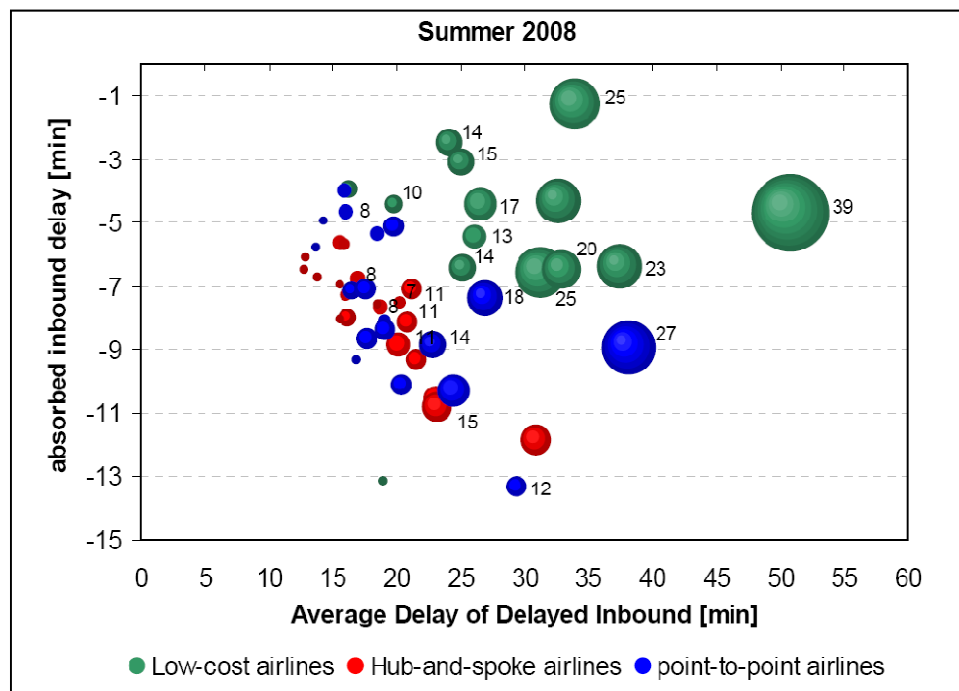


Figure 3: Relation between inbound-, absorbed inbound, and reactionary delays

The correlation between the ADDI and the absorbed inbound delay is evident. The more the bubbles are situated in the upper right corner of the chart – the bigger is the size of the bubbles, meaning the longer the average inbound delay and the shorter the absorbed inbound delay – the higher is the mean reactionary delay on the subsequent flight leg.

Albeit the analysis of sched.pad-G revealed that point-to-point operations show the highest ability to reduce inbound delay, Figure 3 shows that during turn-around phase point-to-point operators absorb actually just about as much as hub-and-spoke carriers. This is consistent with the slightly higher ratio of reactionary to primary delays of point-to-point operations (see Figure 2) and leads to the conclusion that point-to-point operators suffer less primary delay during the turn-around phase than hub-and-spoke operators.

Furthermore Figure 3 confirms that low-cost carriers have by far the highest ADDI and also absorb the least during ground phase (max. 7 min.). This leads inevitably to higher mean reactionary delays on the subsequent flight legs.

Allusively, the graph provides information about the turn-around performance in terms of additional aircraft suffering primary delay. For most of the airlines the mean

reactionary delay of delayed departures is smaller than the difference between the ADDI and the absorbed delay. This is due to the number of aircraft which were not delayed on arrival but added delay during the turn-around phase. They impact the average delay of delayed departures, thus the mean reactionary delay, but not the average delay of delayed inbound.

5. Sequential analysis of reactionary delays

The key factors for the analysis of sequences of reactionary delay need to link performance in the ground and block phase. Here it is crucial to differentiate between primary and reactionary delays.

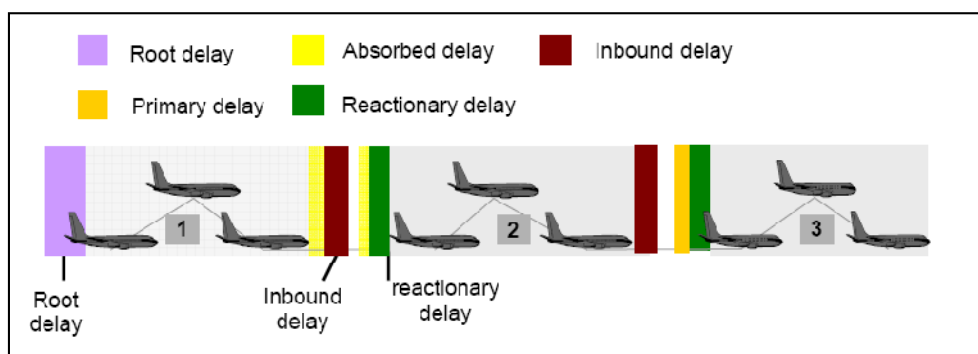


Figure 4: Sequential analysis of reactionary delays

Sequences generally start with a (primary) root delay, which then propagates along the subsequent flight legs. Figure 4 illustrates that parts of the original primary delay can be absorbed along the sequence but new primary delay may be added generating additional reactionary delay on the next flight leg. The key factors within sequences are therefore:

- Root delay
- Inbound delay
- Absorbed inbound delay (used buffer time)
- Additional primary delay
- Reactionary delay.

Firstly, the frequency and impact of sequences are described. Therefore sequences are separated by daytime and length of the root delay as well as depth (number of affected legs). Daytime again is divided into the three parts: morning, afternoon, and night (see section 3). The distribution of the sequences by frequency (number of sequences) and impact (accumulated reactionary delay minutes) grouped by airline business model for 2008 IATA summer season is shown in Figure 5.

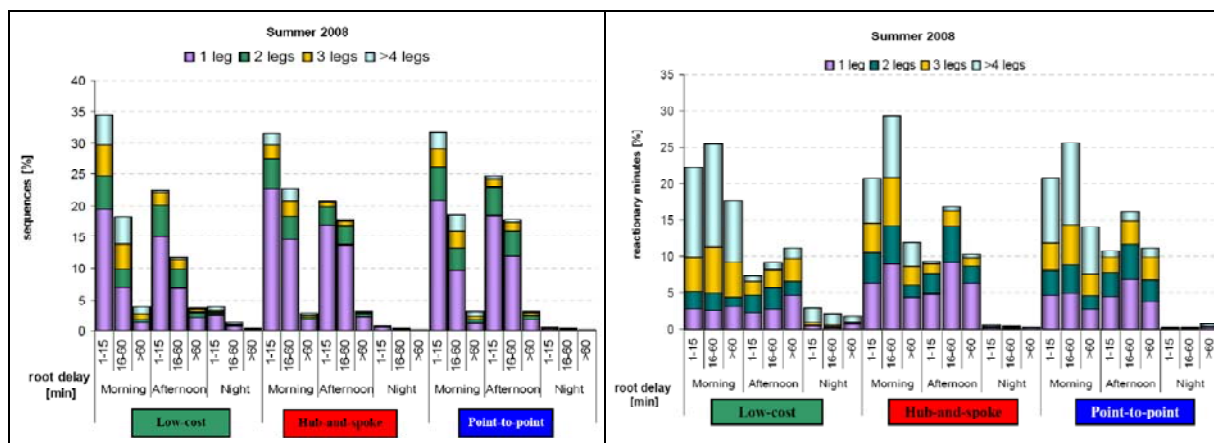


Figure 5: Sequences of reactionary delays by frequency (left) and impact (right)

In terms of frequency following can be observed (Figure 5, left chart):

- Nearly 35 percent of all sequences of low-cost operations had a root delay between one and 15 minutes and occurred in the morning. The main share (≈ 20 percent) of these root delays propagated only on one further flight leg.
- Irrespective of the airline business model, the time of the day and the length of the delay, the majority (50-60 percent) of the root delays are recovered within the first leg after the root delay.
- More sequences start in the morning than in the afternoon or at night. Especially sequences with short root delays (up to 15 minutes) occur more often in the morning.
- On average, sequences following morning-root delays show a higher depth, i.e. propagate on more subsequent legs.
- Also, low-cost and point-to-point operations have on average a higher depth than hub-and-spoke operations.
- Sequences starting at night time account for about five percent of low-cost operations, whereas they are barely seen among traditional scheduled flights.
- Root delays larger than 60 minutes play a minor role. They only account for six to eight percent of all sequences.

Difference between the occurrence and impact are evident (Figure 5, right chart):

- Sequences starting in the morning have the biggest impact in terms of reactionary delay minutes. This corresponds to the high number of sequences in the morning, which also propagate longer.
- Long sequences have a big impact, despite little frequency and/or little root delay.

Sequences in hub-and-spoke operations

Figure 6 illustrates sequences of reactionary delays with four affected flights following departure root delays between one and 15 minutes (first chart), 16-60 minutes (second chart), 61 to 120 minutes (third chart), and 121 to 180 minutes (bottom chart) in Summer 208 for hub-and-spoke operations.

The first column indicates the mean root delay. The other represent the mean inbound and departure delays of the four affected legs. The reactionary delay (green part) is logically what would have been the departure delay, if there was no additional primary delay. Therefore the difference between the inbound and the reactionary delay is what has been absorbed. The yellow fragment indicates the part of the absorbed inbound delay, which is replaced by a new primary delay. Together with the orange part, they symbolise the total new primary departure delay. The difference between the inbound delay and the departure delay visualizes what was previously called sched.pad-G. The DDI-F is the difference between the root or previous departure delay and the inbound delay. It is important to bear in mind, that the charts do not give information about the impact or frequency of these sequences. They only illustrate how, on average, the root delay propagates along the sequence. Note that sequences of reactionary delays can end because all root delay is absorbed or because the sequence of the aircraft ends.

The first chart in Figure 6 shows that after a short mean root delay of 9 minutes, aircraft add around 7 minutes during the first block phase, arriving with 16 minutes delay. During the first ground phase airlines seem not to react to the delay as they absorb only one minute and add more than ten minutes of primary delay. As the propagation goes on more delay is absorbed during ground and block phase. The increase of the reactionary delay is caused by the additional primary delays, especially during the first ground phase. Sequences in the second graph of Figure 6 suffer a mean root delay of 32 minutes. Again aircraft are not able to absorb any delay during the first two block phases and more primary delay is added during the ground phases. It appears that airlines only start to really reduce departure delay when a certain level of around 40 minutes is reached. The mean

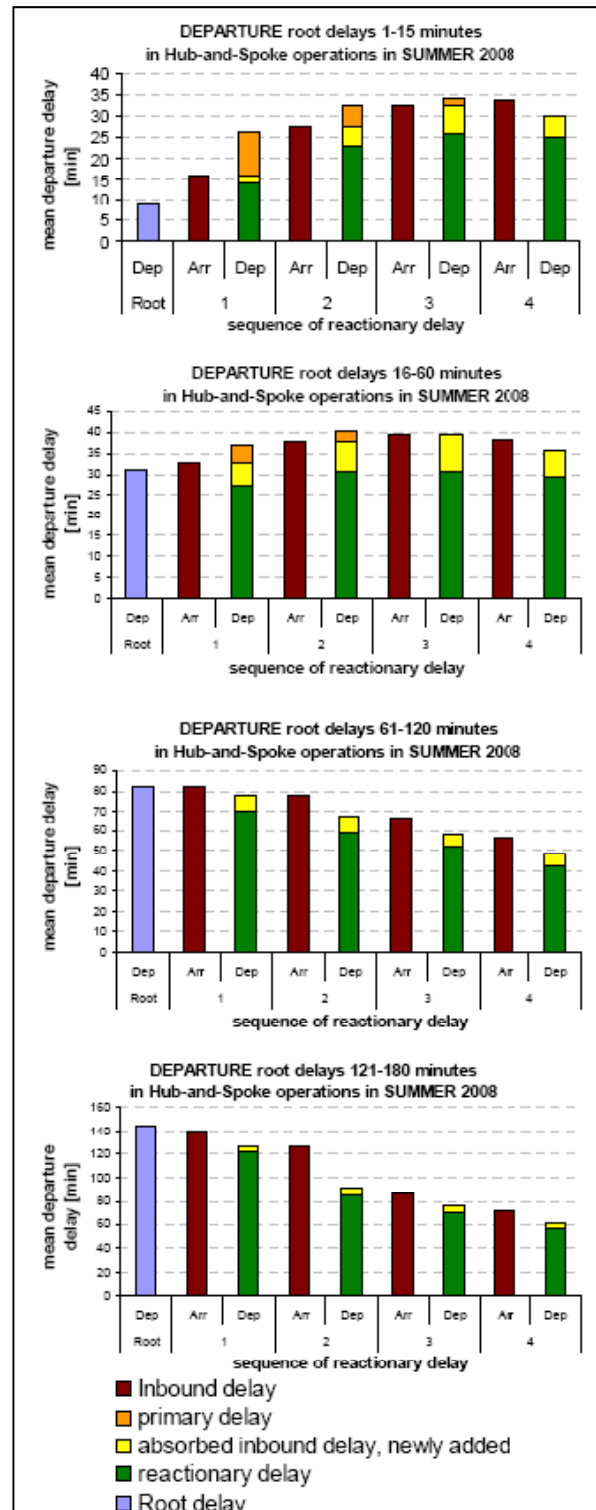


Figure 6: Hub-and-spoke sequences with different root delays

root delay of the third graph equals 81 minutes. The difference to the previous charts is obvious. Airlines start to absorb the delay right away (fewer minutes during block phase and more during the ground phase). They are able to mitigate the root delay despite additional primary delay (yellow parts). Sequences with root delays between 121 and 180 minutes show the actual potential of hub-and-spoke operators to absorb delay. The mean departure delay can be reduced from 144 to only 61 minutes. It seems that the higher the average delay, the more are airlines able to avoid further primary delay, and the more they are able to absorb existing delay.

Following, Figure 7 evaluates the depth of sequences of hub-and-spoke carriers with a root delay between 16 and 60 minutes in summer 2008. As illustrated in Figure 5, this group has the highest impact in terms of reactionary delay minutes. Apparently, when delay propagates on one further leg, only a small amount of delay is absorbed during the block and the turn-around phase. The aircraft departs with 25 minutes of delay, of which 20 minutes are propagated. When the root delay propagates for two legs, the root delay cannot be reduced during the first block-phase. During the first turn-around phase, about seven minutes are absorbed but twice as many minutes added in comparison with sequences with only one affected flight. During the second turn-around phase more than nine minutes are absorbed, leading to 22 minutes of reactionary delay of 29 minutes of total departure delay. The third chart in Figure 7 shows, that reactionary delays account for about 26 minutes on all three affected legs. The new primary delay offsets the delay which is absorbed during turn-around. The small differences between the mean root delays suggest that the depth of a sequence is not necessarily linked to the initial root delay. Although there is no obvious link, longer sequences show a slightly higher mean reactionary delay from the first ground phase onwards. Consequently, the depth of these sequences is strongly correlated with the addition of new primary delay.

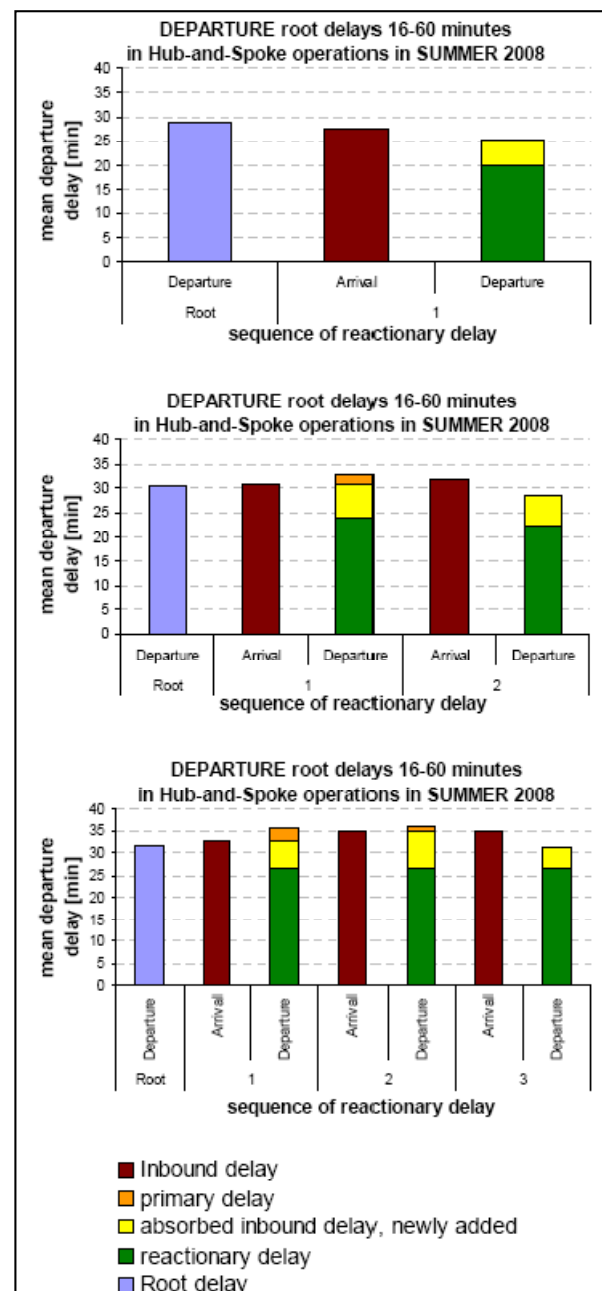


Figure 7: Different depths of hub-and-spoke sequences

Sequences in low-cost operations

The first chart in Figure 8 describes that even low-cost airlines with a mean DDI-F of around minus five minutes add delay during the block phase after short root delays. Furthermore Figure 8 shows that the delay propagation in low-cost operations is predominantly driven by long root delays and additional primary delays. Low-cost operators absorb almost no delay during the turn-around phase, but up to 10 minutes during the block phase, which confirms the results of the DDI-F (section 4). The mean sched.pad.-G of low-cost airlines is positive and indicates a too optimistic ground time scheduling. Note, that reactionary delay increases with every affected leg following a root delay of less than 61 minutes. However, within sequences following root delays of more than two hours, aircraft finally absorb delay in the turn-around phase and do not add further primary delay.

As low-cost operations show a different pattern of delay propagation, Figure 9 illustrates sequences with a root delay of 16 to 60 minutes and different depths for low-cost operations. The first chart suggests that the delay propagation on only one subsequent leg is not due to a decrease in departure delay. The same pattern is seen for all different depths of reactionary delay sequences. Low-cost operators absorb more delay in block-time than in the turn-around phase, in which they on average add around eight minutes of primary delay. Longer sequences generally start with a higher level of reactionary delay on the first affected flight leg. It can be seen, that reactionary delay increases with every affected leg because of the newly added primary delay during every additional turn-around phase and the inability to absorb inbound delay. 78 percent of the analysed sequences with three affected legs and a root delay between 16 and 60

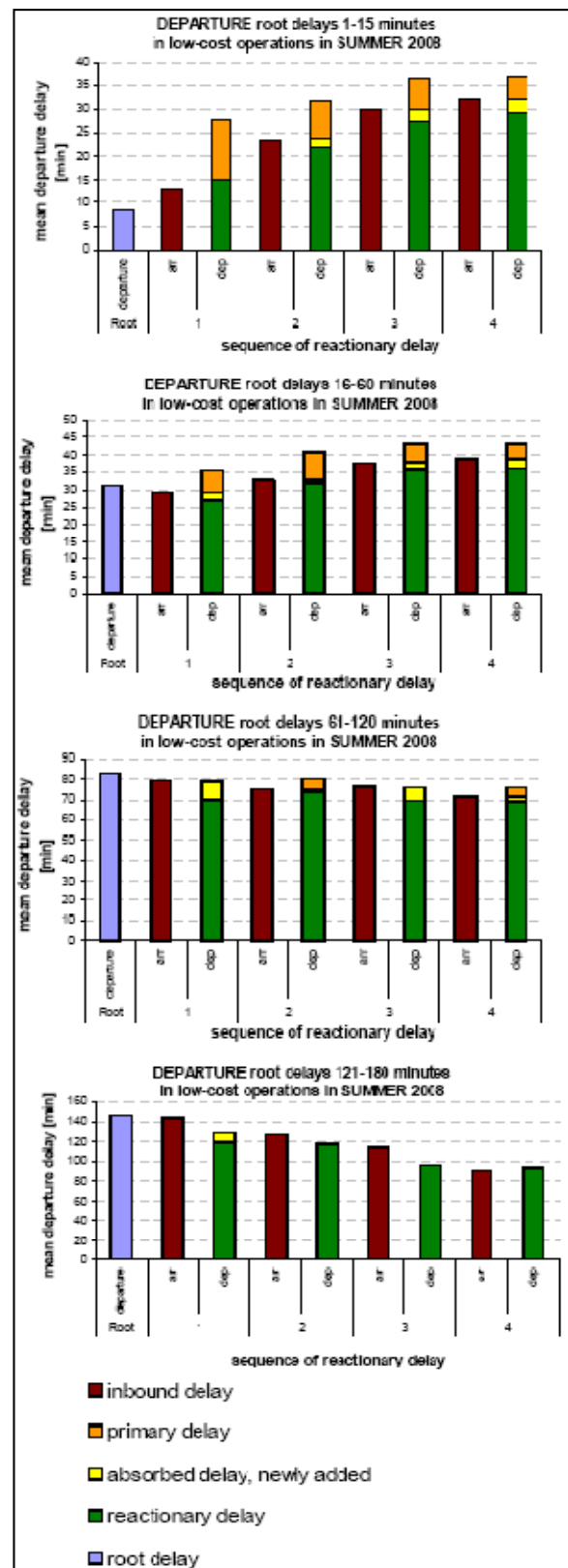


Figure 8: Low-cost sequences with different root delays

minutes end only when the actual rotational sequence ends, usually at the end of the operational day. For longer root delays, less than 20 percent of aircraft can recover within the aircraft actual sequence.

Sequences in point-to-point operations

Point-to-point operations show a similar pattern within sequences of reactionary delays as hub-and-spoke operations. Therefore results are briefly summarized without presenting the corresponding charts.

- Short root delays (1-15 min.) rise significantly due to a positive DDI-F and new primary delay during the first turn-around phase.
- Generally, point-to-point operations absorb the least delay minutes during the block-to-block phase.
- Although on average point-to-point and hub-and-spoke operations absorb about the same amount of minutes during turn-around (Figure 3), point-to-point operations are not able to absorb as many minutes during a single turn-around phase. For instance, after a 144 minute root delay, hub-and-spoke operators manage to reduce the delay after the fourth leg to 60 minutes, while point-to-point operators absorb almost 20 minutes less.
- Notably smaller yellow and orange parts of the columns suggest that overall point-to-point operators do not add as much primary delay in the turn-around phase as hub-and-spoke operators.
- However, point-to-point operations react quite sensitive to primary delay. The limited ability to absorb delay, in the turn-around and block-to-block phase, puts more weight on additional delay.

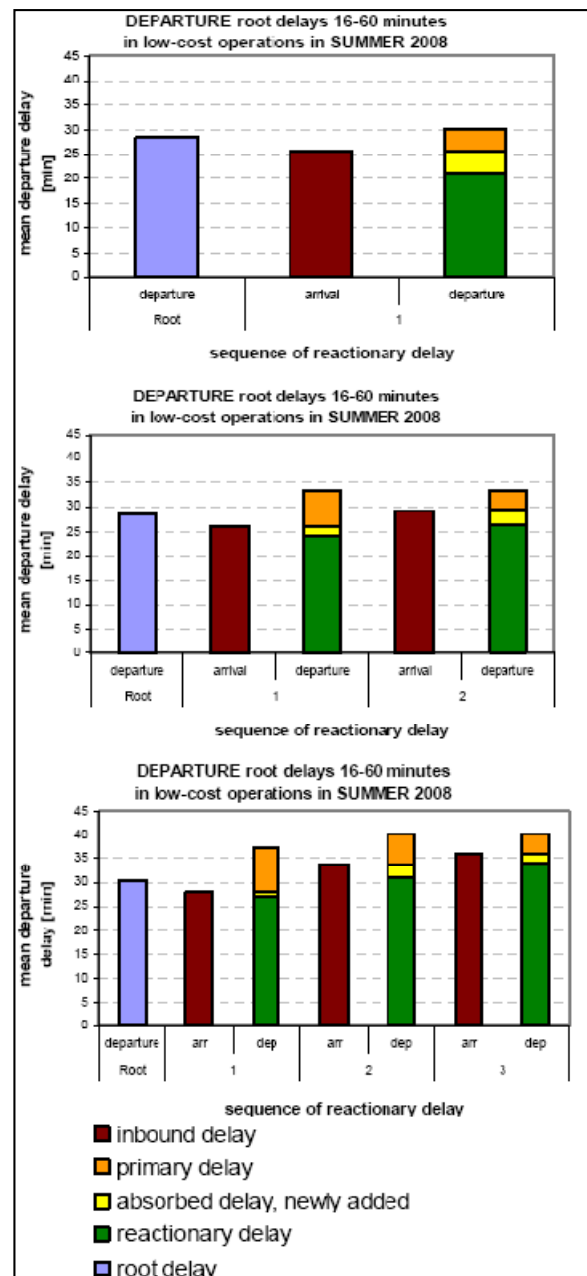


Figure 9: Different depth of low-cost sequences

Differences of sequences by time of the day

As an example, differences in sequences that start in the morning (6:00h-13:59h local time) and in the afternoon (14:00h-21:59h local time) are looked at. Due to the

small number of flights, the night time was not evaluated in more detail. Figure 10 illustrate sequences of hub-and-spoke operations for root delays between 16 and 60 minutes.

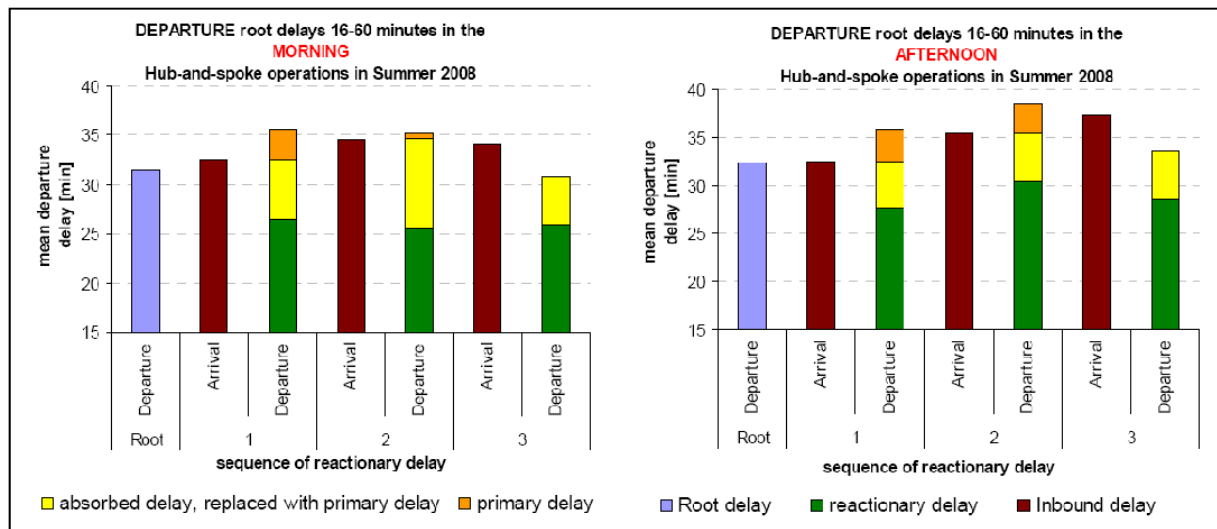


Figure 10: Comparison of morning- and afternoon sequences

It shows that the mean root delay is similar in the morning and in the afternoon. Although there is a little less primary delay (yellow and orange) during the turn-around phase in the afternoon, the mean departure delay is higher. The difference results mainly from fewer absorbed delay minutes, especially in the turn-around phase. This indicates that the increasing ratio in the afternoon (see section 3) is not only the result of ongoing delay propagation from root delays in the morning, but also from a higher level of delay propagation on 'afternoon-sequences'. It confirms that airlines appear to be focusing on punctuality in the morning while they focus on connectivity in the afternoon.

It was observed that generally all three types of operation do not absorb as much inbound delay in the afternoon.

6. Magnitude and depth of sequences affected by reactionary delay

This section analyses the magnitude and the depth (number of affected legs) of sequences of reactionary delay. The magnitude is defined as the relation of all reactionary delays following one root delay to the root delay itself. An important issue to point for the interpretation of the magnitude is its sensitivity to the length of the root delay and to the depth of the sequence.

Figure 11 provides an overview of the mean magnitudes for root delays, depending on the daytime and length of the root delay, in combination with the mean depth of the sequence. Different from Figure 5, which shows the impact in terms of percentage of all reactionary delay minutes, the magnitude is independent of the frequency of the root delay. However, it is influenced by the frequency of the various depths.

The magnitude shows a clear peak for root delays between one and 15 minutes. In the morning it decreases with longer root delays, whereas in the afternoon it stays quite constant for root delays longer than 16 minutes.

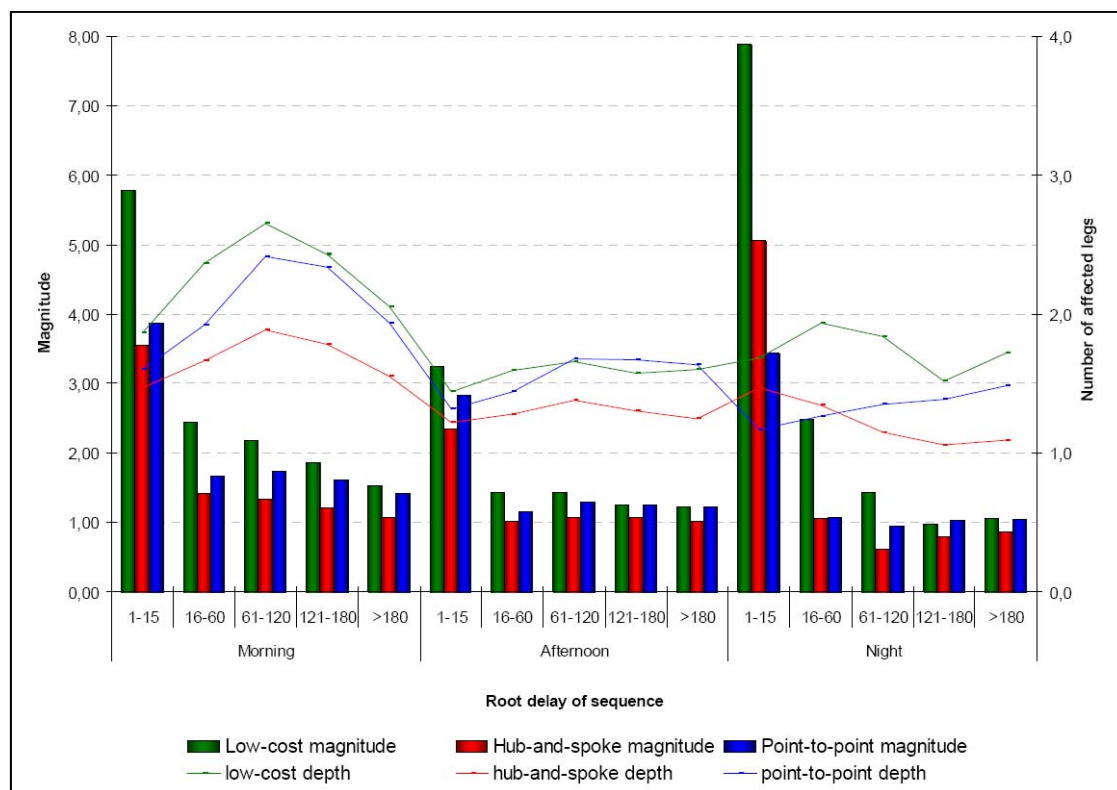


Figure 11: Mean magnitude and depth of different root delays

In the morning the magnitude is generally higher and the sequences are generally longer –rising to even 2,7 legs in low-cost operations. Depth and magnitude of the sequences for root delays over 15 minutes are quite constant in the afternoon.

In Figure 5 it was demonstrated that the impact of sequences starting in the afternoon is lower due to the lower number of rotational frequencies. Figure 11 confirms that sequences are on average shorter in the afternoon, and therefore have a lower impact in terms of magnitude. However, Figure 10 indicates that despite the lower overall impact, the level of delay propagation is higher in the afternoon, thus lifting the magnitude.

Due to the small number of flights, the magnitude for flights during night time is artificially high and should be viewed with a note of caution.

It is also interesting to note that ‘morning-sequences’ with a root delay between 61-120 minutes show the highest mean depth.

Overall, hub-and-spoke operators show the lowest depth and magnitude. In terms of ranking between the three business models, the magnitude reflects the ratio of reactionary to primary delay, analysed in Figure 2. Low-cost operators show a surprisingly high magnitude for short root delays, especially in the morning (5.8). This supports the previous observation that low-cost carriers have a limited scope to absorb delay and are in fact more likely to add new primary delay in the turn-around phase.

In the analysis of hub-and-spoke sequences, it was suggested that the higher the actual level of delay, the more delay can be absorbed and the fewer new primary delay is added. This is also reflected in the 'morning-magnitude' in Figure 11. The magnitude drops although root delay and depth increase. This confirms that the delay propagation is significantly lower on flights with relatively long root delays.

7. Reactionary delays at European airports

Taking the airports point of view, Figure 12 shows the reactionary to primary delay ratio for six major European airports. All other airports are grouped within 'others'. Due to airline data confidentiality reasons, airports are dis-identified, as most of the airports have only one major carrier serving the airport.

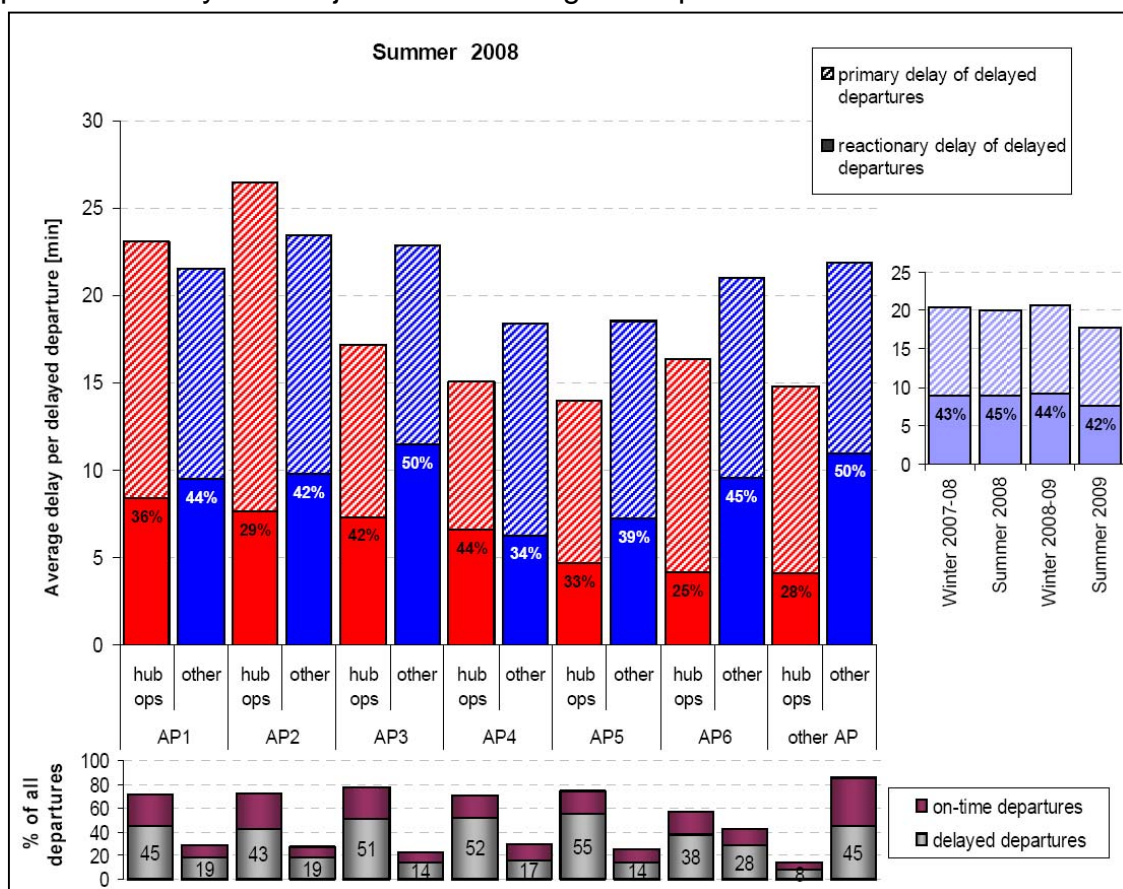


Figure 12: Reactionary delays at European airports

While the top of Figure 12 relates to the distribution of the average delay on delayed departures (ADDD), the bottom part shows the traffic distribution and the actual share of traffic for which a departure delay was reported (grey part). The delay distribution enables a distinction between hub-and-spoke operations (red columns) and other operations (blue columns) and between reactionary (solid colour) and primary delay (diagonal lines). The small chart on the right side shows that the ratio between reactionary and primary delays does not vary significantly over the four analysed seasons.

The ADDD and the reactionary to primary delay ratio vary considerably among airports. The six major hubs are sorted by the length of the mean reactionary delay of hub-operations. AP1 has with 8,4 minutes the highest mean reactionary delay and AP 6 with 4,1 minutes the lowest level of reactionary delay of the analysed airports.

With the exception of AP1 and AP2, the ADDD and the mean reactionary delay (except for AP4) are lower for hub-and-spoke operations. The share of reactionary delay for non-hub operations ranges between 34 and 50 percent and is considerably higher than for hub-operations.

It should be noted that, with the exception of other airports, the share of hub-and-spoke operations outweighs the share of other operations (bottom chart, Figure 12). Consequently, and despite the mostly lower ADDD, hub-and-spoke operations have a considerably higher overall impact on the operations at the analysed hub-airports.

Mean daily impact of an airport

Following, the average daily impact of selected European Hubs - on themselves and on other airports - is shown.

In terms of quantity of affected airports, it is observed that root delays originating from major European hubs daily affect on average between 30 and 50 other airports within the ECAC area.

In terms of reactionary delay minutes, the average daily impact of a root delay originating at the respective airport is determined as illustrated in Figure 13. The first airport is affected by all reported reactionary delay minutes. For the second and third airport in the sequence, the impact is calculated as the minimum of either the reported reactionary delay at departure airport of the inbound flight, the inbound arrival delay or the reported reactionary delay on the subsequent outbound flight leg.

Below, Figure 14 shows the mean daily impact on themselves and on other airports

of root delays originating at the respective airport. It can be seen that major hubs affect their own operations more than other airports because a large number of aircraft return several times during the day to their hub airports. Within this analysis secondary and other hubs, not included in the list of hub airports, are grouped together as “secondary airports”. All other ECAC airports were grouped as “Other”.

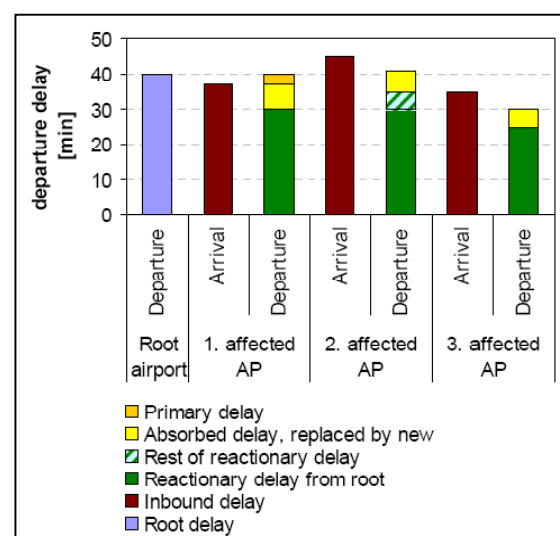


Figure 13: Calculating the original propagating delay minutes

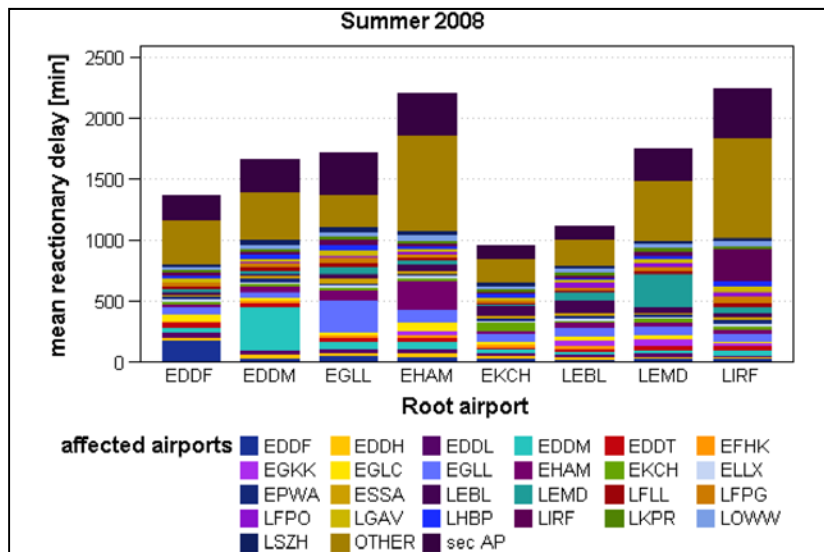


Figure 14: Mean daily impact of an airport by reactionary delay minutes

On average, almost 6 hours of the reactionary delay reported at Munich airport (EDDM) originates from root delays at Munich airport. At Amsterdam airport (EHAM) almost 4 hours of the reactionary delay reported at the airport is generated by root delays originating at Amsterdam airport. Additionally Amsterdam airport shows a notable impact on London Heathrow (EGLL) and London City airport (EGLC). It should be noted that these figures are for illustration only as they relate only to the validated sample used for the analysis and not to all flights at the airport.

In order to take a closer look at the impact an airport on its own operations, a new set of sequences was created. The new data set includes only flights between the analysed airport and one other airport (i.e. every second leg is by definition the analysed hub airport). It turned out that the share of delay returning to the origin airport varies between 20 percent for Zurich-Kloten (LSZH) to 56 percent for London-Gatwick (EGKK). In absolute terms, the average minutes of delay returned to the origin airport range from three minutes at Zurich Kloten (LSZH) to 12 minutes at Rome-Fiumicino (LIRF) airport. For Frankfurt (EDDF), London Heathrow (EGLL) and Copenhagen (EKCH) a notable difference between the reviewed summer and winter seasons can be observed, as the departure delays and the returning-share are higher in wintertime (~10%).

8. Conclusion

The results of this study provide a general overview of the current situation of delay propagation. The findings foster airline and airport planning in order to achieve a higher level of resilience towards predictable and unpredictable primary delays. Furthermore, the findings aim at providing more detailed insights on delay propagation, which can be useful for macroscopic analyses and simulations. Following main results are summarized:

- Overall, almost half of the departure delay is due to reactionary delays.
- The share of reactionary delays increases over the day and overweighs primary delays in the afternoon.

The propagation of air transport delays in Europe

- On average, the DDI-F is negative, i.e. buffer time is included in the scheduled block-to-block phase. However, following short root delays further delay is added during the first block-to-block phase.
- The majority (50-60 percent) of root delays can be recovered within the first leg following the root delay.
- The highest frequency show sequences following short root delays (1-15 min.), the highest impact in terms of reactionary delays are observed for root delays between 16 and 60 minutes.
- Sequences starting in the morning have the most severe impact on reactionary delays and account for about 60-65 percent of all sequences.
- In the morning, the magnitude of root delays decreases although depth and root delay increase (up to root delays of 120 min.). This reflects that within sequences of smaller root delays, a higher level of propagation and increasing reactionary delays are observed. Hence, following longer (root) delays, aircraft absorb more and suffer less primary delays, decreasing the reactionary delay of subsequent legs as well as the magnitude.
- Aircraft absorb less delay during the turn-around phase in the afternoon than they absorb in the morning. The level of newly added primary delay stays relatively constant.
- Due to a lower mean depth of sequences in the afternoon, the magnitude is lower than in the morning. However, the level of delay propagation is higher in the afternoon.

Differences between the three analysed types of operation:

- Within hub-and-spoke operations sequences following shorter root delays are likely to add new primary delay on subsequent flight legs. This increases the overall level of reactionary delay. The response to longer root delays (>120 min.) is different. Aircraft are able to absorb a significant amount of delay in each turn-around phase and manage to avoid additional primary delays which results in a considerable reduction of the overall reactionary delay on each of the subsequent flight legs.
- Low-cost carriers are generally able to absorb more delay in the block-to-block phase and only a limited amount in the turn-around phase in comparison to the other types of operation. This makes them very sensitive to primary delays, so that reactionary delays tend to increase throughout the reactionary delay sequence. Thus, only a small share of sequences with reactionary delays is able to recover within a rotational sequence of the aircraft.
- Although point-to-point operators show a similar mean value for the absorbed inbound delay as hub-and-spoke operators, they propagate a higher share of long inbound delays and are therefore also very sensitive to primary delays.

The analysis of major European airports demonstrates the following:

- Propagation is stronger in non-hub operations where reactionary delays account for up to 50 percent of total reported delays.

- The share of reactionary delays on hub-and-spoke operations was generally lower at the analysed hub airports and accounted for up to 35 percent of all reported delays. Therefore, primary delays at a hub airport have a large impact on the subsequent legs of hub-and-spoke operations.
- Root delays at hub-airports typically affect about 30 to 50 other airports.
- The largest impact of root delays originating from a respective airport is on the hub airport itself as flights return usually several times during the day. On flights only operating between the analysed hub airport and another airport, between 30 and 50 percent of the delay originating from the hub airport is returned to the same airport on successive flight legs.

In conclusion, this study can be used as a sound basis for further research concerning this interrelated complex issue of delay propagation. As a follow on to this study, various IF-cases could be tracked and analysed with the created sequences of reactionary delays, e.g. the impact of EC regulation No. 261/2004 regarding denied-boarding compensation, detailed peak analysis at major airports etc..

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