Quality of hub-and-spoke networks; the effects of timetable co-ordination on waiting time and rescheduling time

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Abstract

Low frequencies of aircraft may have substantial negative effects on scheduling costs and waiting costs at hub airports. Appropriate timetabling of carriers will reduce these costs. In this paper we propose a measure for the quality of the co-ordination of timetables by carriers in hub airports. An application is given for four large European airports. We find that large airports such as London Heathrow and Paris Charles de Gaulle have longer waiting times than the smaller airports Frankfurt and Schiphol even though one would expect shorter waiting times given the higher frequencies of service. The reason is that the flight co-ordination is less efficient and this is clearly reflected by the values of the flight co-ordination coefficient developed in this paper. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Hub-and-spoke networks enable carriers to supply transport services to many combinations of origins and destinations at high frequencies and low costs. The disadvantage for the traveller is of course that she/he may have to make a detour via the hub airport implying an extra stop. For many combinations of origin and destination, travellers can choose between more than one main carrier and/or airport. Competition between carriers serving passengers travelling from A to B via a hub airport takes place by means of frequency, ticket prices, and quality aspects such as reliability and safety (see, for example, Bruinsma et al., 2000). However, frequency alone does not explain total travel costs. Even with high frequencies a bad co-ordination of flight schedules may leave the transfer passenger with long waiting times at airports, or high rescheduling costs at the origin or destination.

In the present paper we address two specific issues of competition between hub airports, i.e. the roles of waiting time at the airport and of rescheduling time at the place of origin and destination. Rescheduling is caused by the fact that with scheduled services one cannot depart or arrive at the desired time. Rescheduling takes place at the place of origin, and/or destination. Waiting takes place at hub airport when there is no seamless connection between the services provided on the links to and from hub airports.

We will use a simple model of rescheduling and waiting in the context of flights taking place via a hub. Given the frequencies on the two legs of the connections, we demonstrate that rescheduling time typically depends on the frequency of the low frequency leg, whereas the waiting time is ultimately determined by the high frequency leg.

Higher frequencies obviously help to reduce waiting time at airports. However, waiting times do not only depend on frequency per se but also on the way departure and arrival times of flights are co-ordinated and on minimal connecting times (see Dennis, 1998). In Section 3 we propose a coefficient to measure this degree of co-ordination. By an inefficient co-ordination of timetables a large airport may arrive at waiting times that are not better than those of smaller airports. Indeed, in congested airports with high frequencies, airlines may find it difficult to realise the appropriate times of arrival and departure.

One should be aware that timetables of carriers result from a large number of considerations and operational constraints. In our analysis we restrict our attention to the question to what extent the time tabling leads to...
short waiting times at airports. In addition some attention will be paid to rescheduling times.

2. Rescheduling time and waiting time

Consider a trip between A and B via a hub airport H. The consumer's evaluation of this trip depends on factors such as the ticket price, comfort levels in planes and at airports, travel time, reliability and local accessibility of airports. The roles of the ticket price and total travel time have been analysed in Bruinsma et al. (2000) for intercontinental trips with European cities as an origin.

In the present paper we give a more detailed analysis of total travel time. The following aspects of total travel time can be distinguished:

- travelling from home to airport A;
- flying time from A to H;
- transfer time at H;
- flying time from H to B;
- travelling from B to final destination;
- rescheduling time at A and/or B.

In our analysis we will not pay attention to local transport times to and from airports and flying time components. The first factor depends on the location and accessibility of the airports within the regions they are serving. The role of these factors has been studied among others by Pels (2000). The second factor is determined among others by aircraft technology, rules of air traffic control, slacks in schedules planned by airlines to avoid delays, congestion on airways and airports, the location of the hub airport in an international setting, etc. For example, Dennis (1998) has analysed the detours involved in using various hub airports. He finds that within Europe the smallest detours occur when Brussels is used as a hub airport. The choice for hub airports in Amsterdam, Frankfurt, London and Paris would lead to an increase in total passenger kilometres of 2–12 per cent.

We will focus on the two remaining factors, i.e., transfer time and rescheduling time. We will demonstrate in Sections 2.1 and 2.2 that both depend on frequencies of flights. When we consider a connection with two legs, the transfer time depends on the frequency at the most frequent leg, whilst the rescheduling time depends on the frequency at the least frequent leg.

2.1. Rescheduling time

Rescheduling means that passengers cannot realise their desired time of departure and/or arrival because of the low frequencies of the services. The actual time of departure and arrival will differ from the desired levels. This implies that the traveller faces various problems before and after his trip.

Before the trip the traveller can choose between:

- interrupting an activity: he cannot complete an activity before the trip at the desired time;
- cancelling a desired activity: because an activity cannot be completed, it is cancelled leading to a choice for a less desired activity such as waiting.

After the trip the traveller can choose between:

- coming late: he does not start the activity at the desired time implying a loss of utility of the activity;
- waiting: he cannot immediately start the activity he most prefers and has to fill his time with another activity.

Activities can be distinguished between scheduled and non-scheduled ones. For example, a meeting can be conceived of as a scheduled activity with fixed times for starting and ending. Watching a video is a non-scheduled activity that is not linked to particular times.

In the case of non-scheduled activities a change in their duration only leads to a change in utility related to their duration (for example leisure time is traded off against waiting time). In the case of scheduled activities it is not so much the duration of the activity that matters but the frictions between actual and scheduled start or end times.

To make the analysis tractable we start with the assumption that rescheduling costs only take place at the activity side. For example, somebody who leaves home early to catch a plane so that he arrives in time (for example implying that he arrives 2 h early) is assumed to have rescheduling costs only at the destination side. At the origin side there are only time costs in the sense that there is less time for leisure or sleep.

Total time costs of travelling cut consist of the costs of travel time plus the costs of rescheduling. The travel time consists of three elements: $t_{AH}$, $t_{H}$ and $t_{HB}$, representing travel time from A to H, waiting time at H, and travel time from H to B, respectively. We assume here that the traveller has equal valuations of the costs per unit time for waiting at H and sitting in the plane.\(^2\)

Let $a$ be the cost of travel time per time unit and $c_r$ the rescheduling costs, then

$$ct = a[t_{AH} + t_H + t_{HB}] + cr.$$  

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1. In reality there are also semi-scheduled activities with less rigid start and end times.

2. For most transport modes one finds that the perceived costs of waiting at transport nodes are higher than those of the in-vehicle time (see Small, 1992). For aviation this may not necessarily be the case. This depends on the quality of the airport infrastructure and services (Doganis, 1992). A specific reason why waiting at transport nodes may be valued negatively is that in the case of unreliability of services the traveller does not know when the next flight will leave. In the present paper we ignore these reliability aspects.
For the costs of rescheduling two regimes can be distinguished: there is a possibility of being late, and a possibility of being early. Let \( v^* \) be the desired arrival time and \( v \) be the actual arrival time. Then we have

\[
\text{cr} = b + d(v - v^*), \quad v > v^* \quad \text{regime 1},
\]

\[
\text{cr} = e(v^* - v), \quad v \leq v^* \quad \text{regime 2}. \tag{2}
\]

Assume that the value of \( b \) is very high: the costs of coming late are so high that the traveller always decides to arrive early. This means that regime 1 can be excluded. Then the costs of rescheduling are simply equal to the costs of waiting time at the destination until the desired time of arrival \( v^* \). In this context rescheduling means that the traveller has to substitute leisure time at the origin for waiting time at the destination. The term ‘waiting’ at the destination is used to reflect that the traveller will arrive earlier than the preferred time of arrival \( v^* \) (for example the start of a business meeting).

Travellers will try making the best of the scheduling problem by using the ‘waiting’ time in some productive or pleasant way. Note also that when the aim of the trip is an unscheduled activity \((b, d, e = 0)\), the notion of rescheduling costs is no longer relevant so that the only remaining aspect is the waiting time at airports. The valuation of the change in the time schedule (more waiting time at the destination versus less leisure time at the origin) depends strongly on the attractiveness of the ‘waiting’ at the destination. When there is no meaningful use of the time at the destination, waiting time can just be interpreted as transport time: comfort levels being equal there is not much difference between sitting in a plane and waiting until the start of the activity after the flight. This would mean that \( e = a \) in the above equations. Another possibility is that the stay at the destination is as attractive as leisure time in the origin. In that case the rescheduling cost would be zero \((e = 0)\).

Consider the frequency of the service from A to H and from H to B within a certain period \( T \) (for example a week). Let \( F_1 \) be the lower frequency of the two and \( F_2 \) be the higher frequency. The potential number of connections between A and B during the period of length \( T \) equals \( F_1 \times F_2 \). Each of these alternatives implies a certain combination of travel time and rescheduling time. When we may assume that the time costs of waiting at the hub are higher than the costs of waiting at the destination \((e < a)\) many of these alternatives can be excluded. This means that there are no secondary reasons why passengers might stay longer at the hub airports than necessary. Then the actual number of alternatives from which travellers will choose is at most \( F_1 \).

Suppose that the flights on both legs are equally spaced in time. Then the intervals between departures are \( T/F_1 \) and \( T/F_2 \), respectively. Therefore the corresponding average waiting times are \( T/(2F_1) \) and \( T/(2F_2) \). Given our assumption that \( e < a \), the traveller gives priority to minimising waiting time at the hub compared with waiting at the destination. Therefore, the average costs of waiting at the destination (the rescheduling time) are equal to

\[
\text{rc} = eT/(2F_1). \tag{3}
\]

The above formula for the rescheduling costs can be interpreted as a benchmark value based on several assumptions:

- Flights are scheduled at equal time intervals.
- The costs of arriving late are so high that passengers will always choose such a flight that they arrive early.
- Waiting at the destination is preferred above waiting at the hub airport.
- There are only rescheduling costs at the destination side.
- The desired arrival and departure times of passengers are uniformly distributed.

Concerning the last point, it may be noted that in reality these distributions may be peaked at certain points in time: for example many business travellers may strongly prefer an arrival time around 10.00 a.m. so that they have the opportunity to spend a full working day at their destination. By realising an arrival time of slightly before 10.00 a.m. the airline could substantially reduce the average rescheduling time. We do not go into an analysis of the consequences of non-uniform distributions of desired arrival times (see Rietveld and Rouwendal (1997) for an example of non-uniform distributions of desired departure times).

### 2.2. Waiting time at hub airports

Given the assumed structure of the travel costs, the traveller puts a larger weight on reducing the waiting time at hub airports than at the destination \((e < a)\). Therefore, the expected waiting time at the hub airports depends on the frequency of the most frequent leg \((F_2)\). Consider, for example, the case where the AH flight is the least frequent one, then the waiting time at H after the arrival is the time until the departure of the first HB flight. Assume again the case that flights are equally spaced in time. When an airline does not try to
co-ordinate its departure and arrival times the expected transfer time at the hub airport equals 

\[ t_H = (0.5)T/F_2. \]  

(4)

A similar result will be obtained with a reversed order of frequent and infrequent flights. A refinement to be added is that even without waiting at H there is a minimal connecting time (mct). Thus (4) has to be rewritten as 

\[ t_H = \text{mct} + (0.5)T/F_2. \]  

(5)

On the return flight a similar approach can be adopted. The only difference is that the reference time \( t^* \) now relates to the end of the activity at the destination. We assume that the traveller does not want to depart before \( t^* \) and that for the return flight waiting at the place of the activity is preferred above waiting at the hub airport. This makes the whole analysis independent of the direction of the flight.

3. A coefficient for the quality of timetable co-ordination in hub airports

We propose to take Eq. (5) for the average transfer time in a hub airport as a starting point. In the case of perfect co-ordination of departure and arrival times this formula would read 

\[ t_{iH} = \text{mct}, \]  

(6)

whereas in the worst case we would have 

\[ t_{iH} = \text{mct} + T/F_2. \]  

(7)

A generalised form of these formulas is 

\[ t_{iH} = \text{mct} + gT/F_2, \]  

(8)

where \( g \) indicates the lack of timetable co-ordination. We introduce 

\[ \alpha = 1 - g \]  

(9)

as the timetable co-ordination coefficient. Some reference values for \( \alpha \) are:

- \( g = 0 \), \( \alpha = 1.0 \) perfect co-ordination
- \( g = 0.5 \), \( \alpha = 0.5 \) no co-ordination
- \( g = 1.0 \), \( \alpha = 0 \) counter productive co-organisation

Consider a set of connections \( i \) (A-H-B) where observations are available on the average transfer time \( t_{iH} \), the minimal connecting time \( \text{mct}_i \), and the highest frequency \( F_i \). Then for every connection \( i \) we can use (8) and (9) to compute \( \alpha_i \) as

\[ \alpha_i = 1 - [t_{iH} - \text{mct}_i]F_i/T. \]  

(10)

The coefficient \( \alpha_i \) can be used to measure the quality of timetable co-ordination within an hub airport. This would imply the computation of the average value of all \( \alpha_i \)’s related to a particular hub airport.

Eq. (8) shows that big hub airports have an advantage because of the higher frequencies of the main carrier. Smaller hub airports can compensate for this problem by offering more efficient airport operations leading to short transfer times, and a better co-ordination of timetables by the airlines concerned. The trade-off is shown in Fig. 1 where various combinations of frequencies and timetable co-ordination lead to the same level of waiting time at the hub airports.

Once \( \alpha \) has been estimated, Eq. (8) can be used to analyse the impacts of frequencies on transfer times in hub airports. This would enable a more complete analysis of the increase of frequencies on travel times. Not only do they lead to lower rescheduling costs, but also to lower transfer times. Another consequence of higher frequencies would be that reliability improves since waiting times are reduced when one misses a connection; this aspect has not been further elaborated in this paper. Another issue not addressed here concerns the influence of alliance formation on service quality in a hub. It leads to higher numbers of destinations served and higher frequencies. However, it does not necessarily lead to better connections at hubs, because this would entail the need for co-ordination of timetables of alliance partners.

Note that the above formula only focuses on the time elements of transfer at hub airports; it does not cover the other dimensions of quality of airports. For example, transfers at airports may involve long distances to be walked and inconvenient bus rides. On the other hand travellers can make use of pleasant opportunities at airports such as tax free shopping, restaurants, internet facilities, etc.\(^5\)

The above analysis is of special relevance for those market segments where travel time and rescheduling costs are important. Most intra-continental business trips fall in this category. In the case of intercontinental business trips the importance of waiting times and rescheduling times is somewhat smaller since total travel time tends to be dominated by the flying times. For the market segments of tourism

\(^4\)In large airports travellers face the problem that they have to move between different gates.

\(^5\)Surveys among travellers indicate that there are substantial differences in the quality of airports. For example in a survey of the traveller magazine ‘Conde Nast Traveler’ carried out in 1999 travellers rated airports according to location/access, ease of connections, customs/baggage claim, food/shops/amenities, comfort/ambiance. The top ten are the airports of Singapore, Amsterdam, Pittsburg, Zurich, Orlando, Hong Kong, Tampa, Reykjavik, Vancouver and Sydney.
and social visits the financial costs tend to be more important than the time costs.

4. Empirical results for timetable co-ordination in European hub airports

In this section we will first compare the flight activity on four main northern European airports—Amsterdam, Frankfurt, London Heathrow and Paris Charles de Gaulle—and then calculate the timetable co-ordination coefficient of those four airports.

4.1. Flight activity patterns at hub airports

Dennis (1998) has already studied the distribution patterns of flight activity on the hub airports considered in our analysis. He finds that Heathrow has a flat pattern of activity across the day, the product of the airport being near to full capacity (see Figs. 2 and 3). The other hub airports considered operate some form of wave pattern: first an incoming wave followed by an outgoing wave as soon as the Minimum Connecting Time has elapsed (see Figs. 4 and 5 for an example for Amsterdam). British Airways has close to 40% of the slots in each time period at Heathrow. In contrast, KLM and its partners operate three main connection waves centred on 9.30, 13.30 and 18.30, together with a developing one at 16.00 on Schiphol (Dennis, 1998).
impact for the number of connections that can be realised is clear: at Heathrow, British Airways offers about 30 connections within 2 h any given arrival time, whereas at Schiphol KLM offers 80 connections within 2 h when arriving at 18:00, however, only 20 when arriving at 10:30.

The analysis of Dennis gives a first indication that the timetable co-ordination coefficient of British Airways on Heathrow will be rather close to 0.5 (no co-ordination) whereas this coefficient will probably be higher for the other hub airports in our analysis.

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**4.2. Waiting times at airports and timetable co-ordination coefficients**

The timetable co-ordination coefficient $\alpha_i$ is most relevant for intra-continental traffic. Therefore, we propose to apply the $\alpha$ for this market segment. As described in Section 3 the $\alpha$ coefficient for a connection $i$ is computed as

$$\alpha_i = 1 - \frac{[t_{H_i} - \text{mct}_i]F_{2i}}{T}. \quad (11)$$

This coefficient is calculated for each possible connection $A-H-B$, defined by different combinations of nine origin airports $A_j$, four hub airports $H_k$ and nine destination airports $B_m$. The origin airports considered are Brussels, Dublin, Glasgow, Copenhagen, Madrid, Milan, Moscow, Oslo and Vienna. The hubs considered...
are Amsterdam, Frankfurt, London and Paris. This results in a total of 72 possible connections per hub airport. Since not all connections are relevant we finally considered about 60 connections per airport.\(^7\) For this analysis we considered only the flights carried out by the hub airport’s home carrier\(^8\) and its allies. The numbers of flights per week on both legs of the connections are given for the four hubs in Table 1.

According to this table, London Heathrow is the ‘largest’ airport. Amsterdam is the smallest of the four. However, the differences are not large, especially not for the least frequent leg of the connection. As indicated above this means that the rescheduling costs will probably be rather close for the hubs considered here. In this subsection we focus on the implications of Table 1 for waiting times at airports.

The items needed to compute the \(x\) coefficient for each connection are the average transfer time, the minimal connecting time, the highest frequency \(F_2\) and the time period.\(^9\) Table 2 shows the average waiting times and minimal connecting times for each of the four hubs. The difference between the waiting times at the four hub airports can be decomposed into three elements: minimal connecting time, frequency and co-ordination of schedules. The minimal connecting times in Frankfurt are about 20 min shorter than in London. Also in Amsterdam and Paris rather low minimal connecting times are applied. However, as shown in Table 2, the net average waiting time for Heathrow is higher than in the other hub airports. The values in Amsterdam are most favourable.

In order to analyse the role of timetable co-ordination as a determinant of airport performance we compute the concerning coefficient. The average \(x\) coefficient for each of the hub airports is computed by averaging the \(x\) coefficients of all considered connections using the specific airport as a hub, while weighing for the number of flights for each connection. The resulting coefficients can be found in Table 3.

The table indicates that there are indeed differences in the \(x\)’s of the airports. The airport of Amsterdam performs better than its competitors, especially better than London Heathrow and Paris Charles de Gaulle. Thus, the better timetable co-ordination in Amsterdam more than off-sets the scale disadvantage compared with the big airports of London and Paris. This clearly illustrates the fact that the frequency of flights is not the only relevant factor determining average waiting times. Smaller airports can out-compete larger ones by better co-ordination of flights.

### 4.3. Rescheduling times

In addition to waiting times at hub airports also rescheduling times at origins and destinations play a role. When we may assume that the desired arrival times of travellers are distributed uniformly in time, and that the interarrival times of the flights are equal, the expected rescheduling time is determined by \(F_1\), the lower frequency of the two legs, as indicated in Eq. (3). In reality, the interarrival times may not be equal. When desired arrival times are uniform, this means that when two flights are separated by a relatively long interarrival time, this will affect a relatively large number of passengers. Thus, let \(t_{i+1} - t_i\) be the interarrival time between two flights \((i = 1, \ldots, F_i; t_{F+1} = T + t_1)\). Then the weight of this interarrival time is proportional to the length of this time interval. Therefore the expected

| Table 1 | Number of flights per week at the most frequent and least frequent leg of a sample of intra-European connections served by four large hub airports |
|------------------|------------------|------------------|------------------|------------------|
| Average of least frequent leg of a connection | Amsterdam | Frankfurt | London | Paris |
| Average of most frequent leg of a connection | 29.2 | 31.1 | 38.1 | 33.0 |

| Table 2 | Average waiting times and minimal connecting times for a sample of connections at European hub airports |
|------------------|------------------|------------------|------------------|------------------|
| Average waiting time including mct | Amsterdam | Frankfurt | London | Paris |
| Average waiting time (i.e., excluding mct) | 0:48 | 1:01 | 0:59 | 1:16 |
| Minimal connecting time mct | 0:50 | 0:45 | 1:04 | 0:53 |

| Table 3 | Average timetable co-ordination coefficients (\(x\)) for a sample of connections at European hub airports |
|------------------|------------------|------------------|------------------|------------------|
| Average timetable co-ordination coefficient | Amsterdam | Frankfurt | London | Paris |

\[^7\]Incoming flights for which the first corresponding outgoing connecting flight does not leave until the day after, thus imposing a nightly waiting time, are not considered within this analysis. When the use of a hub would lead to a large detour (for example, Oslo-Copenhagen via Paris) that connection has been excluded from the analysis. In this context a detour is considered large if the flight distance via a hub is twice or more the distance of a direct flight between a city-pair.


\[^9\]Details of measurement procedures can be found in Bruinsma et al. (2000).
Difficult to see that when the interarrival times are equal, factors such as the number of destinations and the variations the timing of these flights is less flexible. This intercontinental connections. Given time zone considerations the functioning of the hubs for intra European flights. Carriers will of course also take into account their intercontinental connections. Given time zone considerations the timing of these flights is less flexible. This may explain part of the low scores reported above.

5. Conclusions

Hub airports compete with each other on various factors such as the number of destinations and the frequency of the services offered, transfer times, comfort levels at airports, ticket prices charged by carriers, airport taxes, etc. In this paper we paid special attention to the impacts of frequency changes on rescheduling times and waiting times of travellers.

Our analysis is based on the assumption that the dislike of travellers against time spent waiting at hub airports is higher than against time spent at the destination before the desired time of arrival. We find that the average rescheduling time is inversely proportional to the lower frequency of the two legs of the trip. The average waiting time at the hub is inversely proportional to the higher frequency of the two.

A measure has been developed for the quality of co-ordination of timetables at hub airports ($\alpha$). A value of $\alpha$ equal to 1 means that average waiting time is zero (taking into account some level of minimal connecting time). When $\alpha = 0.5$ there is no co-ordination of timetables; a value of $\alpha$ lower than 0.5 means counter productive co-ordination.

We applied the timetable co-ordination coefficient to the four largest hub airports in Europe. We find that large airports such as London Heathrow and Paris Charles de Gaulle have longer waiting times than the (slightly) smaller airports Frankfurt and Schiphol even though one would expect shorter waiting times given the higher frequencies of service. The reason is that the minimal connecting time is higher and flight co-ordination is less efficient. The latter is clearly reflected by the values of the flight co-ordination coefficient developed in this paper.

An issue not addressed here is reliability of services. Delays will not only lead to late arrivals, but also to the probability of missed connections. Obviously there is a trade-off between long minimal connecting times allowing airlines slack in their hub operations and the probability of missed connections. An interesting recent development is the formation of a mini-hub of Cross-Air in Basle that is based on a minimum connecting time of 20 min. In a case like this the risk of high unreliability can only be avoided when special measures are taken. Reliability of hub operations is an obvious candidate for further research on the comparative performance of hub airports.

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