THE TEMPORAL CONFIGURATION OF EUROPEAN AIRLINE NETWORKS

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Abstract

The deregulation of US aviation in 1978 resulted in the reconfiguration of airline networks into hub-and-spoke systems, spatially concentrated around a small number of central airports or 'hubs' through which an airline operates a number of daily waves of flights. A hub-and-spoke network requires a concentration of traffic in both space and time.

In contrast to the U.S. airlines, European airlines had entered the phase of spatial network concentration long before deregulation. Bilateral negotiation of traffic rights between governments forced European airlines to focus their networks spatially on small number of 'national' airports. In general, these star-shaped networks were not co-ordinated in time. Transfer opportunities at central airports were mostly created 'by accident'.

With the deregulation of the EU air transport market from 1988 on, a second phase of airline network concentration started. European airlines concentrated their networks in time by adopting or intensifying wave-system structures in their flight schedules. Temporal concentration may increase the competitive position of the network in a deregulated market because of certain cost and demand advantages.

This paper investigates to what extent a temporal concentration trend can be observed in the European aviation network after deregulation. We will analyze the presence and configuration of wave-system structures at European airline hubs as well as the resulting transfer opportunities. We use OAG data for all European carriers with scheduled services between 1990 and 1999.

We conclude that a temporal concentration trend exists among European airlines. European deregulation has resulted in the adoption or intensification of wave-system structures by airlines. These wave-system structures as well as the overall traffic growth have significantly stimulated the number of indirect hub connections. Airline hubs with wave-system structures perform generally better than airline hubs without a wave-system structure in terms of indirect connectivity given a certain number of direct connections.

Keywords: airline networks, wave-system structure, Europe, connectivity

1. INTRODUCTION

The European aviation market has gradually been deregulated by means of three 'packages' of deregulation measures (1987, 1990, 1992) (Button *et al.*, 1998; Hakfoort, 1999). As a result of deregulation, the balance of power in the European air transport regime has shifted from the governments towards the European airlines. Supported by the Common European Market and experiences with deregulation of the US aviation market, deregulation forced the EU Member states to reduce their strong involvement with respect to the economic regulation of the European carriers with respect to intra-European air services.
After the deregulation of the aviation market in the United States in 1978, airlines took advantage of the possibilities of the liberalised market and reorganised their networks. A number of 'trunkline'-carriers reorganised their networks from 'point-to point' into 'hub-and-spoke' networks (Reynolds-Feighan, 1998, 2000; Viscusi et al., 1998). This reorganisation took place between 1978 and 1985, according to Reynolds-Feighan (2001). Direct flights from medium airports to other medium airports were increasingly replaced by indirect flights via a central airports or 'hubs'.
Spatial concentration and temporal concentration are the two main features of the hub-and-spoke network (Reynolds-Feighan, 2001). The hubbing carrier concentrates its network spatially around one or a small number of hubs. Regarding temporal concentration, the airline operates synchronized, daily waves of flights through these hubs (Graham, 1995; Reynolds-Feighan, 2000). The aim of such a wave-system structure is to optimise the number and quality of connections offered by an airline. The flight schedule optimisation through wave-system structures and spatial concentration can result in certain demand and cost side advantages as well as entry deterrence. The advantages of these hub-and-spoke systems have been extensively discussed elsewhere (see e.g. Button, 2002; Hanlon, 1996; Pels, 2001).
On the other hand, some new and incumbent U.S. airlines continued operating 'point-to-point' networks on a low-cost, no-frill, low-price basis. Low-cost carriers do not need the cost advantages of hub-and-spoke networks because they have low marginal costs per passenger. This is mainly the result of operating high density routes with high utilization rates, high density seating, standardization of aircraft types and maintenance, electronic ticketing, low levels of on-board service, use of under-utilized secondary airports and flexible labor contracts (Dempsey & Gesell, 1997; Doganis, 2001; Reynolds-Feighan, 2001; Williams, 2001).

In contrast to the large amount of empirical studies regarding the changes in airline network structures in the deregulated US air transport market, the number of empirical studies with respect to changing airline network configurations in Europe is rather limited. More knowledge of airline network behaviour in a deregulated European aviation regime is important from a societal perspective because of a number of reasons.

- The structure of airline networks affects airport planning and development including peaking problems at airports, uncertainty in airport traffic forecasting, runway construction plans, terminal lay-outs and regional accessibility (de Neufville, 1995).

- It can be expected that the effects of deregulation on the European airline network configurations will be different from the U.S. aviation network since the geographical, political and historical context is quite different from the European context (see also Bootsma, 1997; Burghouwt & Hakfoort, 2001).

From a scientific point of view, this study adds to the current body of knowledge because:

- This paper tries to reduce the apparent gap in the literature. Most studies take the airport-level as the object of analysis and do not analyze changes in network structures over time at the airline level (for an overview of studies see Burghouwt & Hakfoort, 2001).
- Most existing theoretical studies on airline network economics in a deregulated market use a network dichotomy. Generally, two different networks are considered as a starting point for analyses: the minimally connected network and the fully connected network (see e.g. Berechman & De Wit, 1996). In reality these two extreme network structures rarely exist (Pels, 2000, p. 70). The scale from full hub-and-spoke networks to fully connected (point-to-point) is continuous (Bootsma, 1997, p.4). By focusing on the spatial and temporal organisation of traffic flows insight into the usefulness of these economic models and their application to the European air transport system can be given.
- Most studies consider airline networks that are radially organized in space as an equivalent for hub-and-spoke networks (e.g. Bania et al., 1998; Burghouwt & Hakfoort, 2001; Goetz & Sutton, 1997; de Wit et al., 1999). However, a radial network is not an equivalent for a hub and spoke network as long as timetable coordination is lacking. Hence, this paper acknowledges both the spatial and temporal dimension to define airline networks.

This paper adds to the evidence by *providing an analysis of the changes in temporal dimension of airline network configurations in Europe between 1990 and 1999*[1].

The paper is structured as follows. Section 2 discusses previous studies and the theoretical background of the paper. In section 3, we describe the methodology of the weighted indirect connectivity index and the wave-structure analysis. Section 4 describes briefly the OAG data used in this paper. Section 5 and 6 discuss the empirical results regarding temporal concentration in the networks of the airlines. Section 7 concludes, discusses the policy implications of the results and indicates themes for further research.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Theoretical considerations on the temporal configuration of an airline network

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[1] This paper will not cover the spatial configuration of airline networks. We refer to Burghouwt et al. (2003) for an empirical analysis of the spatial dimension of airline networks in Europe based on the network concentration index.

Temporal concentration and spatial concentration are the two main features of the hub-and-spoke network (Reynolds-Feighan, 2001). Therefore, we define an airline network configuration as the spatial and temporal configuration of the network. The spatial configuration can be defined as the level of concentration of an airline network around one or a few central hub airports. This definition has been used to analyse the geographical structure of airline networks in Europe between 1990 and 1999 (Burghouwt et al., 2003).

Following the thesis of Bootsma (1997) on airline flight schedule development, we define the temporal configuration as the number and quality of indirect connections offered by an airline or alliance by adopting a wave-system structure in the airline flight schedule.

A wave-system structure consists of the number of waves, the timing of the waves and the structure of the individual waves. According to Bootsma (1997, p.53) a connection wave is 'a complex of incoming and outgoing flights, structured such that all incoming flights connect to all outgoing flights [..]'.

Three elements determine the structure of such a connection wave:
1. The minimum connection time for continental and intercontinental flights
2. The maximum connection times
3. The maximum number of flights that can be scheduled per time period

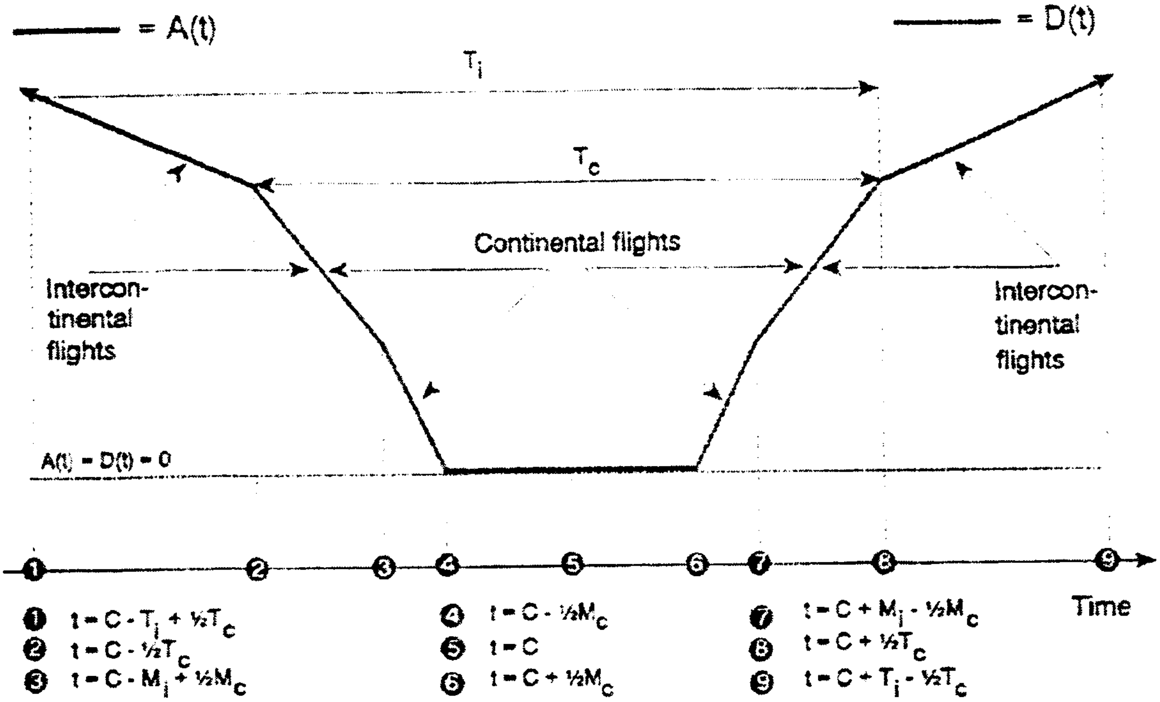
Figure 1 presents an ideal type of connection wave for a European hinterland hub. Connections have to meet the minimum connecting times (M). Then, a trade-off has to be made between the maximum acceptable connection time (T) for the airline and the maximum number of flights that can be scheduled in a time period (A(t)+D(t)). The hub-and-spoke concept favours adding a connection to the same wave. Since no airport has unlimited peak capacity however, adding new flights to the edges of the waves involves long waiting times which may not be acceptable for transfer passengers (Dennis, 2001).

However, in reality, such an ideal picture is not very likely to exist. Bootsma (1997) mentions the following disturbing factors:

- Some spokes may be located to close or to far away from the hub to fit in the wave-system structure. These flights will be located off-wave.
- Strict scheduling may jeopardize fleet utilization.
- Environmental constraints and/or capacity constraints may be an obstacle for airlines to fit all flights into the wave-system.
- In strong O-D markets, it may be attractive to schedule a number of flights off-wave.
- The incoming and outgoing European wave can overlap because not all connection are feasible because of the detour/routing factor
- We can add to this list the fact that an airline may simply not have chosen to adopt or may not be capable of adopting a wave-system structure

Figure 1 Structure of the theoretical connection wave of a European hinterland hub.

A(t)=number of flights that still have to arrive at the hub at time t; D(t)= number of flights that still have to depart from the hub at time t; C=wave centre; M_i=minimum connection time for intercontinental flights; M_c= minimum connection time for continental flights; T_i=maximum connection time for intercontinental flights; T_c= maximum connection time for continental flights.



Source: Bootsma, 1997, p. 57

Bootsma (1997) makes a clear distinction between the actual temporal configuration of the airline flight schedule (the wave-system structure) on the one hand and the effects of the airline flight schedule on the number and quality of the indirect connections generated by the flight schedule (indirect connectivity) on the other hand.

The resulting indirect connectivity of an airline hub will depend on a number of elements in the airline flight schedule (Bootsma, 1997; Dennis, 1998; Rand Europe; Veldhuis, 1997). Firstly, the number of direct flights (frequency) from and to the hub determines the maximum number of indirect connections following the formula n(n-1)/2, where n denotes the number of spoke-airports in the network.
Secondly, the number of indirect flights will depend on the minimum connection time at the airline hub (mct). The mct-window is required to allow passengers and baggage to transfer between two flights as well as to turn around the aircraft itself. Indirect connections not meeting the mct-criterion cannot be considered as a viable connection.

However, not every connection will be as attractive. An indirect flight with a waiting time of five hours will not be as attractive as the same indirect flight but with a transfer time of only 45 minutes.
Attractivity of an indirect connection depends on (Veldhuis, 1997):

- Waiting time at the hub: attractivity declines when waiting time increases.
- Routing factor: the in-flight time for an indirect flight compared to the direct-flight time. Some indirect connections (such as Hamburg-Oslo-Nice) are not attractive for the average air traveller because the detour factor is too large.
- Perception: passengers perceive transfer time longer than in-flight time (Veldhuis, 1997).
- Fares: lower fares may compensate for longer transfer and in-flight times.
- Flights of a certain airline may be attractive because the air traveller participates in the loyalty programme of the airline.
- Amenities of the hub-airport involved in the transfer.

When quantifying the effects of the configuration of the airline flight schedule in terms of indirect connectivity, one should take into account the difference in attractivity of a certain connection. However, since data on fares, airport quality and loyalty programmes are very scarce and unreliable, we will concentrate on the role of waiting time and flight time in this paper (see also Veldhuis, 1997).

Based on these theoretical considerations, we will use the characteristics of the ideal type connection wave as the benchmark for our analysis. We will:

1. Evaluate the indirect connectivity of the airline flight schedule given the presence or absence of a wave-system structure. We define indirect connectivity as the number and efficiency of the indirect connections generated by the existing flight schedule.
2. Analyse the presence of a wave-system structure empirically as well as the determination of the number of waves at the airline hub, based on the definition of a theoretical connection wave.
3. Assess the effects of the presence of a wave-system structure on the indirect connectivity.

However, we will first review existing literature to identify the scientific relevance of our research as well as the methodology used.

2.2 Literature review

A substantial amount of theoretical and empirical research has been carried out on airline network configurations. Most of these studies on airline network configurations focus on the spatial dimension of airline networks. The hub-and-spoke network is generally seen as a spatially concentrated network or minimally connected network. In the hub-and-spoke network, routes are deliberately concentrated on a few key nodes in the network. However, as we stated before, an airline network needs both spatial and temporal concentration of flights to qualify as a hub-and-spoke network.

Table 1 provides an overview of hub-and-spoke definitions of various authors to support the argument of the definition-bias. Besides, most of the studies have a very limited geographical scope. In the case of Europe, only the largest airlines and airports are considered in these studies.

Table 1 Definition of the hub-and-spoke network according to various studies

Study	Definition	Level	Spatial/	Type of

			temporal concentration	**study**
Bania, Bauer & Zlatoper, 1998, p.53	[..] a hub-and-spoke network has most flights coming to a 'hub' airport from 'rim' airports, concentrating airline activity at a few locations. Travel between two rim airports involves flying first to the hub and then on to the final destination.	Airline level	Spatial and temporal concentration	Empirical, United States
Berry, Carnall & Spiller (1996), p.1	'[In Hub-and-spoke networks], passengers change planes at a hub airport on the way to their eventual destination	Airline level	Spatial concentration	-
Bootsma, 1997, p.4	[..] in case of hub-and-spoke, the network is designed as such, that routes are deliberately concentrated at a limited number of connection facilities called *hubs*. Destinations from each of these hubs are called spokes. [..]. In order to maximize these connection possibilities, the hub-carrier usually schedules its flights in a limited number of time-windows.	Airline level	Spatial and temporal concentration	Empirical, Europe major hubs
Burghouwt & Hakfoort, 2001, p. 311	HS-network entail the combination of point-to-point with transfer traffic at a central hub	Airline level, but analysis takes place at the airport level	Spatial concentration	Empirical, all European airports
Button, 1998, p.20	In hub-and-spoke operations, [..] carriers generally use one or more large airports [..]. Flights are arranged in banks which allow passengers continuing on to be consolidated on outbound flights to further destinations'	Airline level	Spatial and temporal concentration	-
Button, 2002, p. 177	Airline networks that entail consolidating of traffic from a diverse range of origins and are destined to a diverse range of final destinations at large, hub airports	Airline level	Spatial concentration	-
Dempsey & Gesell (1997, p. 200)	Consolidation of operations around hubs by airlines	Airline level	Spatial concentration	-
Dennis (1998, p.2)	[Airline HS networks aim] 'to carry connecting passengers with both origin and destination outside their home country'	Analysis at airline level	Spatial and temporal concentration	Empirical, Europe's major hubs
Goetz & Sutton, 1997	Major connection complexes for airlines	Airline level but analysis at airport level	Spatial concentration	Empirical, U.S. airport system
O'Kelly &	'Hubs [..] are special nodes that are part of	Airport	Spatial	Theoretical

Bryan (1998)	a network, located in such a way as to facilitate connectivity between interacting places'	level	concentration	
Oum, Zhang and Zhang (1995, p. 837)	Hub-and-spoke networks concentrate most of an airline's operations at one, or a very few, hub cities. Virtually all other cities in the network are served by non-stop flights from these hubs'	Airline level	Spatial concentration	Theoretical
Pels, 2000, p. 13	In a HS-network, the hub airport is the only airport with a direct connection to all other airports. All passengers travelling between two 'spoke airports' (an indirect market) are channelled through the hub airport. The market between a hub and spoke is a spoke market	Airline level	Spatial concentration	Theoretical
Rietveld &Brons, 2001	Hub-and-spoke networks enable carriers to supply transport services to many combinations of origins and destinations at high frequencies and low costs.	Airline level	Spatial concentration and temporal concentration	Empirical, Europe's 'big 4'
Veldhuis & Kroes, 2002	Hub airports consider the *indirect* connections via their hub of essential strategic importance	Airport/ airline level	Spatial and temporal concentration in analysis	Empirical, Europe's major hubs

Thus, only a small number of empirical studies has been carried out to measure temporal concentration of airline networks. Let us briefly discuss the methodology and results of the studies dealing with temporal concentration. We will then present an alternative to the existing methodologies.

Bania, Bauer & Zlatoper (1998)
Bania et al. provide a methodology for measuring the extent to which airlines operate hub-and-spoke networks. They take into account the spatial concentration of the network using the McShan-Windle index. Moreover, they take into account the possibility of making transfers from one flight to another at the hub airports. However, they consider every possible indirect connection as a viable connection, regardless of transfer time and routing factor. As we have seen, transfer time at the hub and routing factor are essential elements for the efficiency of the hub-and-spoke system. Therefore, we reject the Bania-methodology because of theoretical considerations.

Dennis (1998)
In his paper dealing with the competitive position of the main European hub airports, Dennis distinguishes three factors that determine the success of a hub airport: markets served, geographical location and transfer times/ schedule coordination.

Firstly, independent from location and transfer times, the number of flights on two origin-destination pairs served determines the number of indirect connections in comparison to other hubs. Dennis defines the hub potential as the share of the product of the frequency on the first and second leg of an indirect trip in a certain market at a certain airport in the sum of this product for all airports. He concludes that London Heathrow, Frankfurt and Paris Charles de Gaulle have the highest hub potential.

Secondly, the geographical location is important. Dennis studies this aspect by computing the total number of passenger kilometres necessary to connect every hub with all other hubs in the system. Brussels is most centrally located in Europe, even corrected for passenger numbers. Peripheral hubs Athens, Lisbon and Helsinki are worst located in terms of total passenger kilometres necessary to connect all the hubs.
Thirdly, having a good hub potential and geographical location would be sufficient to operate a successful hub. However, passengers are not prepared to wait an infinite time. Hence, transfers require the concentration of flight activity into a limited number of peaks or waves during the day in order to minimize waiting time. Dennis calculated the performance of the hubbing airline in generating an effective wave structure by computing the number of connections possible for each airline at each hub between the minimum connecting times and six hours as well as looking at the wave structure graphically. In 1998, Lufthansa at Frankfurt, Air France at Paris CDG and KLM at Amsterdam scored best.
The methodology of Dennis works well in getting a first impression of an airline hub, but does not result in insight into the level of timetable co-ordination since the effects of waiting time on the quality of a connection are not taken into account.

Rietveld & Brons (2001)
Rietveld & Brons (2001) state that waiting time at a hub airport is dependent on three factors: frequency, the minimal connection time (mct) and the time table co-ordination by the hub carrier. Knowing the mct values for a certain connection, the frequency for the flights concerned and the waiting time for that connection, the level of timetable co-ordination can be derived. From the total number of operating hours per day and the frequency on the most frequent leg of the connection (F_2), an expected average waiting time can be computed (T_h). The deviation from the real waiting time minus the mct is called alfa.

$$t_h = mct + g\frac{T}{F_2} \qquad (1)$$

$$\alpha = 1 - g \qquad (2)$$

The basic problem of the approach is the fact that the study assumes that the observed frequency on the route is one of the determinants for the waiting time at the hub. This seems to be a right conclusion: average waiting time decreases as frequency decreases. However, frequency is not the factor decisive for the waiting time (T_h) at the hub. It is the other way around: waiting time is decisive for the frequency. Airlines choose frequency based on O-D demand and transfer demand. Both determine the wave-system structure (time table coordination) including the number of waves (Bootsma, 1997). Ideally, every destination is being served in every wave. However, markets with very strong O-D demand may validate off-wave scheduling of these services. At the same time, connection with insufficient demand may result in connections not served in every wave.
Without the time table coordination in the flight schedule/ wave structure, certain frequencies would not be possible because of lack of O-D demand. The Rietveld &

Brons-model has been based on the inaccurate assumptions creating a loop in the model. The model measures the level of timetable coordination based on frequency that is the result of the same timetable coordination because it assumes that frequency is only generated by O-D demand. However, as stated before, frequency is the result of both O-D and transfer demand which is partly the result of the wave-system structure adopted by the airline.

Veldhuis, 1997

Veldhuis (1997) uses the concept of connectivity units (cnu) to measure the competitive position of an airline or airport network. The frequency of a connection (direct or indirect), the non-stop travel time, perceived travel time, maximum perceived travel time and the transfer time are the inputs for the measure. The measure scales indirect travel time to the travel time of an indirect flight, making comparisons possible between indirect and direct connectivity.

The measure has been applied to various cases (see IATA, 2002; Veldhuis, 1997; Veldhuis, 2002; Veldhuis & Kroes, 2002) and has proved its usefulness. Drawback of the methodology is the fact that assumptions have to be made on the valuation of time by air passengers to make comparisons possible between indirect and direct connectivity.

We will use a somewhat simplified cnu-measure to assess the effects of the temporal configuration of an airline's network. It resembles to connectivity unit in weighing the number of frequency for the quality of the indirect connection. Our measure differs in the sense that we do not aim at comparing indirect and direct connectivity.

Yet, the cnu-methodology or a similar measure does only give insight in the consequences of a certain flight schedule on connectivity. Its basic handicap is the fact that such as measure does not give information about the structure of the flight schedule itself.

Bootsma, 1997

Bootsma uses the theoretical model of an ideal connection wave as the benchmark for the analysis of the wave-system structure and for the analysis of the effects of the wave-system structure on indirect connectivity (see also section 3.1 and 3.2). In contrast to the studies discussed above, it is important to notice that Bootsma distinguishes between the *description* of the temporal configuration of an airline network and the analysis of the *effects* of a certain temporal configuration on indirect connectivity. We will make the same distinction in this paper.

For the descriptive part of the analysis, Bootsma identifies the presence, timing and number of actual waves by identifying *local maxima* in the actual daily distribution of arriving and departing flights using the theoretical model of an ideal connection wave. This methodology will be discussed and adapted in section 3.1.

For the measurement of the indirect connectivity of an airline's flights schedule, he proposed a number of yardsticks, e.g. the number of indirect connections and the quality of those connections. One problem with the approach is the fact that the analysis of the quality of connections is very rough. A distinction is made between excellent, good and poor connections, based on waiting time at the hub. A continuous approach, such as the approach of Veldhuis (1997), might be more accurate. Moreover, Bootsma did not consider the relevance of the connections, such as backtracking. Finally, the study considered only a few airline hubs empirically for the year 1994.

In summary, a small number of studies has analysed the temporal dimension of airline networks. These studies analyse the structure of the airline flight schedule itself (Bootsma, 1997; Dennis, 1998) or aim to assess the consequences of an actual flight schedule for the level of (in)direct connectivity (Bootsma, 1997; Veldhuis, 1997, 2002; Veldhuis & Kroes, 2002) or waiting time (Rietveld & Brons, 2001).
The methodology of Rietveld & Brons was rejected based on theoretical considerations. The methodology of Dennis works well getting a very first glance of the connectivity of an airline network or airport, but does not take into account the quality of an indirect connection.
Bootsma offers a very valuable methodology for describing the structure of an actual flight schedule. We will use a slightly adapted methodology to do the same. Both Bootsma and Veldhuis have developed a measure (cnx and cnu respectively) to analyse the effects of a certain flight schedule. We will use elements of both approaches for this study (see section 3).

3. METHODOLOGY

In section 2 we stated that this paper has a two-fold aim. Firstly, a description of the presence of a wave-system structure and the number of waves at an airline hub will be given. Secondly, an analysis of the effects of the wave-system structure on indirect connectivity will be performed. The first question can be answered using the theoretical wave-system structure developed by Bootsma (1997) (section 3.1). The second question will be answered using a simplified connectivity measure (section 3.2).

3.1 A methodology for the identification of the wave- system structure

Recalling figure 1 and Bootsma (1997, p.61), the time windows for departing and arriving intercontinental (ICA) and departing and arriving European (EUR) flights can be determined:

- ICA-arriving window: $[C-T_i+0.5T_c, C-M_i+0.5M_c]$ (3)
- ICA-departing window: $[C+M_i-0.5M_c, C+T_i-0.5T_c]$ (4)
- EUR-arriving window: $[C-0.5T_c, C-0.5M_c]$ (5)
- EUR-departing: $[C+0.5M_c, C+0.5T_c]$ (6)

Where:
T_i is the maximum connecting time involving intercontinental flights;
T_c is the maximum connecting time for connecting European flights;
M_i is the minimum connecting time involving intercontinental flights;
M_c is the minimum connecting time for connecting European flights;
C is the wave centre.

Bootsma (1997) has defined standard maximum connection times for different types of connections: the quality thresholds (see table 2). Minimum connection times are unique for every hub airport and can be derived from the Official Airline Guide (OAG). For the sake of simplicity of the wave-structure analysis, we have chosen a minimum connection time of 40 minutes for all flights and a maximum connection time of 90 minutes for all flights for the analysis performed in section 6. The analysis shows that this choice does not influence the results significantly[2].

Table 2 Connection quality thresholds (minutes) for different types of connections

Type of connection	$T_{excellent}$	T_{good}	T_{poor}
EUR-EUR	90	120	180
EUR-ICA	120	180	300
ICA-ICA	120	240	720

Source: Bootsma, 1997, p.68

Given the theoretical definition of an ideal connection wave, the actual wave-system structure can be identified. This can be done by creating artificial wave centres every x-minutes of the day. Whether an airline actually operates a wave structure at that time of the day for that wave-centre, is determined by counting the number of flights within the departure and arrival windows for the specific wave-centre.

We have illustrated the procedure for the network of Lufthansa at Munich (figure 2). We have created artificial wave centres every 6 minutes of the day. Maximum connection time is 90 minutes for all flights. Minimum connection time has been set on 40 minutes. Hence, flights have to arrive between t=C- 45 and t=C-20. Flights have to depart between t=C+20 and t=C+45 to fit into the artificial wave. A wave-centre of a wave can be identified when the wave-centres for incoming and outgoing flights coincide almost completely.

At Lufthansa's hub Munich, we can identify a clear wave-system structure with three connection waves: morning, afternoon and evening. The wave centres for departures and arrivals overlap. Local maxima differ significantly from the following local minima, resulting in a clear peak-pattern in the flight schedule.

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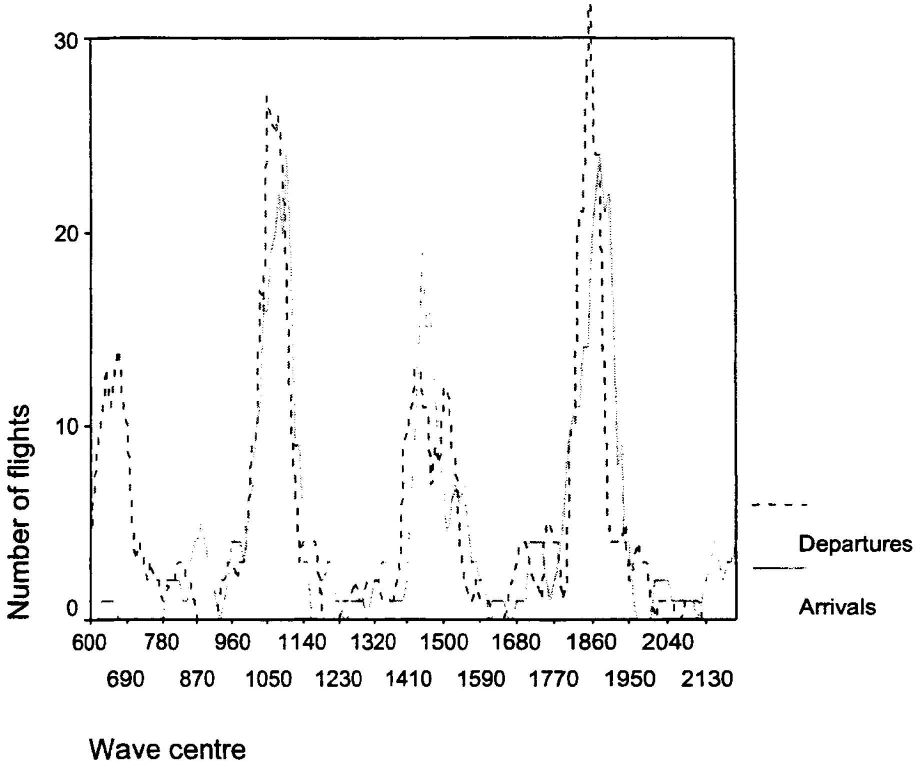
[2] For the analysis performed in section 5 (see also section 3.2) unique minimum connection times for every airport have been applied.

Figure 2 Wave-system analysis for Lufthansa at Munich, 1999



Source: OAG/ ABC

The research of Bootsma shows that this methodology is a helpful approach for identification of the presence of a wave-system structure, the number of waves and the timing of the waves. The approach needs a numerical or graphical representation to capture the 'local maxima' (Bootsma, 1997, p. 60).

For a large number of airline hubs, identification of 'local maxima' per airline hub becomes very time-consuming. Therefore, we will first evaluate the effects of airline flight schedules on indirect connectivity (section 3.2). Only airline hubs with significant indirect connectivity will be analysed to identify the characteristics of the wave-system structure. Airports without significant indirect connectivity are not being considered as competitive hubs for the transfer market.

3.2 Evaluation airline flight schedule effects: indirect connectivity

For the purpose of this paper, we propose a combination of the Bootsma (1997)-methodology and the approach of Veldhuis (1997) for analysis of the indirect connectivity as the result of a certain airline flight schedule.

In section 2, we stated that the number of direct frequencies, the minimum connection times and the quality of the connection determine indirect connectivity.

Therefore, we have defined a weighted indirect connection[3] as:

$$WI = \frac{2.4 * TI + RI}{3.4} \tag{7}$$

where

$$TI = 1 - \frac{1}{T_j - M_{i,j}} Th \tag{8}$$

where Th>M
and
TI=0 when Th>T

$$RI = 1 - (2\frac{1}{2}R - 2\frac{1}{2}) \tag{9}$$

and

$$R = \frac{IDT}{DTT} \tag{10}$$

where
1<=R<=1.4
and
RI=0 when R>1.4

Where,
WI= weighted indirect connection
TI= transfer index
RI= routing index
Mi,j= minimum connection time for connection j at airport i
T= maximum connection time for connection j
Th= transfer time at the hub
IDT= actual in-flight time indirect connection
DTT= estimated in-flight time direct connection based on great circle distance
R= routing factor

The weighted connectivity of an indirect connection depends both on the quality of the connection at the hub (TI) as well as the quality of the indirect flight compared to the direct flight (RI). Both are defined as being a linear function of the flight time and transfer time respectively.

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[3] Only intra-line, same day transfer connections (on a Wednesday) were considered in this paper. Future research should include transfer connections between flights of alliance partners

The transfer index (TI) equals 1 when the transfer time T_h equals 0. The transfer index (TI) equals zero when the transfer time T_h exceeds the maximum connection quality threshold T_{poor} (table 2). We have not chosen to set the TI-index at 1 when T_h equals the minimum connection time in order to include differences in minimum connection times between airports.

The routing or circuity index (RI) equals zero when the routing factor exceeds a certain limit. The maximum routing factor for distance is typically 1,25 (Bootsma, 1997). However, since we take in-flight time as the input for the routing factor instead of Great Circle Distance, we should allow some time for take-off and landing. Therefore, we have added 0.15 points to the maximum routing factor. This results in a maximum routing factor of 1.4.
The routing of circuity index (RI) equals 1 when total in-flight time for an indirect connection equals 0. This is an impossible situation because of time needed for take-off and landing but it takes into account the negative impact of a transfer on the attractivity of a certain connection.

We have taken the weighted average of TI and RI. We have made the assumption that passengers perceive transfer time 2.4 times as long as in-flight time. This factor is based on preliminary research of Lijesen (2002). Future research should further distinguish between perception of in-flight versus transfer time for leisure and business passengers.

The WI-index can be aggregated in different ways. We have used:

$$WNX = \Sigma (WI)$$

Where
WNX= Total number or weighted indirect connections

4. DATA

The data set used consists of OAG/ABC data for the years 1990 – 1999. The OAG/ABC data set contains variables based on published information on scheduled flights. Variables include airline, flight number, departure time, arrival time, departure airport, destination airport, flight frequency, airplane type and seat capacity for each flight and the number of stops during the flight. The data are based on a representative week of July of each year. For our analysis, we took all flights departing and arriving on Wednesday.
The OAG/ABC[4] data suffer from a number of limitations. First, OAG data only provides insight into scheduled flights and not into realized demand or supply. Load factors, weather conditions, technical problems and congestion can lead to differences between the two. Given that we are interested in the structure of the aviation network, we do not consider this to be much of a problem. Second, the OAG data only registers scheduled services. We have deleted full freight flights from the data set and consider passenger flights (including the so-called 'combi' flights) only. Finally, the original data set only lists direct flights.

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[4] For a detailed description see Burghouwt & Hakfoort (2001)

Minimum connection times were derived from the Official Airline Guide of 1999 for the analysis presented in section 5.

5. AIRLINE FLIGHT SCHEDULE EFFECTS: INDIRECT CONNECTIVITY

Using the methodology described in section 3, we will discuss the outcome of the flight schedule coordination in terms of indirect connectivity. To do so, we will use the WNX index of indirect connectivity. WNX is the number of indirect connections weighted by transfer time and routing factor.

5.1 Indirect connectivity

Figure 3 shows the WNX index for the top 31 European hubs in terms of indirect connections in 1999. In 1999, Frankfurt, Paris CDG, London Heathrow and Amsterdam dominated the market for indirect connections.

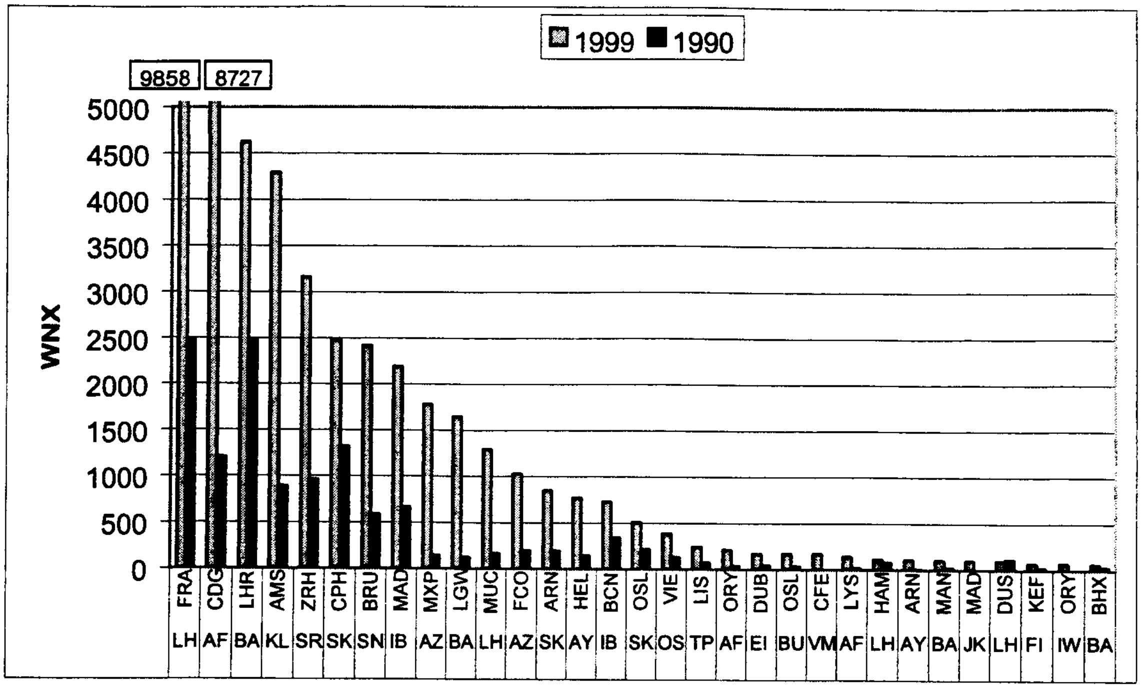
KLM at Amsterdam significantly improved its position as a hubbing carrier during the period of analysis. The carrier added an extra wave structure to the daily wave structure system, achieving a competitive frequency at Schiphol without a large investment in aircraft (see also section 6) (Caves, 1997). Air France started hub operations at Paris Charles de Gaulle in March 1996 with five waves a day (Dennis, 2001) with another 6th wave added by 1999 (figure 4). This resulted in an increase of the WNX values by a factor 7.

In contrast, BA at London Heathrow faced a relative decline in its competitive position for transfer traffic compared to the other major hub. From a first position in 1990, BA at London Heathrow moved to a third position in 1999.

We can observe some new hubbing strategies among the national carriers. Alitalia made use of the newly constructed airports of Milan Malpensa to increase indirect connections significantly compared to the hub position of the old airport Milan Linate. Malpensa overtook Rome Fiumicino's position as the primary hub for Alitalia (Dennis, 2001).

British Airways started to build up hub operations at London Gatwick because of capacity problems at Heathrow that prevent the carrier from implementing a wave structure at that airport. BA reorganized their schedules from and to Gatwick in order to allow connections within 26 minutes in Gatwicks North Terminal (Caves, 1997). However, as we will see in section 6, the wave-system structure is still very weak compared to wave-system structures of hubs such as Paris CDG and Frankfurt.

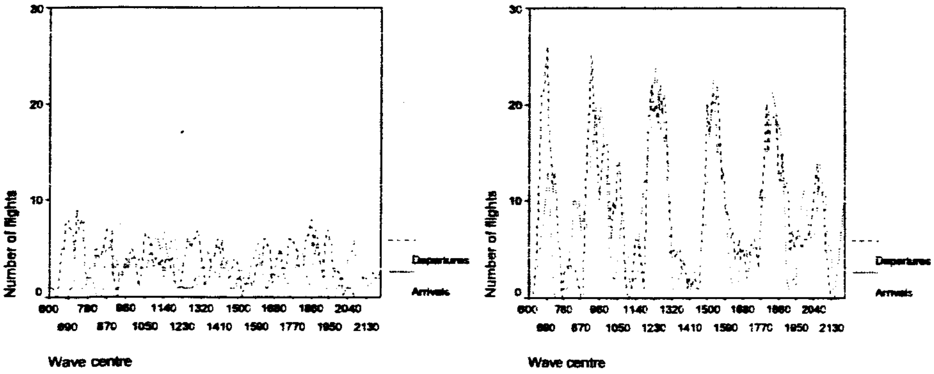
Figure 3 Number of weighted indirect connections (WNX) in 1990 and 1999 for the primary European airline hubs



Source: OAG/ ABC; own calculations. Note that WNX value for Alitalia (AZ) at Milan (MXP) are values for Malpensa in 1999 and Linate in 1990. WNX values for Oslo are for Fornebu in 1990 and Gardemoen in 1999. See appendix for carrier and airport codes.

Munich saw it indirect connectivity increase by a factor seven as a result of Lufthansa's policy to shift some of the service from Frankfurt because of capacity restrictions and the opening of the new airport in 1992. Sabena intensified its Brussels hub, mainly on the intra-European market. However, both Munich and Brussels suffer from the fact that most of the connections have a large routing factor, resulting from the fact that they are orientated towards intra-European indirect connections. Intra-European indirect connections are not as attractive as intercontinental connections because of the large transfer time compared to in-flight time. This factor has slowed down the growth of the indirect connectivity.

Figure 4 Wave-system structure of Air France at Paris CDG in 1990 (left) and 1999 (right)



Source: OAG/ ABC

At the lower level of the airport hierarchy, regional hub strategies have emerged. Dennis (2001) argues that the introduction of regional jets, such as the Embraer 145 and the Candadair Regional Jet, has facilitated the growth of these niche hubs. Regional Airlines implemented a wave structure system at Clermont-Ferrand. Air France started regional hub operations at Lyon. However, the weighted number of indirect connections generated by these carriers remains very small compared to the large hubs. They can only be successful when located far enough from the large hubs (Lyon, Clermont-Ferrand, Crossair at Basel/Mulhouse, Maersk at Billund) or in an alliance with a major carrier (Crossair at Zürich).

5.2 Geographical submarkets

Being an overall airline hub does not mean being an airline hub in all market segments. A clear market division can be observed between the different airline hubs. For the 15 main European airline hubs, we have analysed the competitive strength in terms of the number of weighted indirect connections in eight geographical submarkets for the year 1999:

1. From Europe to Europe (EUR-EUR)
2. From Europe to Eastern Europe (EUR-ESE)
3. From Europe to North America (EUR-NAM)
4. From Europe to Latin America (EUR-LAM)
5. From Europe to Asia and the Pacific (EUR-APA)
6. From Europe to Africa (EUR-AFR)
7. From Europe to Middle East (EUR-MEA)
8. Between non-European submarkets (directional)

Analysing the submarkets, we can divide the airline hubs roughly into four categories: the allround hubs, the specialized hinterland hubs, the European hubs and the directional or hourglass hubs (figure 5 and table 3).

The 'allround' hubs

Only a few 'allround' hubs can be distinguished (figure 5). Allround hubs are hinterland hubs: hubs with a high degree of indirect connectivity from hinterland Europe to all geographical submarkets. Allround hubs are also directional or hourglass hubs for an airline. They do not only offer hinterland connections but also 'hourglass' connections between different continents.

The European allround hubs are Frankfurt (LH), London Heathrow (BA), Amsterdam (KL), Paris CDG (AF) en Zürich (SR). Amsterdam and London Heathrow perform poor in the Eastern-European market. London Heathrow has also a bad position in the Southamerican market and is somewhat biased to the North American market. About 30 % of its indirect services from European airports are directed towards this market. London Gatwick could be considered as an allround hub. However, its Asia-Pacific market is very poorly developed.

Specialized hinterland hubs

A number of airline hubs has a bias towards one or a number of intercontinental submarkets, such as Brussels, Madrid, Milan Malpensa, Munich, Paris Orly and Dublin. Moreover, they do not provide significant service to all of the submarkets nor do they have large numbers of hourglass connections. We call these hubs specialized hinterland hubs.

Most of the geographical biases seem to be related to historical relations with the area considered. Others are based on geographical proximity. Munich and Vienna are clearly biased towards the Eastern European market for their transfer traffic, which is related to the geographical location of both hubs (Allett, 2002). Madrid devotes a large share of indirect connectivity to Latin American destinations whereas Brussels and Paris Orly have a comparatively large share of indirect connectivity direct towards Africa. Aer Lingus' hub Dublin has a bad position in a geographical sense (RI=0,1) for intra-EU traffic but strongly orientated towards North America.

Table 3 Categorization of airline hubs in 1999 by weighted indirect connectivity and market orientation

		Market orientation			
		Allround	Biased hinterland	European	Directional
Number of weighted indirect connections	High (>2500)	Amsterdam (KL) Zürich (SR) Frankfurt (LH) Paris CDG (AF) London Heathrow (BA)			
	Medium (500-2500)		Brussels (SN) London Gatwick (BA) Munich (LH) Madrid (IB) Milan MXP (AZ)	Copenhagen (SK) Rome FCO (AZ) Stockholm Arlanda (SK) Helsinki (AY) Barcelona (IB) Oslo (SK)	Vienna (OS)
	Low (<500)		Paris Orly (AF) Reykjavik (FI) Dublin (EI)	Clermont-Ferrand (VM) Lisbon (TP) Olso (BU) Lyon (AF) Hamburg (LH) Stockholm Arlanda (AY) Manchester (BA) Madrid (Spanair) Düsseldorf (LH) Paris Orly (IW) London Stansted (FR) Vienna (VO) Cologne (LH) Stavanger (BU) Bergen (BU) Birmingham (BA) Milaan Linate (AZ)	

Source: OAG/ ABC; own calculations. See appendix for carrier codes

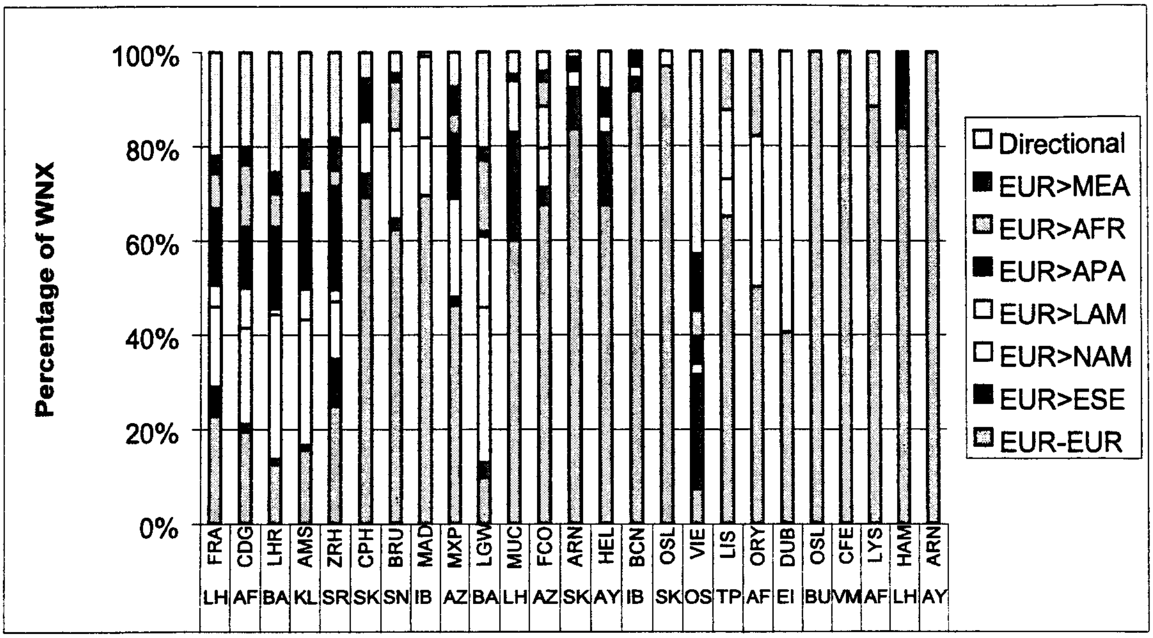
European hubs

Airline hubs such as Copenhagen, Rome Fiumicino, Stockholm Arlanda, Helsinki, Barcelona, Oslo, Lisbon, Clermont-Ferrand, Lyon and Hamburg offer a number of indirect connections but these are mainly intra-European (over 70% European). This kind of transfer traffic seems to be the most vulnerable one. On the one hand, more and more indirect intra-European services will be replaced by direct, point-to-point services because of the introduction of regional jets and the growth of low-cost carriers as well as the construction of the high-speed rail network. On the other hand, European hubs suffer from large routing factors because of the short in-flight time compared to the transfer time at the hub airport.

Directional or hourglass hubs

These are the airports offering indirect connections between different continents. Austrians hub Vienna is the only hourglass hub in Europe. It mainly offers connections between other continents and Eastern Europe. However, the absolute number of these connections is small compared to the directional connections of the allround hubs.

Figure 5 Share of different geographical submarkets in total number of weighted indirect connections (WNX) for the primary European hubs. Note that only submarkets with WNX>10 have been included



Source: OAG/ABC; own calculations. See appendix for carrier and airport codes

6. WAVE-SYSTEM STRUCTURES

In section 5 we have analysed the weighted number of indirect connections of airline hubs. We have seen that only a few airline hubs are highly competitive in the indirect market. Small airline hubs play an insignificant role outside the direct O-D markets. Therefore, for the analysis of the airline flight schedule itself, we will only consider airline hubs with a WNX value of 10 and higher in 1990 as competitors in the indirect market. This resulted in a sample of 62 airports. Subsequently, we have analysed the sample on the presence of a wave-system structure using the methodology of section 3.1.

Have European airline adopted flight schedules characterised by a wave-system structure, one of the characteristics of hub-and-spoke networks?

6.1 The presence of wave-system structures in airline flight schedules

Hub-and-spoke networks need both spatial and temporal concentration of flights. Burghouwt et al. (2003) have concluded that most airline networks, especially national airline networks, were already heavily concentrated in space in the regime of bilateral regulation. Only a few regional airlines demonstrate spatial concentration strategies. A development towards temporal concentration into wave-system structures can be observed however.

Based on the sample of 62 airline stations, we can conclude that European airlines have increasingly adopted wave-system structures or intensified the existing structures (table 4). The number of airline hubs (those airline stations with a wave-system structure) doubled during the period of analysis. A number of airlines intensified the wave-system structure by adding more waves or increasing the quality of the wave-system structure (table 5). Only one airport was 'de-hubbed': Lufthansa's Cologne. After the German Government moved its headquarters to Berlin, the importance of Cologne/ Bonn airport decreased ad did the role of the airport in the network of Lufthansa.

Table 4 Presence and quality of wave-system structures for a sample of 62 airline stations (airports) with more than 10 daily indirect connections in 1999, 1990 and 1999

Presence and quality of wave-system structure	Number of airline stations	
	1990	1999
absent	52	40
very poor	5	6
poor	1	2
limited	3	3
good	1	10
very good	0	1
TOTAL	62	62

Source: OAG/ ABC; own calculations

Table 5 Presence of wave-system structures[5] (wss) and number of waves, 1990 and 1999 for primary European hubs (WNX>10)

		Quality of wave-system structure		Number of waves	
		1990	1999	1990	1999
Air France	Paris CDG	absent	good		6
Air France	Lyon	absent	good		3
Air France	Marseille	absent	absent		
Air France	Paris Orly	absent	very poor		3>4
Finnair	Stockholm Arlanda	absent	absent		
Finnair	Helsinki	absent	very poor		2>3
Finnair	Turku	absent	absent		
Alitalia	Rome Fiumicino	very poor	poor	2	5
Alitalia	Milan Linate	absent	absent		
Alitalia	Milan Malpensa	absent	limited		4
BA	Birmingham	absent	absent		
BA	Johannesburg	absent	absent		

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[5] Criteria for the assessment of the quality of the wss are available from the authors upon request

BA	London Gatwick	absent	very poor		
BA	London Heathrow	absent	absent		
BA	Manchester	absent	absent		
British Midland	East-Midlands	absent	absent		
British Midland	London Heathrow	absent	poor		2
Braathens	Bergen	absent	absent		
Braathens	Oslo	absent	absent		
Braathens	Stavanger	absent	absent		
Braathens	Trondheim	absent	absent		
Maersk	Billund	absent	absent		
Maersk	Copenhagen	absent	absent		
Aer Lingus	Dublin	absent	absent		
Aer Lingus	Shannon	absent	absent		
Icelandair	Reykjavik-Kevlavik	absent	absent		
Ryanair	London Stansted	absent	absent		
Air Littoral	Nice	absent	very poor		4
Iberia	Barcelona	very poor	good	2	2
Iberia	Madrid	very poor	limited	3	3>4
Air Liberté	Paris Orly	absent	very poor		2
AOM	Paris Orly	absent	absent		
Spanair	Madrid	absent	absent		
KLM	Amsterdam	limited	good	3	4>5
Lufthansa	Cologne	very poor	absent	2	
Lufthansa	Düsseldorf	absent	absent		
Lufthansa	Frankfurt	good	good	4	4
Lufthansa	Hamburg	absent	absent		
Lufthansa	Munich	absent	good		3
Lufthansa	Stuttgart	absent	absent		
Lufthansa	Berlin Tegel	absent	absent		
LTU	Düsseldorf	absent	absent		
Crossair	Basle	absent	good		2
Crossair	Zurich	absent	absent		
Lauda Air	Vienna	absent	absent		
Binter Canarias	Tenerife Norte	absent	absent		
Austrian	Vienna	poor	good	2	4
SAS	Stockholm Arlanda	absent	absent		
SAS	Copenhagen	limited	limited		5>6
SAS	Oslo	absent	absent		
SAS	Stavanger	absent	absent		
SAS	Tromso	absent	absent		
Sabena	Brussels	limited	good	4	4
Swissair	Geneva	absent	absent		
Swissair	Zurich	very poor	good	3	7
TAP Air Portugal	Lisbon	absent	very poor		2
TAP Air Portugal	Oporto	absent	absent		
Easyjet	London Luton	absent	absent		
Air Europa	Madrid	absent	absent		

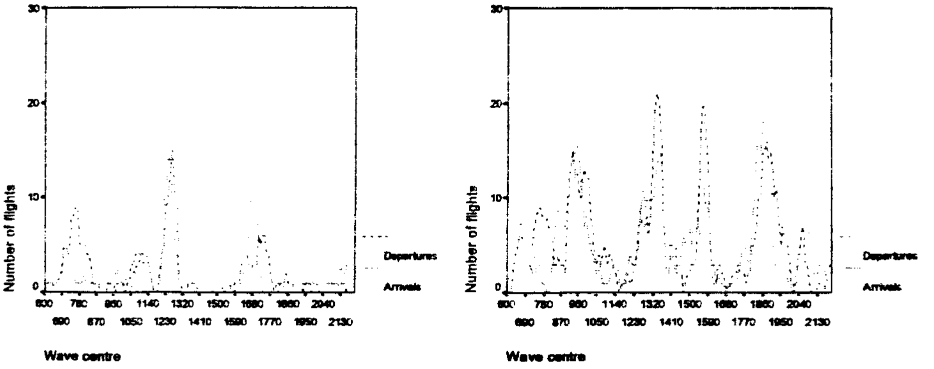
Régional Airlines	Clermont-Ferrand	absent	very good			4
Tyrolean	Vienna	absent	very poor			2
Wideroe's	Bodo	absent	absent			

Source: OAG/ABC; own calculations.

Air France has adopted a six-wave system at Paris CDG, reconfiguring the airport in a real traffic pump (figure 4). Alitalia has done the same at Milan Malpensa with a four-wave system. Lufthansa, as stated before, moved some of its hub operations from Frankfurt to Munich. The three waves at Munich fit exactly in the wave-system structure at Frankfurt in order to increase synergies between the two hubs. Regional Airlines, Air France, Iberia set up wave-system structures at Clermont-Ferrand, Lyon and Barcelona respectively. Crossair implemented a wave-system structure at Basel.

Some airlines intensified their hub operations during the period of analysis. KLM added two extra waves to its three-wave system (figure 6). Swissair consolidated all its intercontinental operations around Zürich (Burghouwt et al., 2002) and added four waves to its hub operations at this airport. Austrian made its operations at Vienna more efficient and added an extra wave to the wave-system structure.

Figure 6 Flight schedule structure of KLM at Amsterdam, 1990 (left) and 1999 (right)

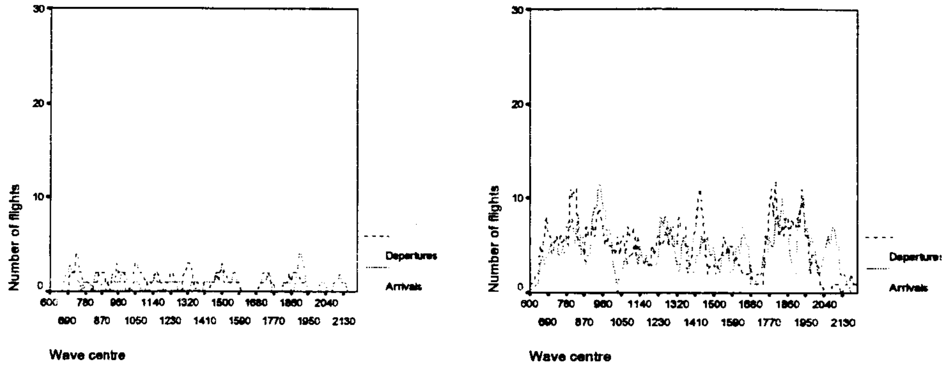


Source: OAG/ABC

Four major exceptions to the temporal concentration trend exist. The majority of the airports (40 airline stations) did not have a wave-system structure in 1999.

Firstly, the major British hubs lack flight schedule coordination. British Airways was not able to implement a wave-system at Heathrow, Gatwick (figure 7), Birmingham or Manchester. Capacity shortages at these airports make it extremely difficult for the airline to implement a schedule structure. However, the high frequencies still generate quite a large number of connections and high transfer efficiency in the case of Gatwick.

Figure 7 Flight schedule structure of British Airways at London Gatwick, 1990 (left) and 1999 (right)

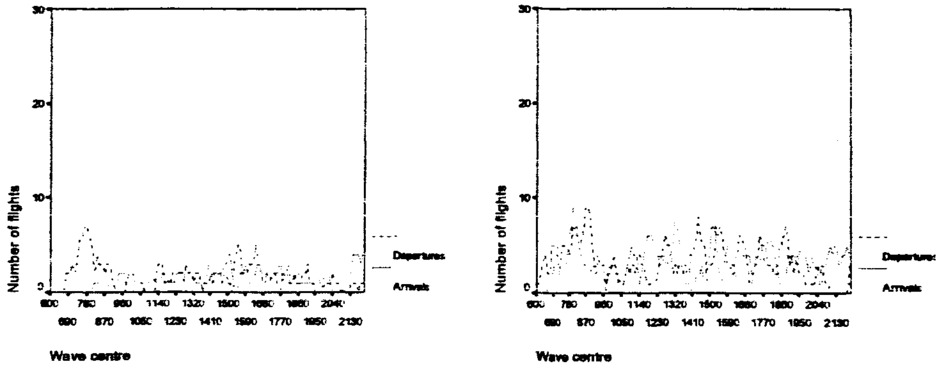


Source: OAG/ ABC

Secondly, the southern European airports show no or limited wave-structures, except from Milan Malpensa and Barcelona. Their geographical position makes it difficult to compete with the traffic flows into northern Europe (Bootsma, 1997). Instead, the home carriers of these airlines seem to focus on O-D traffic and some indirect connections in the domestic and Latin-American market.

Thirdly, a number of smaller airports such as Oslo (SAS/ Braathens), Stockholm Arlanda (SAS) (figure 8), Helsinki (Finnair), London Stansted (Ryanair) and Dublin (Aer Lingus) are not hub airports in a strict sense. The network of the home carriers is to some extent centred around these airports, but a clear schedule structure is lacking. The carriers do no have specific schedules to facilitate transfers although a number of connections is generated 'by accident'. They focus on O-D traffic and/or traffic feed to the major hubs.

Figure 8 Flight schedule structure of SAS at Stockholm Arlanda, 1990 (left) and 1999 (right)



Source: OAG/ ABC

6.2 The impact of wave-system structures on indirect connectivity

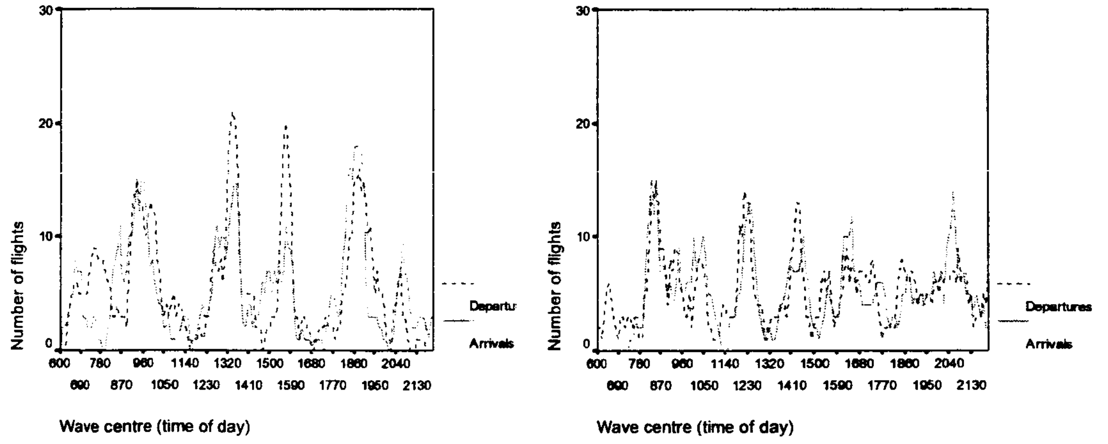
We have seen that a number of European airlines have adopted wave-system structures in their flight schedules. Another group of carriers did not implement or did not fully implement such a wave-system structure in the flight schedule. If airlines implement a wave-structure, do these wave-system structures indeed improve significantly the total weighted indirect connectivity of a hub airport?

Wave-system structures indeed seem to have a positive impact on the total indirect connectivity of a hub airport. Wave-system structures have the objective to maximize the number of connecting opportunities within a limited time frame given the number of direct flights. Hence, the ratio between a given number of direct connections on the one hand and the number of indirect connections at the airline hub on the other hand should theoretically be larger for airports with a wave-system structure than for airports without a wave-system structure.

In figure 12, we have ranked the top 50 airline stations according to the number of daily direct flights in 1999. As can be expected, the ratio between the weighted number of indirect connections (x-axis) increases when the number of direct flights increases due to the quadratic nature of hub-spoke traffic. Every new direct connection results in a multiplicity of new indirect connections. Therefore, airlines offering more direct flights from an airport will show a larger ratio between indirect and direct connectivity. However, the increase in the ratio is far from constant. Increases in this ratio seem to be heavily influenced by the presence and quality of the wave-system structure. Airline hubs with a full wave-system structure have generally a larger ratio between indirect and direct flights than carrier hubs with a poorly developed wave-system structure or without a wave-system structure.

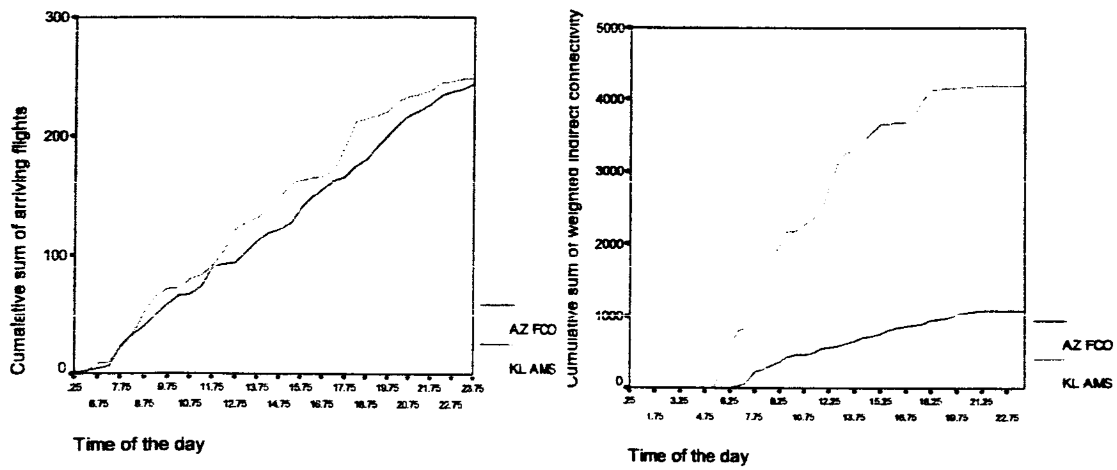
KLM's hub at Amsterdam Schiphol for example, is comparable to Alitalia at Rome FCO in terms of the number of direct flights (figure 10). However, KLM manages to offer a lot more indirect connections per direct flight than Alitalia. KLM operates a well-developed wave-system structure at Amsterdam whereas the wave-system structure of Alitalia at Rome is somewhat less efficient because of the smaller waves and may-off wave connections (figure 9). Moreover, minimum connection times at Amsterdam are smaller than at Rome resulting in more possible connections for every arriving flight.
The result of a poorly developed wave structure system is the slow increase during the day of the total number of weighted indirect connections as in the case of Alitalia at Rome Fiumicino (figure 10). Well-developed waves offer a carrier large stepwise increases of the number of weighted indirect connections as in the case of KLM at Amsterdam Schiphol.

Figure 9 Wave-system structure of KLM at Amsterdam (left) and Alitalia at Rome Fiumicino (right) in 1999



Source: OAG/ABC

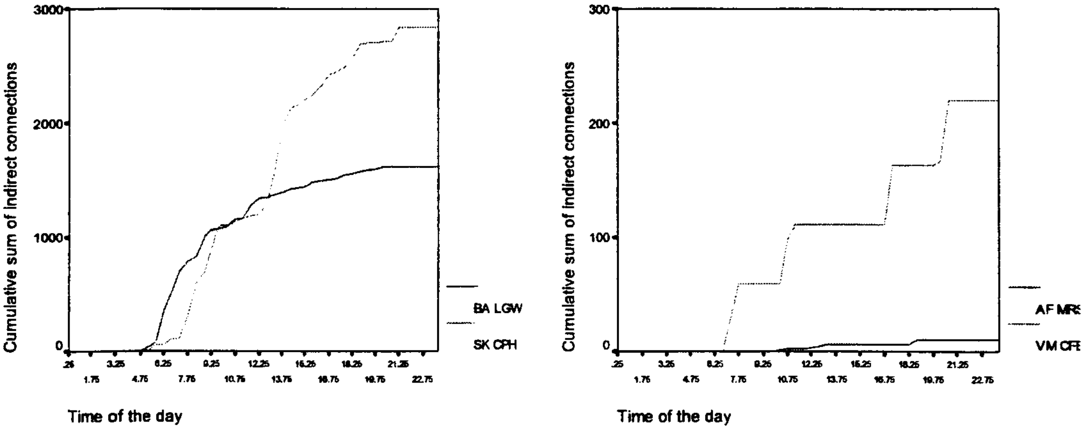
Figure 10 Cumulative number of daily direct flights for Alitalia at Rome Fiumicino and KLM at Amsterdam in 1999 per time unit (left) and the cumulative number of weighted *indirect connections for Alitalia at Rome Fiumicino and KLM at Amsterdam in 1999 per time unit (right)*



Source: OAG/ABC

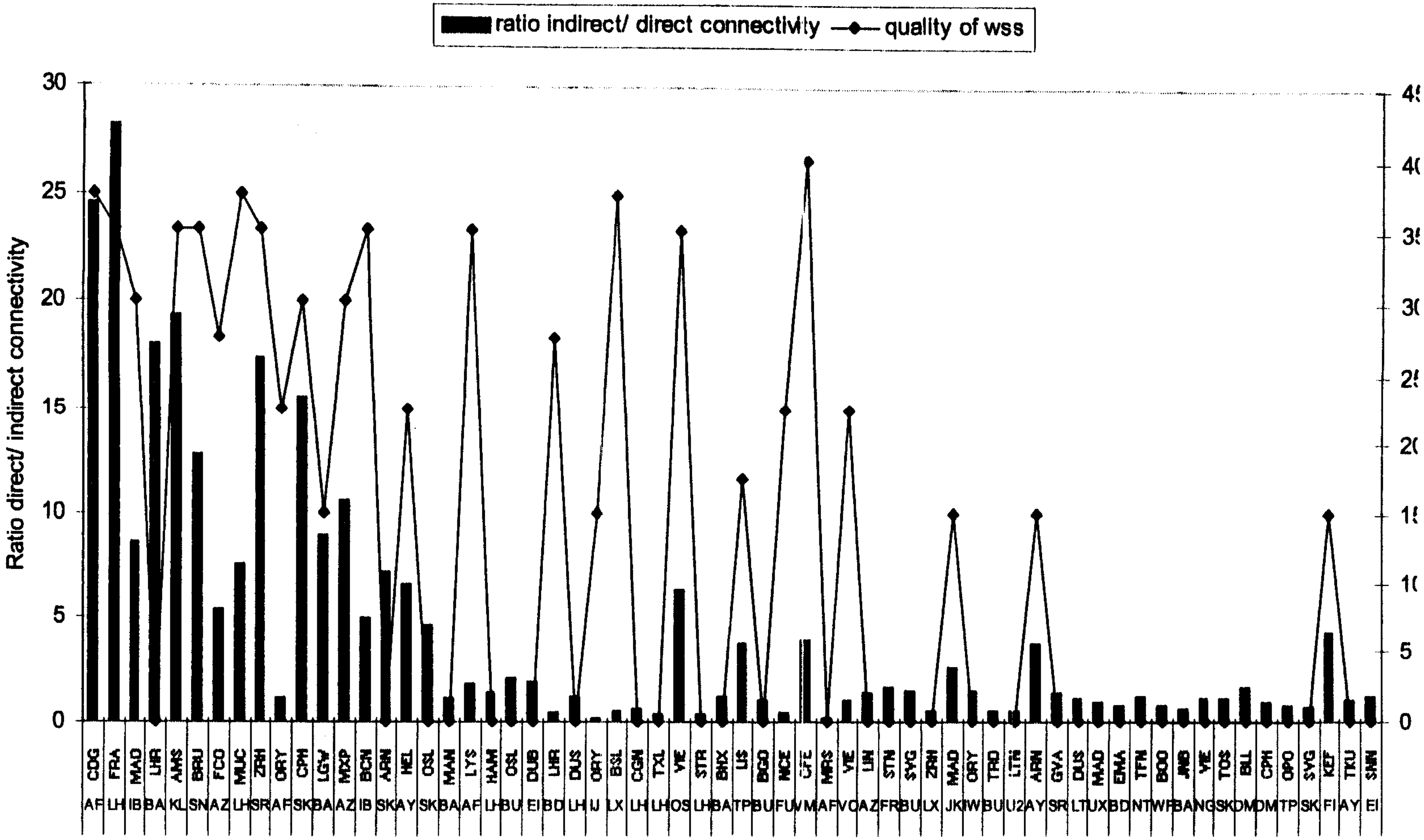
Another example is the situation of SAS at Copenhagen and BA at London Gatwick. SAS operates a full wave-system structure at Copenhagen whereas such a system is lacking at Gatwick. Both airports are comparable in terms of the number of direct daily flights. However, the number of weighted indirect connections is much larger for Copenhagen than for Gatwick as a result of the wave-system structure (figure 11, 12). The same holds true for the hub of Regional Airlines at Clermont Ferrand (with a wave-system structure) compared to Air France at Marseille without such a wave-system structure (figure 11, 12).

Figure 11 Cumulative number of weighted indirect connections for British Airways at London Gatwick and SAS at Copenhagen (left) and the cumulative number of weighted indirect connections for Régional Airlines at Clermont Ferrand and Air France at Marseille (right)



Source: OAG/ABC

Figure 12 Ratio between weighted indirect connectivity and the number of daily direct flights from the hub airport versus the presence and quality of the wave-system structure (40=very good; 35-37.5=good; 30-32.5=limited; 25-27.5=poor; 15-25=very poor; <15=absent)



7. Conclusions and discussion

After the deregulation of the U.S. aviation market, airlines adopted hub-and-spoke networks to benefit from cost and demand side economies as well as to deter entry. The question rises if European airlines followed the same network strategy after deregulation of the EU aviation market.

The hub-and-spoke system can be considered as a network with two principal characteristics. On the one hand, spatial concentration of traffic around one or a few hub airports and on the other hand, temporal concentration of flights in a number of daily connection waves. Airports cannot be considered as real hubs as long as airlines have not implemented a clear wave-system structure. Previous research shows that the networks of major European airlines were already concentrated in space around a limited number of central airports at the beginning of deregulation. This can be explained by the system of bilateral air service agreements, that originally required airlines to only operate from their national home base (nowadays modern asa's allow to operate from any point in the national market).

What about the temporal configuration of airline networks in Europe?

A trend towards increasing temporal concentration can indeed be identified. Major European airlines implemented or intensified their wave-system structures at the major hubs during the period of analysis (1990-1999). Especially the major airlines and some niche-carriers have followed this hub-and-spoke strategy.

Most of the smaller airlines as well as the new entering low-cost airlines are focused on O-D traffic and do not play a significant role in the market for transfer traffic. An explanation for the difference between large and small carriers might be the fact that large hub-and-spoke networks have a very large demand and cost advantage in terms of the number of city pairs served compared to smaller airlines hubs. According to Oum et al. (1995), a new entrant has to compete at the entire HS network of the incumbent hub carrier and operate out of its own hub in order to compete successfully. This would be a very costly and risky undertaking. Therefore, small airlines will focus on O-D and hub-hub markets unless their hubs are sufficiently separated from the major hubs as in the case of Régional Airlines and Crossair.

The increase in wave-system structures has stimulated the number of connecting opportunities at hub airports. We have shown that airports with wave-system structures offer generally more indirect connections than airports without a wave-system structure, given a certain number of direct flights.

Between 1990 and 1999, the adoption of wave-system structures by airlines and the overall growth of frequencies have resulted in a significant increase of indirect connections, especially for the major hubs (due to the network economies of hub-and-spoke networks). Being an airline hub does not mean being an airline hub in all submarkets. We have distinguished allround, hinterland, European and directional hubs.

We have restricted our analysis to transfers within one airline. Future research should also take into account transfer opportunities between partners of the same alliance.

European airline networks were already concentrated in space around a limited number of home bases before deregulation. The regime of bilateral regulation bounded airlines to their national airports. These radial networks were not an equivalent for hub-and-spoke networks since most transfer connections were created 'by accident'. With the deregulation of the EU air transport market from 1988 on, a second phase of airline network concentration started. European airlines concentrated their networks in time by adopting or intensifying wave-system structures in their flight schedules at central airports. Temporal concentration may increase the competitive position of the network in a deregulated market because of certain cost and demand advantages.
The second phase of network concentration in Europe has changed the context in which airport planners operate. Hub-and-spoke networks have stimulated the amount of transfer traffic at hub-airports. Transfer traffic is footloose since it can easily divert to other hub airports. Hub-and-spoke networks and the freedom of entry and exit in deregulated markets induce therefore the volatility of future airport traffic volumes and change the requirements for airport terminal lay-out (de Neufville, 1995). Within this constantly changing and uncertain arena, research on more flexible approaches to strategic airport planning in Europe will be needed.

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Appendix: carrier and airport codes

code	airline	code	airport	code	airport
AF	Air France	AMS	Amsterdam	MXP	Milan Malpensa
AY	Finnair	ARN	Stockholm Arlanda	NCE	Nice
AZ	Alitalia	BCN	Barcelona	ORY	Paris Orly
BA	British Airways	BGO	Bergen	OSL	Oslo
BD	British Midland	BHX	Birmingham	STN	London Stansted
BU	Braathens S.A.F.E.	BRU	Brussels	STR	Stuttgart
EI	Aer Lingus	BSL	Basle	SVG	Stavanger
FI	Icelandair	CDG	Paris Charles de Gaulle	TRD	Trondheim
FR	Ryanair	CFE	Clermont-Ferrand	TXL	Berlin Tegel
FU	Air Littoral	CGN	Cologne	VIE	Vienna
IB	Iberia	DUB	Dublin	ZRH	Zurich
IJ	Air Liberté	DUS	Dusseldorf		
IW	AOM	FCO	Rome Fiumicino		
JK	Spanair	FRA	Frankfurt		
KL	KLM	GVA	Geneva		
LH	Lufthansa	HAM	Hamburg		
LT	LTU	HEL	Helsinki		
LX	Crossair	LGW	London Gatwick		
OS	Austrian Airlines	LHR	London Heathrow		
SK	SAS	LIN	Milan Linate		
SN	Sabena	LIS	Lisbon		
SR	Swissair	LTN	London Luton		
TP	TAP Air Portugal	LYS	Lyon		
U2	Easyjet	MAD	Madrid		
UX	Air Europa	MAN	Manchester		
VM	Régional Airlines	MRS	Marseille		
VO	Lauda Air	MUC	Munich		