IMPACT OF TIMETABLE SYNCHRONIZATION ON HUB CONNECTIVITY OF EUROPEAN CARRIERS

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ABSTRACT

This paper evaluates the net impact of timetable synchronization on the connectivity of the key European carriers at their main hubs. We measure hub connectivity using a weighted connectivity score (WCS) that takes into account the number and the trip time related quality of flight connections. Based on WCS, we compare hub performance resulting from the existing schedule against a random expectation calculated from multiple randomized schedule simulations. In each simulated schedule scenario we randomly vary the flight departure and arrival times within the operation hours at a hub and at outbound stations keeping all other flight parameters from the real schedule unchanged.

We observe that the timetable synchronization leverages hub connectivity of most analyzed airlines by 40% to 60%. The highest increase of connectivity is achieved by medium-sized carriers that operate peaky wave systems with flights concentrated in many short and non-overlapping banks, as well as by carriers that organize their flights in directional waves. The lowest increase is achieved by airlines that operate at highly congested airports. At most hubs, connections to long-haul flights operated with wide-body aircraft are better synchronized than connections between short-haul flights.

Keywords: *Hub connectivity, airline timetable synchronization, connection building, hub wave system.*

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1 INTRODUCTION

1.1 Motivation

Connectivity and hub-and-spoke networks play an important role in the air transport industry. Concentration of many flight operations at hub airports allows airlines to maximize the number of transfer connections and city-pairs served by their network and, thus, to increase their offer to passengers. To fully utilize the hub potential for generating connecting flights, the departures and arrivals at hub should be temporarily synchronized so that the passengers from incoming flights could transfer to a maximal number of outgoing flights with convenient transfer times.

The design of the timetable has a direct impact on airline's connectivity at a given hub. Other factors that impact the hub connectivity (like total number of flight movements, geographic location, destination portfolio, demand distribution, curfews, slot restrictions etc.) have more exogenous character and can be usually influenced only to a limited extend within one or even several planning periods. In this context, improving the timetable synchronization can be seen as the most relevant means the carriers have to maximize their connectivity of a given hub.

The impact of timetable synchronization on the hub performance is difficult to measure and to isolate from other factors that determine the hub connectivity of a given airline. Any hub will generate a certain number of connections even with a random or counter-productive scheduling of flight operations. Since the number of hub connections increases over-proportionally to the number flights served at the hub, a large hub with a non-connectivity driven or simply poorly designed timetable may offer more and better connections than a smaller, well-optimized hub system.

1.2 Objective and Methodological Outlook

The objective of this paper is to evaluate the net impact of timetable synchronization on the overall airline connectivity at hubs. Similar to previous studies, hub connectivity is measured using a weighted connectivity metric based on the number and the quality of flight connections. We assess the impact of timetable synchronization on airline hub connectivity by comparing the existing connectivity from the published schedule to the expected connectivity resulting from a random temporal flight scheduling.

The expected airline connectivity at hub is calculated from multiple simulation runs. In each simulated schedule scenario we randomize only the flight departure and arrival times. All other parameters of the existing schedules (like frequencies per route, origin/destination portfolio, fleet types, block times, terminals etc.) are kept unchanged. The simulations take into account airport operating hours (congestion and night flight limitations) at analyzed hubs and all outstations. As result, each simulation generates a feasible schedule scenario that is further analyzed just like the existing schedule using a fully defined connection builder (e.g. minimum connection time exceptions and traffic restrictions applicable to any specific flight combination) with parameter settings calibrated in previous research (Seredynski et al., 2014). This allows us to use an advanced connectivity metric to evaluate hub connectivity and, by comparing it with the random expectation, to better assess what share of the airline connectivity is leveraged by the hub timetable synchronization.

1.3 Literature Review and Contribution

Many studies examine airline connectivity at hub airports. In general, connectivity is measured by summing up the (weighted) number of connections or origin and destination (O&D) pairs available at the corresponding hubs. The main differences in the published approaches are (a) the algorithms and parameters that are applied to construct the connections and (b) the assessment or weighting of the individual connections.

Typically, connection time, geographical detour or trip time related quality features are used as the main parameters for connection building. Some studies apply maximum acceptable thresholds directly on connection time and detour (Bootsma, 1997; Danesi, 2006; Dennis 1994; Doganis and Dennis 1989; Lee et al., 2014) Others combine these two parameters to limit the maximum acceptable trip time of a connection Allroggen et al., 2015; Burghouwt and de Wit, 2005; Burghouwt and Veldhuis, 2006; Burghouwt, 2007; De Wit et al., 2009; Grosche et al., 2015; Suau-Sanchez and Burghouwt,2012; Veldhuis,1997). In some approaches, the above parameters are complemented or even replaced by benchmarking each connection to the fastest connection on the corresponding O&D. Connections that don’t satisfy certain benchmark criteria are disqualified (Grosche and Klophaus, 2015; Malighetti et al., 2008; Paleari et al., 2010; Redondi et al., 2011). The settings of the connection building parameters or rules vary a lot among the studies. For example, maximum connection time ranges from 90-180 minutes (Danesi, 2006; Dennis, 1994; Doganis and Dennis 1989) to 180-720 hours (Bootsma, 1997; Burghouwt and de Wit,2005). Few studies use parameter settings calibrated against ticket or booking data (Allroggen et al., 2015; Grosche et al., 2015). In most other cases the parameters are chosen according to the authors’ discretion.

The total number of hub connections that satisfy the above criteria can serve as a simple connectivity metric (Dennis 1994; Doganis and Dennis 1989). However, most of the above mentioned studies further evaluate the generated connections and put a higher weight to faster connections that are more attractive to passengers. Typically, a value between 0 (the slowest possible connection allowed by the connection building) and 1 (a perfect connection) is assigned to each connection and the aggregated hub connectivity metric is calculated as a weighted sum of all connections served at the respective hub. In addition to such measures, some researchers include supplementary metrics and/or weighting criteria to further assess the competitive position of hubs (e.g. average frequency, connection time, detour, trip time (Redondi et al., 2011), connected seat capacity (Grosche and Klophaus, 2015), O&D traffic volume –(Grosche et al., 2015), GDP or wealth adjusted population data for origins or destinations (Allroggen et al., 2015; Malighetti et al., 2008)).

Burghouwt and Redondi (2013) provide a detailed overview and comparison of various methods to measure hub connectivity. One of the interesting conclusions of their work is that, although the analyzed approaches use very different parameters, the resulting hub performance measures are all strongly correlated with the size of the hubs and lead to a similar performance ranking of the analyzed European hubs.

The studies briefly reviewed above provide a valuable contribution to research area of airline network planning. The proposed measures of hub connectivity can be used in many practical applications, especially to benchmark the competitive position of airlines and hubs on certain markets or to evaluate the network performance of various schedule scenarios. However, because of the underlying scale effects it is difficult to isolate the net impact of airline timetable design on the resulting hub connectivity.

Only selected studies (Danesi, 2006; Dennis, 1994; Doganis and Dennis, 1989; Rietveld and Brons, 2001) aim to evaluate how the timetable synchronization impacts airline connectivity at hubs. In all these approaches, the quality of hub timetable synchronization is calculated as a ratio between the observed connectivity at a hub and the connectivity that would result from a random (or rather uniform) scheduling a departure and arrival flights along the timeline. Early studies (Dennis, 1994; Doganis and Dennis, 1989) use the number of hub connections that satisfy assumed minimum and maximum connection time (set to 90 minutes) restrictions as the hub connectivity performance indicator. The number of connections is compared to the number expected to occur if the arrival and departure times were uniformly distributed across a typical airport operation period (7:00-22:00). Danesi (2006) proposed an enhancement of this approach and developed a “weighted connectivity ratio” index. This approach allows to apply various connection building parameters depending on the market type (e.g. continental, intercontinental) and to classify connections in various quality levels depending on their detour and connecting time. Rietveld and Brons (2001) assumed that the expected average transfer time for an airport-pair connected via a given hub depends on the frequency of the most frequent leg and the minimum connection time at the hub.

The authors compared the observed average transfer times for selected hubs and airport-pairs with the respective expectation resulting from a uniform distribution of flights and calculated a coefficient of timetable coordination.

The above approaches to measure the impact of timetable synchronization on hub connectivity are limited to simple connectivity metrics and they are further biased by simplifying assumptions (e.g. airport operation hours ignored, MCT globally fixed etc.). The methodology presented in this paper overcomes these limitations and allows to use any, even complex connectivity metrics to measure how the timetable synchronization impacts airline connectivity at hubs.

1.4 Organization of the Paper

The next section presents the methodological set-up of the analysis. We present the settings of the connection building algorithm and introduce the weighted connectivity score (WCS) to measure hub connectivity. WCS takes into account the number and the trip time related quality of hub connections. We also discuss the assumptions and settings of the schedule randomization used in the simulations. In section 3, we present the results and discuss the impact of timetable synchronization on connectivity of the top European network carriers at their main hubs. Given the importance of long-haul operations, in a dedicated analysis we examine the connectivity and timetable synchronization for long-haul and short-haul flights separately. Finally, we investigate the sensitivity of key results with respect to different connection building parameters and connectivity metrics. We conclude with a brief discussion of the key observations.

2 ANALYSIS SET-UP

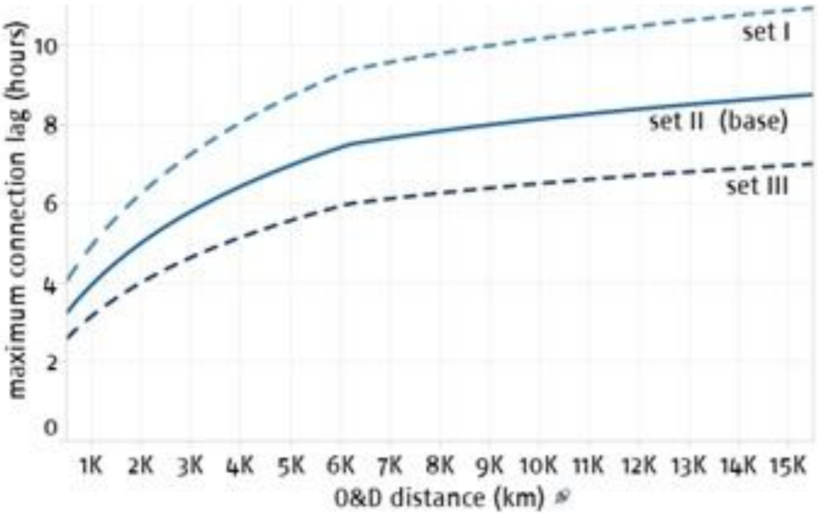
2.1 Connection Builder

The connection builder (CB) applied in this paper generates single-stop, online connections. All connections are feasible with regard to traffic restrictions on the given airport-pair level (freedoms of the air). In addition, for each connection the individual minimum connection time (retrieved from the full list of exceptions) is applied. The maximum acceptable geographical detour factor, defined as the ratio between the total distances of the connecting flights and the direct distance between the given origin and destination (O&D) airports, is globally restricted to 2.0 and further limited by the next parameter described below.

The key parameter of the CB applied is the maximum connection lag (*maxConLag)*. The detailed introduction of this parameter is given in (Seredynski et al., 2014). Connection lag is the sum of connection time and the additional flight time due to geographical detour. It can be interpreted as the difference between the total travel time of a given connection compared to the travel time of a hypothetical "ideal" connection involving no geographical detour and no connecting time. By setting a maximum value *maxConLag* as a parameter of a CB, a limit to the acceptable total trip time of each connection is set. This approach works similarly as the trip time related parameters used in several other studies e.g. (Allroggen et al., 2015; Burghouwt and de Wit, 2005; Burghouwt and Veldhuis, 2006; Suau-Sanchez and Burghouwt, 2012; Veldhuis, 1997) but it allows us to use parameter settings calibrated with the passenger booking data from previous research (Seredynski et al., 2014). We choose the parameter setting of *maxConLag* according to Figure 1. The solid line (set II) represents values of *maxConLag* over O&D distance that cover approximately 95% of the global bookings for two-segment, online and code-share connections. This setting is used to generate the base set of connections used in this study. In addition, to generate connection sets for the sensitivity analysis, we chose additional settings of *maxConLag* that result in approximately 98% (set I) and 90% (set III) of the bookings, represented in Figure 1 by dashed lines.

We apply one more CB restriction to disqualify non-competitive connections. If two connections on the same origin and destination airport pair (O&D) use the same flight leg, the faster option is more preferable for passengers (Coldren et al., 2003; Garrow, 2010). Of all connections that share a common flight leg (in- or outbound) and connect the same O&D, usually the fastest two options (#1 and #2 in Figure 2) attract most passengers (Seredynski et al., 2014). Other connection options are not attractive to passengers and they are hardly valuable from a network planning perspective. Hence, we limit the set of generated connections to the most competitive ones by allowing only the fastest (#1) and the second-fastest (#2) connections.

Figure 1. Connection builder settings: Maximum acceptable connection lag depending on the O&D distance.

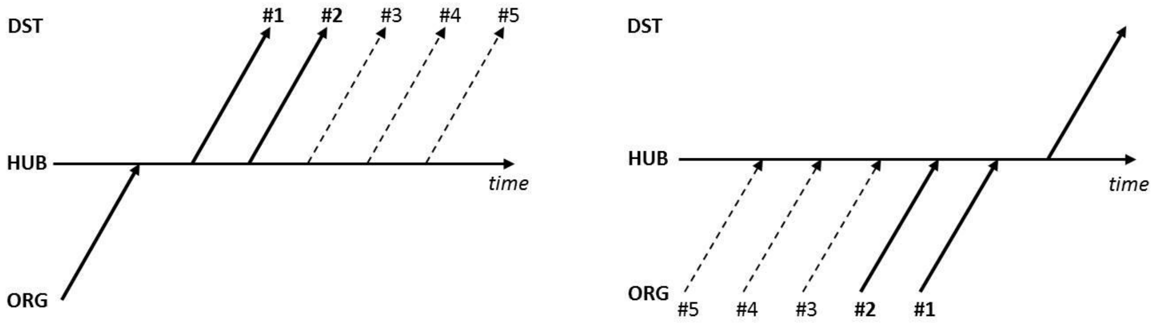


2.2 *Connectivity and Timetable Synchronization Measures*

Most of the studies reviewed in section 1.3 measure airline connectivity at hubs by analyzing the number and the quality of available connections. The quality of the connections are usually evaluated with some trip time related (e.g. connection time, detour) parameter. In this study we follow a similar approach and propose a trip time dependent quality measure. The quality of each connection is computed according to the following *score* function:

$$\mathrm{score_c}=1-\frac{\mathrm{ConLag_c}}{\mathrm{maxConLag_c}}$$

Figure 2. Connection builder settings: Fastest (\#1) and second-fastest (\#2) connections sharing a common leg on a given O&D (ORG-DST)



a) Inbound perspective **b) Outbound perspective**

The *score* of a given connection *c* depends on its connection lag (*ConLag*) and on the *maxConLag* parameter applicable to this connection based on its O&D distance (see Figure 1). It ranges between 0 (if the connection lag approximates the respective maximum allowed) and 1 (if the connection lag approximates zero); so the faster the connection c the higher the score.

The overall airline connectivity is calculated as the total score of all connections generated at the corresponding hub. Since fast connections get a higher score, they have a higher weight in the hub's total score than slower connections. Therefore, the overall connectivity of an airline at a given hub is referred to as weighted connectivity score (*WCS*).

$$\mathrm{WCS}=\sum_{c}\mathrm{score_c}$$

For each airline hub, *WCS* for the existing schedule (WCS_{obs}) is calculated. Analogically, for each randomized variation *i* of the departure/arrival times of flights at the hub, the weighted connectivity score of the hub resulting from a corresponding flight schedule scenario is calculated (WCS_i). Having N different variations (randomized schedule scenarios), the overall, average weighted connectivity score (WCS_{random}) for the hub is calculated as:

$$\mathrm{WCS_{random}} = \frac{\sum_i^N \mathrm{WCS_i}}{\mathrm{N}}$$

WCS_{random} can be interpreted as the expected level of airline connectivity at the given hub assuming a random temporal distribution of flights. The ratio between the observed hub performance WCS_{obs} and the random expectation WCS_{random} is defined as timetable synchronization index (*Sync)*.

$$\mathrm{Sync} = \frac{\mathrm{WCS_{obs}}}{\mathrm{WCS_{random}}}$$

Sync measures how much better is the connectivity resulting from the real airline schedule at a given hub compared to a random expectation.

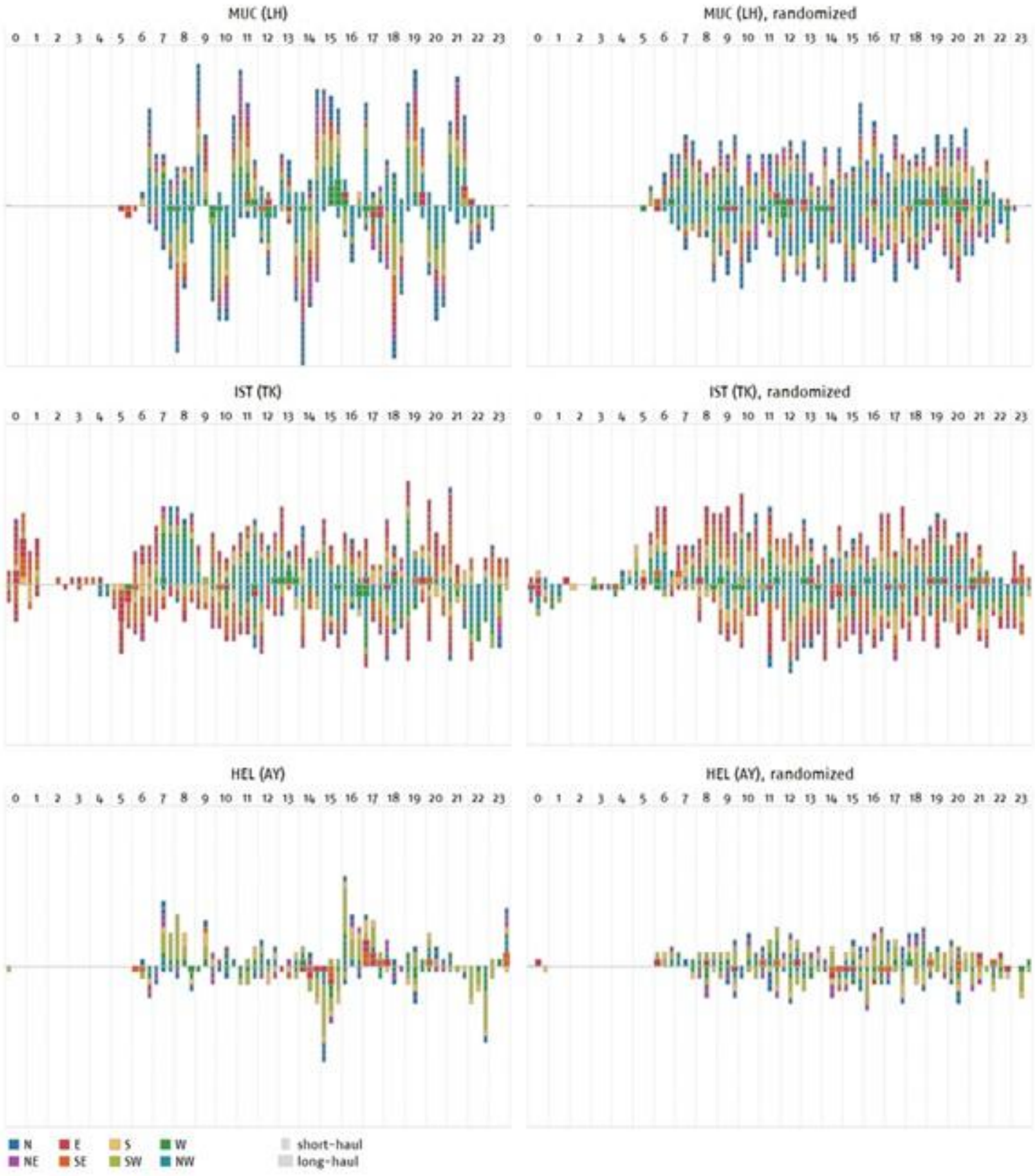
2.3 Timetable Randomization and Simulation Design

The analysis is based on Innovata flight schedule data for one day of operations (5 June 2013). Connections are generated for the real schedule and for one hundred (N=100) randomized schedule scenarios. To create a schedule scenario for a given hub, all flights operated by the corresponding airline are rescheduled to a randomly drawn five-minute interval. Each rescheduling has to satisfy the operating hours of the hub as well as of the origin or destination airport. For each flight, the time period within which the flight can be rescheduled is determined by the block time, the time zone difference and the operating hours of the respective airports.

As we are not aware of any publicly available source on airport operating hours and detailed night flight limitations we derive this information from the schedule data. We assume that all airports operate with no limitations during the day from 7:00 to 22:00 local time. For the remaining period, we check how many flights are scheduled at what time. The longest period of time with no scheduled operations at a given airport is assumed as being not available for flight rescheduling. For the remaining time periods between day and night we calculate the number of flights per hour and put this number into relation to the average number of flights per hour at the airport during the day. The resulting ratio is used as a base to calculate the probability of time interval selection for the simulations. For example, if the average number of flight movements operated per hour during the day is 50 and only 5 movements are scheduled between 23:00 and 0:00 then the probability of flights being rescheduled to the time intervals within this hour is ten times lower than the probability of flights being rescheduled to any time interval within the day period. This procedure ensures that the generated schedule scenario do not violate any major airport capacity and curfew restrictions; neither in the peak times during the day (the randomized timetables are per design more “flat” than the real schedules) nor during the night (the night flight limitations are taken into account).

As example, Figure 3 shows three example wave patterns of airline timetables at their hubs resulting from a randomized schedule scenario (right), compared to the actual timetable (left). The horizontal line represents the local time at hub in 20-minute intervals; arrivals are plotted below the horizontal line, departures above it. Each rectangle represents one flight. The color coding of each rectangle shows the direction of a given flight (blue=north, red=east, yellow=south, green=west). Long-haul flights (distance greater than 4000 km) operated with a wide-body aircraft are highlighted with wider rectangles.

Figure 1. Wave patterns of selected carriers at their main hubs based on the actual schedule (left) and on a selected randomized schedule scenario (right).



The selected examples presented in Figure 3 represent three different types of connectivity-driven hub wave systems. The Lufthansa (LH) flights in MUC[4] are organized in several waves of inbound and outbound flights. Individual waves are short (1-2 hours) and hardly overlap. This is a typical example of a connectivity driven system that aims to maximize the number of fast connections at a hub serving a star-shaped, largely short-haul network (theoretical considerations on the design of hub wave systems can be found e.g. in (Goedeking, 2010). The wave pattern of Turkish Airlines (TK) in IST shows no evident departure or arrival peaks or periods of no activity. Instead, TK flights are organized in directional waves. For example, flights from south-east arrive (red) arrive between 5:00 and 7:00 and flights to north-west (green) depart between 7:00 and 9:00. This structure aims to maximize connectivity between Asia or Middle East and Europe, the key transfer market of TK. The number of waves in IST is lower than in MUC and individual waves are longer (up to few hours); this results in longer connection times and slower connections. The timetable of Finnair (AY) in HEL is also designed to maximize connectivity between Europe and Asia but AY clearly focuses on fast connections. AY operates only one dominant wave in the afternoon (arrivals between 14:00 and 15:00 and departures between 16:00 and 17:00) and two smaller waves late in the evening and early in the morning.

In the randomized schedule scenarios, departures and arrivals are distributed more evenly during the day and no wave patterns can be identified. Like in the real schedules, no night flights are allowed in MUC and HEL, and only a limited number of flights are randomly rescheduled outside of the normal operation hours (1:30 and 5:00 in IST, 5:30-6:30 in MUC, 00:00-1:00 in HEL).

It is worth to point out that the resulting distribution of the randomized departures and arrivals is not uniform; more departures are positioned in the morning and more arrivals are positioned in the evening. This can be explained by the night flight restrictions on many European airports. For example, very late departures from MUC would result in curfew violation at arrival to many European destination airports. Analogically, early arrivals to MUC would imply departures before the begin of operations at many European origin airports. The impact of operation hours at outstations on the pattern of randomized timetables are stronger for HEL and IST than for MUC (and most other airports analyzed in this paper) due to their more distant geographic location. For example, most European flights cannot arrive in IST before 10:00 or depart after 20:00 because of night flight restrictions at many European airports.

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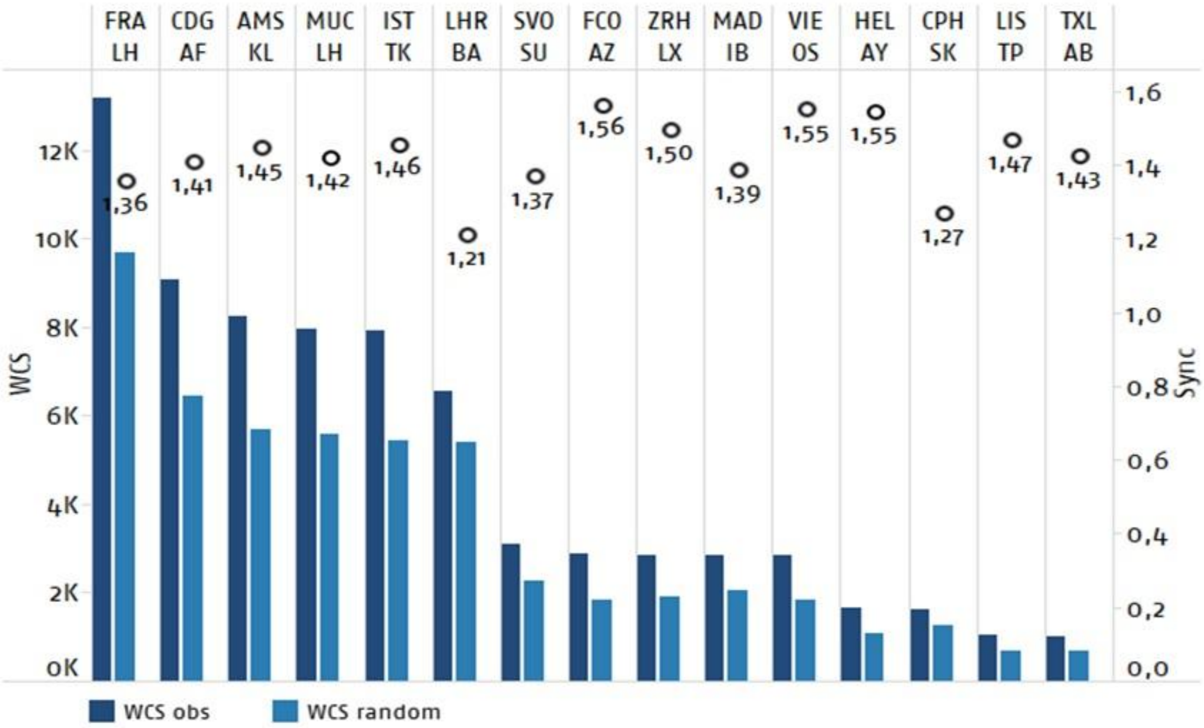
[4] See appendix A for the list of airport and airline codes

3 RESULTS

3.1 Hub Connectivity and Timetable Synchronization

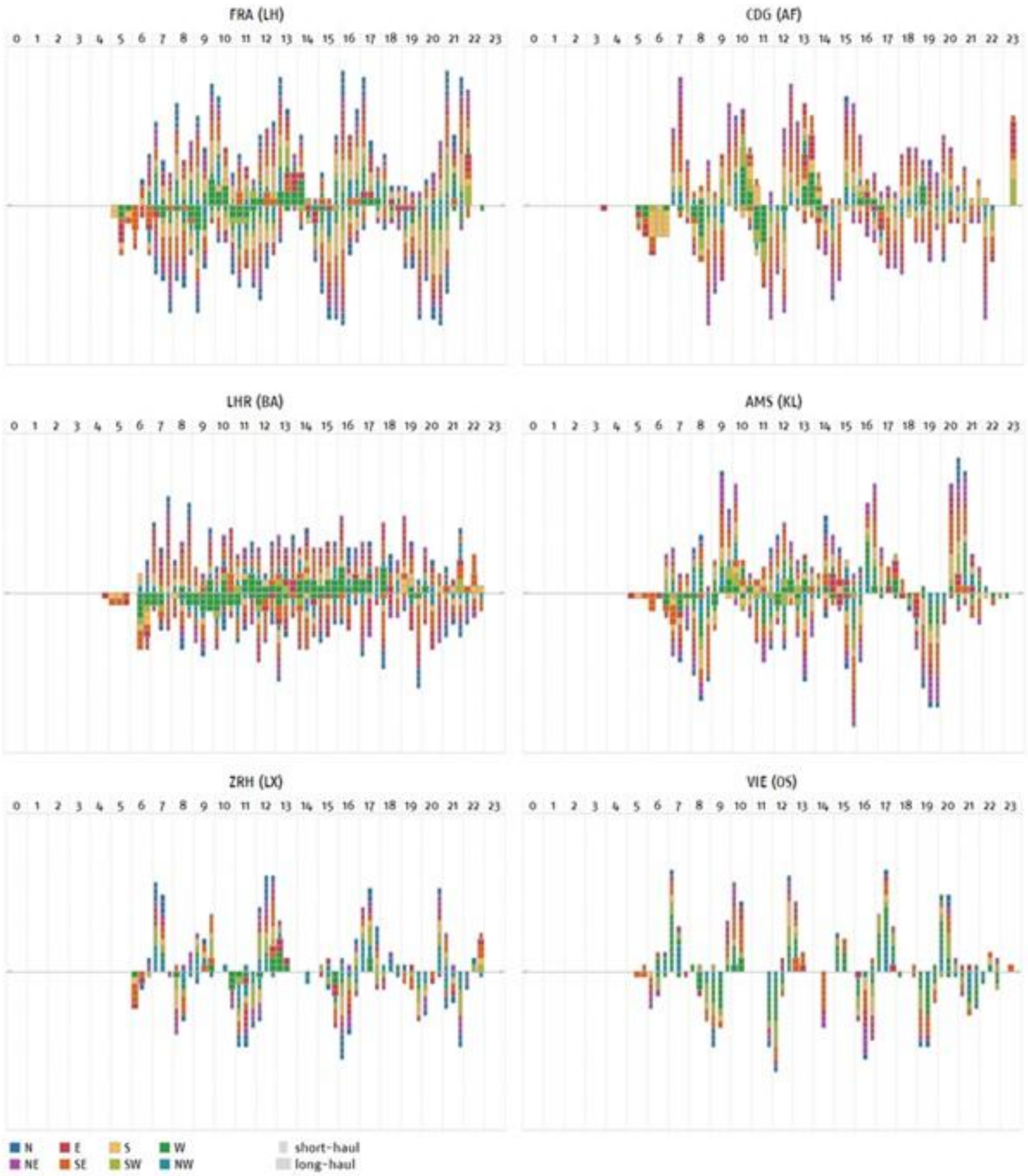
Figure 4 shows the results for the dominant carriers at the top 15 European hubs by WCS_{obs}. It plots the actual (WCS_{obs}) and the expected (WCS_{random}) hub connectivity scores (dark and light bars respectively) on the left scale, and the timetable synchronization index *Sync* (bubbles) on the right scale. Detailed results in table form are provided in the appendix B (Table B 1). LH in FRA offers by far the highest connectivity (WCS_{obs} =13,200). AF in CDG ranked second with WCS_{obs} of 9,000. KL in AMS, LH in MUC and TK in IST followed with WCS_{obs} ranging between 7,900 and 8,300. BA in LHR ranked sixth with WCS_{obs} of 6,500. Smaller hubs offered lower connectivity, WCS_{obs} of approx. 3,000 or less. In the reminding part of the paper we will refer to the top six hubs as "big hubs" and to the remaining hubs as "medium hubs".

Figure 2. Weighted connectivity score (WCS) and timetable synchronization index (*Sync*) of the 15 analyzed European hubs.



Timetable synchronization leverages the connectivity (measured with *WCS*) of the analyzed airline hubs by approx. 45% on average. There are of course considerable differences between individual carriers. The highest values of the timetable synchronization index *Sync* can be observed for medium sized airlines: AZ in FCO, OS in VIE, AY in HEL and LX in ZRH. The temporal synchronization of flight arrivals and departures contributes to more than 50% increase of hub connectivity of these carriers. Four of the big airline hubs: KL in AMS, TK in IST, LH in MUC and AF in CDG also show a high level of timetable synchronization with *Sync* ranging between 1.40 and 1.45. It is worth to point out that the flat wave structure of TK in IST, strongly focused on the directional connectivity, results in a similar *Sync* as the peaky wave structures of AF in CDG, KL in AMS and LH in MUC that operate more multidirectional waves (compare Figure 3 and Figure 5). Timetable synchronization of LH in FRA contributes to 36% increase in connectivity. Lower *Sync* for LH in FRA than for AF in CDG and KL in AMS that serve comparable networks can be explained by LH's rather flat wave system in FRA with a lot of overlap between individual waves. This is partly a consequence of a high congestion in FRA. At LHR, BA operates no evident wave system. Only the long-haul flights to Asian and African destinations form a connectivity driven wave pattern early in the morning (arrivals) and late in the evening (departures). On a side note, this is a typical timing pattern for flights from/to these regions also at all other big European hubs (see Figure 3 and Figure 5). The timetable synchronization index for BA in LHR equals 1.21, the lowest value of all analyzed hubs. LHR is the most congested airport in Europe so obviously the lack of a more connectivity driven wave system of BA in LHR is largely caused by the airport capacity shortage.

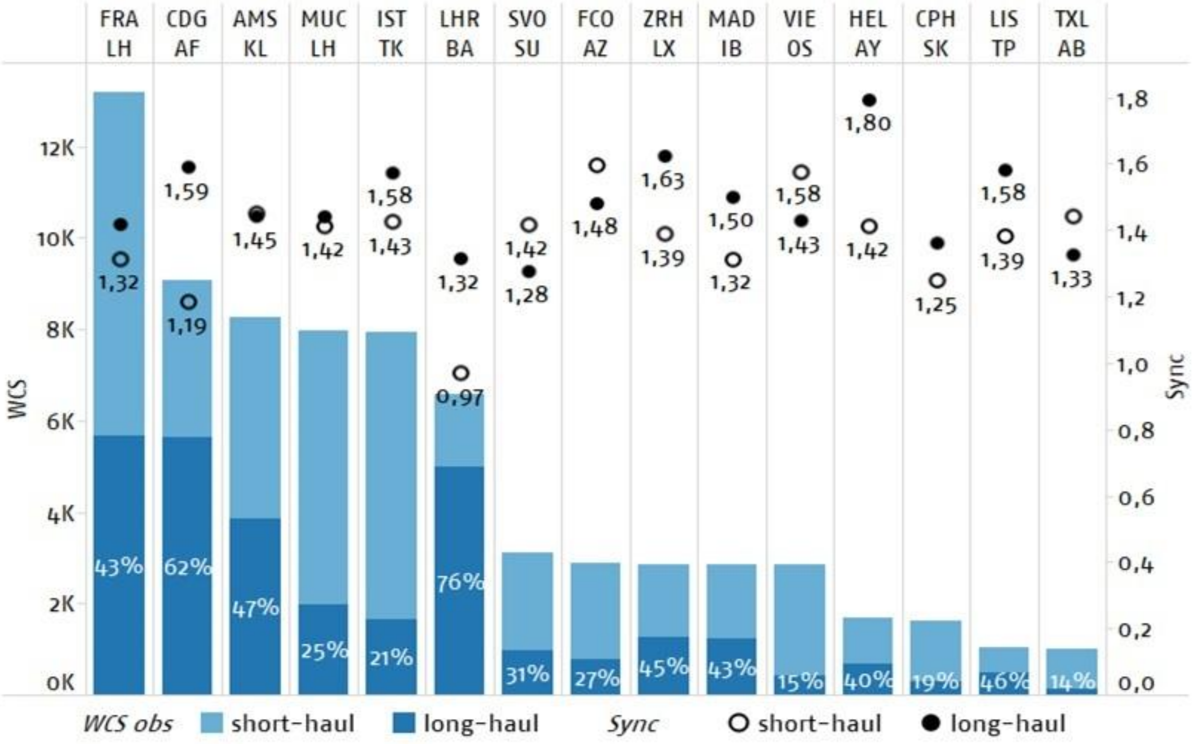
Figure 3. Wave patterns of selected carriers at their main hubs.



3.2 *Long-haul Connectivity*

Long-haul flights served with wide-body aircraft play a particularly important role for most network carriers, see e.g. (Burghouwt, 2014). Many long-haul operations fully depend on flights connecting at the hub to feed and de-feed with transfer passengers. Consequently, most carriers aim to maximize especially the connectivity on their long-haul flights by optimized temporal coordination of their feeder and de-feeder flights. Therefore, we further focus our analysis on the hub connectivity WCS_{obs} generated by long-haul flights (O&D distances greater than 4000km operated by a wide-body aircraft). We analyze what portion of airline connectivity at their hubs (WCS_{obs}) is generated by long-haul flights and we compare the impact of timetable synchronization (*Sync*) on connectivity of long-haul vs. short-haul flights.

Figure 4. Weighted connectivity score (WCS_{obs}) and timetable synchronization index (*Sync*) of the 15 analyzed European hubs. Long-haul vs. short-haul flight connectivity.



Results are illustrated in Figure 6. The share of WCS_{obs} generated by long-haul flights (dark blue bars) is very different across the analyzed airline hubs. It ranges from 76% for BA in LHR and 62% for AF in CDG to less than 20% for OS, SK and AB in VIE, CPH, and TXL respectively. At FRA, AMS, ZRH, MAD, HEL and LIS this share ranges between 40% and 50%; in MUC, IST, SVO and FCO between 20% and 30%. Detailed results are provided in the appendix B (Table B 2).

As expected, for most of the analyzed carriers the level of timetable synchronization for long-haul flights is higher than for short-haul flights. The differences are particularly interesting for AF in CDG ($Sync_{long\text{-}haul}$=1.59 compared to $Sync_{short\text{-}haul}$=1.19) and BA in LHR $Sync_{long\text{-}haul}$=1.32 compared to $Sync_{short\text{-}haul}$=0.97). In case of BA the temporal synchronization index for the short-haul flights is even slightly below the random expectation. These results suggest that both AF and BA focus mainly on their long-haul connectivity. The highest *Sync* in our analysis can be observed for the long-haul flights in HEL ($Sync_{long\text{-}haul}$=1,80), where AY operates a specific system of one dominant and two supplementary waves focused on the Europe to Asia connectivity, see Figure 3.

Interestingly, for some carriers (OS, AZ, SU and AB) the temporal schedule synchronization appears to leverage the connectivity of short-haul flights stronger than of the long-haul flights. These carriers, with exceptions of SU, operate a very peaky wave systems (see e.g. OS in VIE in Figure 5) that result in a good connectivity of all flights, short-haul as well as long-haul. This is particularly true in the case of AZ in FCO and OS in VIE where *Sync* equals respectively: 1.6 and 1.58 for the short-haul flights and 1.48 and 1.43 for the long-haul flights. Consequently, higher $Sync_{short\text{-}haul}$ than $Sync_{long\text{-}haul}$ for these carriers is a result of a very good temporal synchronization of the short-haul network rather than a poor synchronization of the long-haul connections.

3.3 Sensitivity to Parameter Settings of WCS

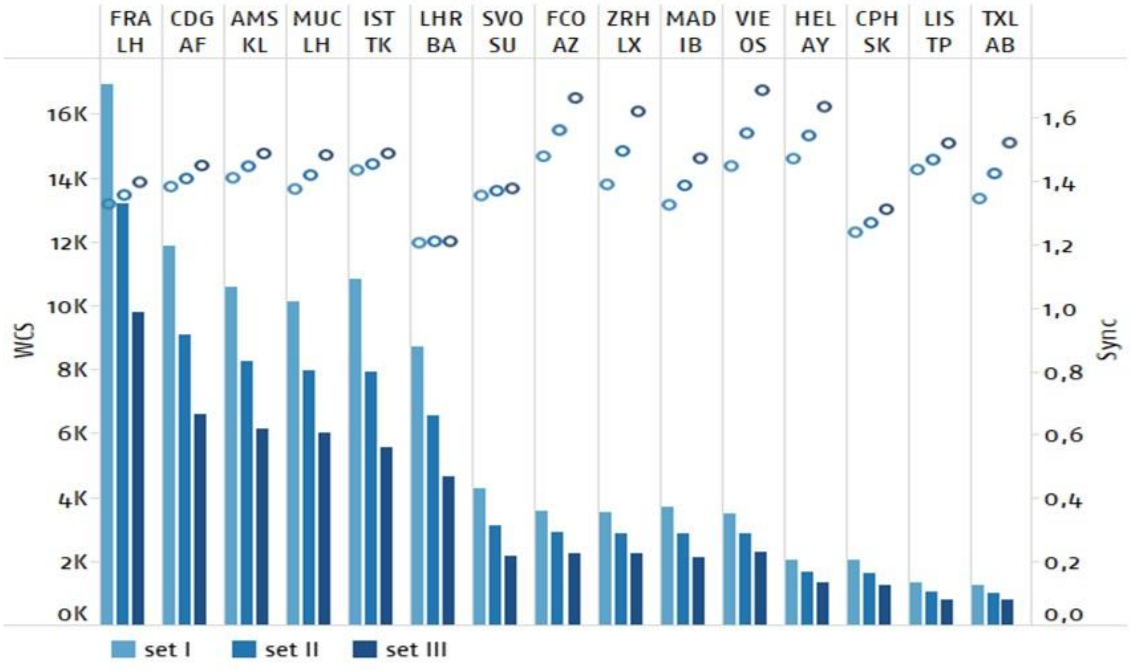
The above analyses built upon the base CB setting of maximum connection lag (see set II in Figure 1). *MaxConLag* also serves as a parameter of the weighted connectivity score *WCS*, see section 2.2. Using less restrictive settings of *maxConnLag* (set I) would result in slower connections getting a relatively higher score. Analogically, more restrictive parameter settings (set III) would result in relatively lower scores of slower connections. Consider for example, two connections between Gothenburg and Barcelona with connection lag of 2 and 3 hours respectively. The maximum connection lag allowed for these connections (2000km O&D distance) is roughly 6 hours if we use set I, 5 hours if we use set II (the base one), and 4 hours if we use set III. Depending on the used parameter set, the resulting score for the first (faster) connection equals 0.67 (set I), 0.6 (set II) and 0.5 (set III), and for the second (slower) connection it equals 0.5, 0.4, and 0.25 respectively. The relative quality difference between these two connections is greater if the score is calculated using the more restrictive set III (0.5 vs. 0.25) than if it is calculated using the less restrictive set I (0.67 vs. 0,5). As result, choosing more restrictive (more trip time sensitive) parameters of *WCS* assigns relatively higher weight to faster connections.

Results of applying the three different parameter sets (I, II, and III, worldwide connecting passenger coverage of approx. 98%, 95% and 90% respectively) to the connectivity analysis of the

European carriers are shown in Figure 7. Hub connectivity resulting from the real schedule WCS_{obs} is plotted on the left axis (bars) and the timetable synchronization index *Sync* on the right axis (bubbles). Detailed results are given in the appendix B (Table B 3). For all analyzed hubs the timetable synchronization index *Sync* is highest if calculated using *WCS* based on set III (the most trip time sensitive set, lowest passenger coverage, relatively lower score assigned to slow connections). This is expected since most carriers aim to optimize not only the number of available connections but also the quality of the connections in terms of their overall trip time.

The sensitivity of *Sync* to the parameter settings of *WCS* (sets I, II, and III) differs across the analyzed hubs. For OS in VIE and LX in ZRH Sync calculated with set III is more than 0.2 higher than *Sync* calculated with set I; 1.69 vs. 1.45 (OS) and 1.62 vs. 1.39 (LX). For the biggest airline hubs (LH in FRA and MUC, AF in CDG, KL in AMS) the difference between set I and set III is lower and ranges between 0.07 and 0.11; for TK in IST it equals 0.05 and for BA in LHR only 0.01. A higher sensitivity to the parameter settings of *WCS* (larger differences) is observed for carriers that focus on fast connections, see wave-patters in Figure 3 and Figure 5. For example, OS and LX both operate a system of many short (1-2 hours) and almost non-overlapping waves that results in very short connection times. The systems of LH, AF and KL are characterized by longer and more overlapping waves that lead to slower connection times. The flat wave-structure of BA in LHR does not facilitate fast connections.

Figure 7. Weighted connectivity score (*WCS_{obs}*) and timetable synchronization index (*Sync*) for the 15 analyzed European hubs calculated using three different parameter sets of *WCS*.



The analysis of the overall connectivity performance of hubs and the according ranking also depends on the parameter settings of *WCS*. Choosing more trip time sensitive parameters of *WCS* leads to a relatively lower weighting of slow connections. Thus, it "rewards" carriers that focus on fast connections. Overall, the hub performance ranking based on *WCS* calculated on sets I, II and III is similar; with LH in FRA being the top airline hub, AF in CDG ranked second, KL in AMS, LH in MUC and TK in IST better than BA in LHR and way better than the remaining medium hubs. However, there are some differences when comparing individual hubs. For example, TK in IST scores slightly better than KL in AMS and LH in MUC if *WCS* is based on the least restrictive set I (relatively high weight assigned to slow connections) but KL and LH (that offer faster connections than TK) score considerably better if *WCS* is based on the more trip time sensitive set III. Similar differences can be observed when comparing LX in ZRH and OS in VIE (focused on fast connections) with SU in SVO or IB in MAD (slower hubs). It is worth to point out, that other studies on hub connectivity also lead to different hub performance rankings depending on the connectivity measure applied. Burghouwt and Redondi (2013) compared the connectivity of European hubs according to various metrics. They found that e.g. LHR (that serves no connectivity driven wave pattern and generates mainly slow connections) scored higher than AMS and MUC according to the less trip-time sensitive connectivity metric of Burghouwt and de Wit (2005) but these hubs ranked in reverse order according to the more restrictive metric of Danesi (2006). This confirms our observations that using a more trip time sensitive measure results in relatively higher connectivity performance indicators of hubs that focus on fast connections. It is therefore recommended for the airline analysts and network planners to use a broad set connectivity metrics and/or settings that put a different weight to various aspects of connection quality rather than to focus only on one aggregate performance indicator.

4 CONCLUSIONS AND FUTURE RESEARCH

This paper analyzed the net impact of timetable synchronization on the connectivity of the top European carriers at their main hubs. For each carrier, we evaluated its hub connectivity resulting from the existing schedule and compared it to the average connectivity calculated from one hundred randomized schedule scenarios. In each schedule scenario, we randomly varied the flight departure and arrival times within the operation hours at a hub and at outbound stations keeping all other parameters of airline schedule unchanged. We measured hub connectivity using the weighted connectivity score (*WCS*) calculated as a quality-weighted number of airline online, single-stop connections generated at a given hub.

Using the base parameter setting of *WCS* selected for this study, we observed that the timetable synchronization leverages the hub connectivity of most analyzed carriers by 40%-60%. In general, airlines that operate systems of many short and non-overlapping hub waves achieve the highest increase of their hub connectivity. Such design of timetable is not possible at highly congested airports where airlines have to manoeuvre within limited airport capacity. Especially at such airports, it is important to identify flights with the highest connectivity potential and to leverage this potential by a careful and systematic coordination within the available slot framework. Typically, long-haul flights contribute most to the airline connectivity at hubs and they are also best coordinated within the timetables of the analyzed European carriers. Taking the directionality of inbound and outbound flights into account, airlines have to plan their directional traffic flows to not dilute flights with a good detour factor with long connection times and vice versa. With a well panned directional wave structure an airline can greatly improve its connectivity even on a strongly congested airport. This is for example the case of TK in IST; although its wave structure is rather flat, TK leverages its connectivity comparable or even better than the other big European carriers that operate more multi-directional and peaky wave systems at their main hubs. A good temporal coordination of directional waves is also a prerequisite to utilize the competitive advantage of medium-sized airlines in their strategic market, e.g. connecting traffic between Europe and North-East Asia in case of AY in HEL or between Europe and South America in case of TP in LIS.

The application of the approach presented in this paper can help airlines to better assess how their timetable leverages connectivity at their hubs and/ sub-networks. It can be used to benchmark and monitor the performance of competitors and to evaluate various schedule scenarios, especially when re-designing the airline network at strategic level.

This study has some limitations and can be enhanced in future research and in practical applications. In this paper we focused on the online connectivity of the analyzed carriers. To our knowledge, for most carriers the online perspective remains the primary performance indicator by the design of timetables at strategic level. However, given the increasing role of globalization and airline partnerships, the analysis can be extended in practical applications to take into account airline connectivity with its code-share and/or alliance partners. In such analysis it is recommended to take into account various degrees of airline partnership. Some airlines partner only on specific flights. Some don’t partner at all, even if they belong to the same global alliance. Consequently, additional steps and assumptions might be needed to differentiate what share of partner connectivity (e.g. within an alliance) is leveraged by the joined coordination of timetables and what share is determined by the level of partnership (or lack of it) between the corresponding partners or alliance members.

The *WCS* connectivity metric used in this study was calculated based on the number of airline connections at hub and their quality in terms of trip time. There are of course many other factors that determine the attractiveness flight connections to passengers and their value for an airline. Since the randomized schedule scenarios can be analyzed in a similar way as the existing schedules the *WCS* connectivity metric can be enhanced with additional weighting criteria (e.g. seat capacity, flight distance, demand potential of origins and destinations, O&D traffic volume, number and quality of competing connections on an O&D (Allrogeen et al., 2015; Grosche et al., 2015; Redondi et al., 2011) or even replaced by performance indicators calculated based on more complex models used in network planning such as e.g. itinerary choice modeling combined with demand estimations (Grosche, 2009; Lieshout et al., 2005).

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Appendix A

Table A 1. Airline and airport codes.

Airline	Hub
LH - Lufthansa	FRA - Frankfurt
AF - Air France	CDG - Paris Charles de Gaulle
KL - KLM Royal Dutch Airlines	AMS - Amsterdam Schiphol
LH - Lufthansa	MUC - Munich
TK - Turkish Airlines	IST - Istanbul Atatürk
BA - British Airways	LHR - London Heathrow
SU - Aeroflot	SVO - Moscow Sheremetyevo
AZ - Alitalia	FCO - Rome Fiumicino
LX - Swiss International Airlines	ZRH - Zurich
IB - Iberia	MAD - Mardid Barajas
OS - Austrian Airlines	VIE - Vienna
AY - Finnair	HEL - Helsinki Vantaa
SK - SAS Scandinavian Airlines	CPH - Copenhagen Kastrup
TP - TAP Portugal	LIS - Lisbon
AB - Air Berlin	TXL - Berlin Tegel

Appendix B

Table B 1. Weighted connectivity score (WCS) and timetable synchronization index (Sync) of the 15 analyzed European hubs.

Airline	*Hub*	*WCS obs*	*WCS random*	*Sync*
LH	FRA	13178	9693	1.36
AF	CDG	9078	6432	1.41
KL	AMS	8268	5701	1.45
LH	MUC	7961	5597	1.42
TK	IST	7943	5450	1.46
BA	LHR	6575	5419	1.21
SU	SVO	3113	2268	1.37
AZ	FCO	2892	1850	1.56
LX	ZRH	2846	1903	1.50
IB	MAD	2845	2047	1.39

OS	VIE	2844	1830	1.55
AY	HEL	1669	1079	1.55
SK	CPH	1615	1270	1.27
TP	LIS	1032	702	1.47
AB	TXL	998	699	1.43

Table B 2. Weighted connectivity score (WCS obs) and timetable synchronization index (Sync) of the 15 analyzed European hubs. Long-haul vs. short-haul flight connectivity.

Airline	*Hub*	*WCS obs total*	*WCS obs long -haul*	*WCS obs short-haul*	*% share obs long-haul*	*% share obs short-haul*	*Sync total*	*Sync long -haul*	*Sync short-haul*
LH	FRA	13178	5685	7493	43%	57%	1.36	1.42	1.32
AF	CDG	9078	5651	3427	62%	38%	1.41	1.59	1.19
KL	AMS	8268	3864	4404	47%	53%	1.45	1.45	1.45
LH	MUC	7961	1990	5971	25%	75%	1.42	1.44	1.42
TK	IST	7943	1648	6295	21%	79%	1.46	1.58	1.43
BA	LHR	6575	4975	1600	76%	24%	1.21	1.32	0.97
SU	SVO	3113	969	2144	31%	69%	1.37	1.28	1.42
AZ	FCO	2892	788	2104	27%	73%	1.56	1.48	1.60
LX	ZRH	2846	1271	1575	45%	55%	1.50	1.63	1.39
IB	MAD	2845	1222	1622	43%	57%	1.39	1.50	1.32
OS	VIE	2844	432	2413	15%	85%	1.55	1.43	1.58
AY	HEL	1669	670	999	40%	60%	1.55	1.80	1.42
SK	CPH	1615	307	1309	19%	81%	1.27	1.36	1.25
TP	LIS	1032	477	555	46%	54%	1.47	1.58	1.39
AB	TXL	998	144	854	14%	86%	1.43	1.33	1.45

Table B3. Weighted connectivity score (WCS obs) and timetable synchronization index (Sync) for the 15 analyzed European hubs calculated using three different parameter sets of WCS.

Airline	*Hub*	*WCS obs set I*	*WCS obs set II (base)*	*WCS obs set III*	*Sync set I*	*Sync set II (base)*	*Sync set III*
LH	FRA	16913	13178	9782	1.33	1.36	1.40
AF	CDG	11883	9078	6613	1.39	1.41	1.45
KL	AMS	10597	8268	6131	1.41	1.45	1.49
LH	MUC	10115	7961	5998	1.38	1.42	1.49
TK	IST	10831	7943	5575	1.44	1.46	1.49
BA	LHR	8711	6575	4658	1.21	1.21	1.21
SU	SVO	4281	3113	2141	1.36	1.37	1.38
AZ	FCO	3573	2892	2227	1.48	1.56	1.67
LX	ZRH	3519	2846	2239	1.39	1.50	1.62
IB	MAD	3677	2845	2105	1.33	1.39	1.48
OS	VIE	3466	2844	2285	1.45	1.55	1.69
AY	HEL	2032	1669	1329	1.47	1.55	1.64
SK	CPH	2049	1615	1226	1.24	1.27	1.31
TP	LIS	1319	1032	782	1.44	1.47	1.52
AB	TXL	1239	998	772	1.35	1.43	1.52