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Connectivity in air transport networks: models, measures and applications

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Guillaume Burghouwt, Renato Redondi

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Guillaume Burghouwt

Amsterdam Aviation Economics and Airneth (Netherland)

Renato Redondi*

University of Brescia and ICCSAI (Italy)

Abstract

The paper aims to analyze the different connectivity models employed to measure hub connectivity and airport accessibility. They are classified in terms of considered variables, underlying models and obtained results. We compute eight different measures of hub connectivity and airport accessibility for all the European airports. The results show the similarities and differences among the measures. With respect to the correlation to the traditional measures of airport size, small airports may have high accessibility if they have just a few flights to well-connected airports. On the other hand, big airports do not necessarily have a proportionally high hub connectivity since it requires very intense temporal coordination of flights that can be obtained only by large hub carriers with efficient wave-system structures.

JEL classification: L90, L93

Keywords: Connectivity measures, hub connectivity, airport accessibility, empirical comparison, airline network

* Corresponding author: Via Branze, 38 – 25123 Brescia, renato.redondi@unibs.it, +39 035 2052360

1. Introduction

Since the deregulation of the domestic air transport market in the United States in 1978, hub-and-spoke networks have become an essential feature of airline network operations around the world. Hub-and-spoke networks (HS) allow the hub-airline to maximize the number of connected city pairs given a certain number of flights by means of spatial and temporal concentration of the network (Burghouwt 2007). Due to the consolidation of different origin-destination markets on a limited number of routes, the hub-airline may benefit from higher load factors, higher frequencies and the use of larger aircraft with lower unit cost (Dennis 1994a, 1994b).

The widespread use of hub-and-spoke networks models has made the analysis of the competitive position of airports and airline networks as well as the measurement of air accessibility available to the consumer a challenging task. Traditionally, the competitive position of airlines and airports and the level of air accessibility are expressed in terms of 'top ten' lists. Airlines, airports and passenger air service provision are compared with respect to total passenger enplanements, number of aircraft movements or tonnes of freight.
Although such indicators are valuable in itself, they do not give us all information on the competitive position of airline networks, airports or the level of air accessibility. This is because hub-and-spoke operations have changed the competition between airlines in a structural way. Through their networks, airlines compete both directly and indirectly. On the one hand, airlines compete on direct routes (from A to B). On the other hand, they compete indirectly with a transfer at a hub (from A to B via hub H).

Therefore, various authors have argued that the analysis of the connectivity performance of airline networks, airports and air accessibility should take into account both direct and indirect connectivity (Bootsma 1997; Burghouwt & Veldhuis 2006; Matsumoto et al. 2008; Reynolds-Feighan & McLay 2006).

The relevance of connectivity measures

From a societal perspective, the need for adequate connectivity measures that take into account both types of connectivity is obvious. First of all, such measures are an indicator of the performance of airline networks, airports and regions. They allow policy makers and industry professionals to benchmark and monitor the network performance against that of other airports, airline networks and regions and identify the most important competitors (Burghouwt & Veldhuis 2006; IATA 2000; Malighetti et al. 2008; Matsumoto et al. 2008; Veldhuis & Kroes 2002). Such analyses deliver the information necessary to design strategies to improve the competitive position of airports. For example, these measures make it possible to demonstrate to what extent an airport plays a role as a connecting hub in a certain origin-destination market, in comparison to competing hubs. In addition, connectivity measures allow policy makers, airports and airlines to monitor network performance over time and assess the impact of various measures to maintain or enhance network performance (Burghouwt & Veldhuis 2006; IATA 2000; Matsumoto et al. 2008; Veldhuis & Kroes 2002). For these reasons, connectivity measures are often used as input for broader strategic airport and airline plans. From a regional economic point of view, connectivity measures can help policy makers by evaluating the travel times to reach a given share of world GDP or population from a predefined region (Malighetti et al. 2008).

Finally, connectivity is, besides ticket price, an important variable in route choice of passengers and may be included in disaggregated forecasting and economic impact models (Irwin & Kasarda 1991; Ivy et al. 1995).

State-of-the-art overview lacking

Not surprisingly, academic studies have brought forward a broad range of connectivity measures, which take into account both direct and indirect connectivity in airline networks. Some of them originate in network topology and complex network theory (Cronrath et al. 2008; Guimerà et al. 2005; Paleari et al. 2008) whereas others take the operational nature of airline hub-and-spoke networks as the point of departure (e.g. (Bootsma 1997; Burghouwt & de Wit 2004; Danesi 2006; Dennis 1998; Veldhuis 1997) or are based on insights from social science research (Budde et al. 2008).

However, a state-of-the art overview of the different connectivity measures in air transport research, their characteristics and empirical performance is lacking in the academic literature. In other words, there is no systematic knowledge available to compare the various connectivity measures that allows academics and practitioners to choose the appropriate measure given certain objectives and data availability.

Therefore, this paper fills in this gap by providing (1) an overview of the existing connectivity measures in air transport research and their characteristics and (2) an empirical, comparative analysis of these connectivity measures using airline schedules data for all European airports.

The paper is organized as follows. First, we elaborate the concept of connectivity and its different dimensions. Then, we then describe and classify a number of individual connectivity measures as found in the air transport literature along these dimensions. In section 4, we discuss the methodology and dataset in order to assess the various measures empirically. The results of the analysis will be presented in section 5. We will answer the question to what extent the ranking of the same set of airports differs using different connectivity measures. In addition, we will compare the performance of connectivity measures to a simpler, size-based measure. Finally, we discuss the application and usefulness of the various connectivity measures in different research contexts.

2. Dimensions of connectivity in air transport networks

According to graph theory, connectivity can be defined as the degree to which nodes in a network are connected to each other. Air transport research has brought forward a broad range of connectivity measures. In table 1 we have listed the measures that we will look in detail at in this paper. The mathematical elaboration of the measures can be found in Appendix A.

Although these measures are the most frequently used and cited connectivity measures in recent air transport research, we realize that the measures listed in table 1 are not exhaustive. Variation to these measures are possible, for example by weighing connectivity by certain node attributes, such as airport seat capacity or the airport region's GDP (Malighetti et al. 2008; Reynolds-Feighan & McLay 2006). In addition, measures for the level of timetable coordination at an airline's hub airport during the day are not being considered here (see for example, Bootsma 1997; Budde et al. 2008; Danesi 2006; Rietveld & Brons 2001; Martín & Voltes-Dorta 2008). The level of timetable coordination is one of the instruments for an airline to increase connectivity via its home base. Nor do we consider the growing branch of literature that focus on methodologies for measuring the topology of airline networks. We refer to Guimera et al. (2005), Bagler (2008), Bonnefoy & Hansman (2005, 2007), and Reggiani et al. (2008) for discussions on and analyses of the structure of airline networks from the perspective of complex network theory.

Model	Short definition	Main references
Hub potential	Incoming * outgoing frequency	Dennis (1998)
'Doganis & Dennis' connectivity	Number of connections. Indirect connections meet conditions of minimum & maximum connecting time and routing factor	Dennis & Doganis (1989); Dennis (1994a&b)
'Bootsma' connectivity	Number of connections. Indirect connections meet conditions of minimum & maximum connecting time and are classified as 'excellent', 'good' and 'poor'	Bootsma (1997)
WNX (weighted number of connections)	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time	Burghouwt & De Wit (2004); Burghouwt (2007)
Netscan connectivity units	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time relative to a theoretical direct flight	Veldhuis (1997); IATA (2000); Burghouwt & Veldhuis (2006); Matsumoto et al. (2008); Veldhuis & Kroes (2002)
WCn (Weighted Connectivity Number)	Number of direct and indirect connections weighed by their quality in terms of transfer and detour time	Danesi (2006)
Shortest Path Length centrality	Number of connections lying of O-D shortest paths. The shortest path is the path involving the minimum number of steps from O to D	Cronrath et al. (2008); Malighetti et al. (2008); Shaw (1993), Shaw & Ivy (1994)
Shortest Path Length accessibility	Average number of steps to reach any other airport in the network	Cronrath et al. (2008); Malighetti et al. (2008); Shaw (1993), Shaw & Ivy (1994)
Quickest Path Length centrality	Number of connections lying of O-D quickest paths. The quickest path is the path involving the lower travel time from O to D	Malighetti et al. (2008); Paleari et al. (2008)
Quickest Path Length accessibility	Average travel time to reach any other airport in the network	Malighetti et al. (2008); Paleari et al. (2008)
Gross vertex connectivity	Sum of all possible paths (of any number of steps) to other airports weighted by a scalar value that lessen the importance of indirect connections	Ivy (1993); Ivy et al. (1995)
Number of connection patterns	Number of statistical significant patterns of incoming and outgoing flights	Budde et al. (2008)

Table 1. Connectivity measures, definition and studies

We will classify these measures along a number of dimensions, which have been described below.

Accessibility versus centrality

According to various authors (Burghouwt 2007; Malighetti et al. 2008; Veldhuis 1997), we can distinguish between two basic perspectives on connectivity: (1) the accessibility perspective or (in)direct connectivity and (2) the centrality or hub connectivity perspective. Whereas the first perspective considers the number and quality of direct and indirect air travel connections available to the consumer at a certain airport, the second perspective measures the number of transfer opportunities available via a specific airport (figure 1).

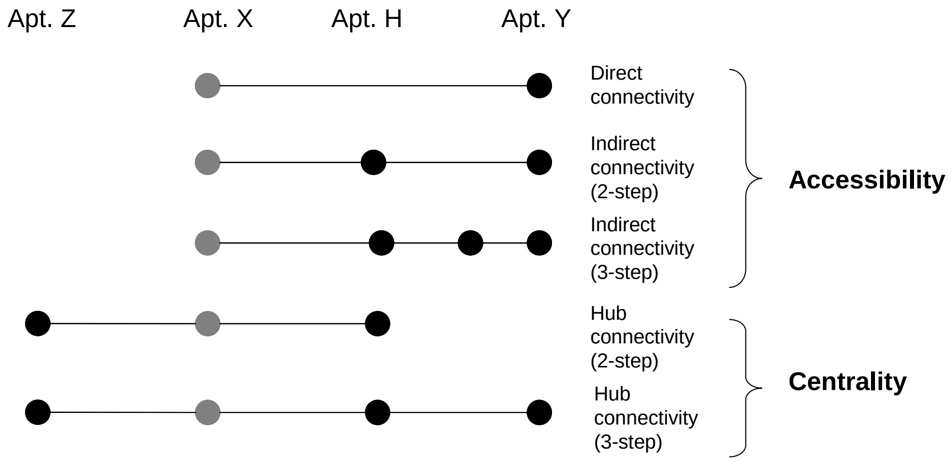

Figure 1. *Types of connectivity at airport X*

The accessibility and the centrality perspective can be used for most of the connectivity measures available in the air transport literature. However, the focus in empirical studies has been on the centrality perspective in order to measure the performance airline hubs (Bootsma 1997; Budde et al. 2008; Burghouwt & de Wit 2004; Dennis 1994a, 1994b; Dennis 1998). Exceptions are the studies of Burghouwt & Veldhuis (2006) on the connectivity of European airports on the Transatlantic market, Malighetti et al. (2008) on the potential benefits of 'self-help hubbing' in Europe, Shaw (1993) and Shaw & Ivy (1994) on the hub structures of US passenger airlines.

Temporal coordination

A second dimension to classify connectivity measures is the temporal coordination of indirect flights by hub carriers via their respective hubs. The route choice of passengers travelling between airport A and B depends on factors such as ticket price, in-flight time, frequency but also waiting time at the hub in case of an indirect flight. Carriers can limit the waiting time at the hub by means of increasing frequency and/or operating an efficient wave-system structure.

Passengers are not prepared to wait an indefinite time at the hub. When transfer time becomes to long, travellers look for alternative travel options or do not travel at all. In addition, a minimum connecting time is always required for a hub transfer because of the turn-around time of aircraft, walking distances within the airport, controls, baggage handling etc.
Therefore, a number connectivity measures include some kind of minimum and maximum quality thresholds in terms of transfer time (for example, Bootsma 1997, Burghouwt and De Wit 2005, Veldhuis 1997, Danesi 2006, Doganis and Dennis 1989 and Budde et al. 2008). Others (for example, Bania et al. 1998; Cronrath et al. 2008; Dennis 1998; Malighetti et al. 2008) do not apply such a criterion. In the latter case, the connection models consider an indirect connection as viable when an arriving and departing flight are simply available for the passenger via a certain hub airport without taking into account actual arrival and departure times.

Routing factor

A number of connectivity measures discussed apply a threshold on the routing factor or circuitry factor (Burghouwt & De Wit 2005; Danesi 2006; Malighetti et al. 2008). The routing factor is the ratio between the actual flight distance (km/time) and the (theoretical) distance of a direct flight. Typical routing factors vary between 120% and 150%. The Netscan model (Veldhuis 1997; Burghouwt & Veldhuis 2006: IATA 2000) does not apply a maximum routing factor as such but the connection quality decreases as the routing increases, depending on the theoretical direct flight time. However, in practice the maximum routing factor of Netscan does not exceed 150%.

Connection quality

A fourth dimension is the extent to which measures take into account the quality of a connection. Measures that take into account connection quality do not only consider the temporal coordination/routing thresholds but also the strength of the relationship of the individual connection. They do so by attaching a quality indicator to each viable connection determined by the transfer time and routing time. The most simple form of connection quality, is binary: a connection is viable if it meets transfer time and routing factor thresholds (Budde et al. 2008; Dennis 1994a&b; Malighetti et al. 2008). Somewhat less information on the connection quality is lost in the discrete measures: discrete measures classify connections in various categories, for example in excellent, good and poor connections (Bootsma 1997; Danesi 2006). Some of the measures (Burghouwt 2007; Burghouwt & de Wit 2004;

Burghouwt & Veldhuis 2006; Matsumoto et al. 2008; Veldhuis 1997; Veldhuis & Kroes 2002) apply a continuous measurement of connection quality. For example, Burghouwt & De Wit (2004) and Veldhuis (1997) weigh transfer time heavier than in-flight time as passengers dislike waiting time at the hub more than in-flight time (Lijesen 2004). This type of measures allows for making fair comparisons in the number and quality of connections between hubs and between various connections at the same hub. Since indirect connections are weighted and scaled to the maximum quality of a theoretical direct connection, connectivity of direct and indirect flights can be compared and aggregated.

A variation is the average quickest path length applied by Malighetti et al. (2008) and Paleari et al. (2008). The average quickest path length is time the average minimum travel time needed to reach all other airports in the population. A minimum connection criterion is used to define all possible, viable paths, but no upper maximum connection time limit is applied. In addition, a connection is only counted when it is the quickest in a certain origin-destination market.

Maximum number of steps allowed

Indirect connections can be either 2-step (one hub transfer, 2 legs) or more than 2-step (figure 1). According to Swan (2008), over 50% of the OD passengers travelling more than 8.000 miles face two or more hub transfers. On the short-haul, double connections are less important: 2-step connections are often between minor airports. Malighetti et al. (2008) show that more than 2-step connections account for less than 7% of all available connections in Europe, weighted by the offered seats of the linked airports. In other words, particularly for ultra-long haul markets and connections between very small airports, both single connect and double connect travel options should be taken into account. However, existing connectivity measures focus primarily on the one-step connections. Only few measures such as the quickest and shortest path measures (Cronrath et al. 2008; Ivy 1993; Malighetti et al. 2008; Shaw 1993; Shaw & Ivy 1994) take into account indirect connections consisting of more than two legs. One reason of this omission in most studies might be a technical one: the steep exponential rise in computing time for >2-step connections as the number of flights considered grows.

Local versus global models

Local connectivity models count each individual connection from a certain airport. In contrast, global models yield relative connectivity indicators in the sense that the connection quality of a certain connection is compared with the quality of all other possible connections in the same origin-destination market. Only the best connection is then counted. In essence, in comparison to local models, global models add a second condition in addition to the level of temporal coordination and routing factor: being the shortest or quickest connection.

For example, the shortest path models in this paper measure the total number of *shortest* paths for a certain airport needed to reach all other airports in the airport population, including one-step but also all multi-step connections (Malighetti et al. 2008). In contrast, the CNU connectivity model of Veldhuis (1997) measures the total number of direct and two-step indirect connections available for the consumer at that airport, including the connections that are not the shortest paths.

Global models are obviously more demanding in terms of data and computational requirements. At the same time, they cover a larger percentage of the actual connections made by passengers than local models do.

Overview of connectivity measures

Based on the dimensions discussed in the former section, we have classified the most important connectivity measures in the academic air transport literature and the studies in which they appeared. We have also indicated which measures are going to be used in the empirical analysis. The Dennis (1998) and Ivy (1993) measures have been left out of the study since they are simpler versions of those employed in Dennis (1994a&b) and Malighetti et al. (2008). The mathematical elaborations of the measures can be found in the appendix A.

In conclusion, all measures discussed here are suitable for both centrality/hub analyses and accessibility studies. Major differences between the different models result mainly from the Temporal coordination, connection quality, the number of steps allowed and the global/ local perspective. A consequence of choosing a model with a lower scale of measurement is a loss the information on the quality of the connection. This may not be a problem as long as the level of analysis is high, for example at the airport level. The effect of the size of the airport on total connectivity outweighs the loss of information about the quality of individual connections. However, on lower levels of analysis (for example the route or route group level), the loss of information in models, which do not take into account connection quality, may lead to distortion of the results.

Name of the measure	Studies	Temporal coordination	Routing factor	Connection quality	Number of steps	Local / global	This study?
Hub potential	Dennis 1998	No	No		2	Local	
Doganis & Dennis connectivity	Doganis & Dennis 1989; Dennis 1994a, 1994b	Yes	No	Binary	2	Local	X
Bootsma connectivity	Bootsma 1997	Yes	No	Discrete	2	Local	X
WNX (Weighted Number of Connections)	Burghouwt 2007; Burghouwt & de Wit 2004	Yes	Yes	Continous	2	Local	X
Netscan Connectivity Units (CNU)	Burghouwt & Veldhuis 2006; IATA 2000; Matsumoto et al. 2008; Veldhuis 1997; Veldhuis & Kroes 2002	Yes	Yes	Continous	2	Local	X
WCn (Weighted Number of Connections)	Danesi 2006	Yes	Yes	Discrete	2	Local	X
Gross Vertex Connectivity	Ivy 1993; Ivy et al. 1995	No	No		>2	Local	
Shortest Path Length	Cronrath et al. 2008; Malighetti et al. 2008; Shaw 1993; Shaw & Ivy 1994	No	No		>2	Global	X
Quickest path length Centrality	Malighetti et al. 2008; Paleari et al. 2008	Yes	Yes	Binary	>2	Global	X
Quickest path length Accessibility	Malighetti et al. 2008; Paleari et al. 2008	Yes	Yes	Continous	>2	Global	X
# of connection patterns	Budde et al. 2008	Yes	No	Binary	2	Local	X

Table 2. Characteristics of the various connectivity models

Most connectivity models reflect real travel behaviour only partially because these models do not include connections with more than two steps. Although there are technically valid reasons not to include >2-step connections, for ultra-long haul trips and trips between very small airports in particular, >2-step connections are important for consumer welfare.

In the next section, we will compare the connectivity measures empirically.

3. Methodology and data

In the empirical analysis we consider all passengers scheduled flights departing or arriving in European airports (25 members of European Union, Switzerland, Norway and Iceland) in September 2008, including also multi-stop direct connections. Our data provider is Innovata[1].

When building connections in intermediate airports, only online transfers or interline transfers between carriers belonging to the same alliance are considered. Connections between flag carriers of different alliances or between low cost carriers and flag carriers are then not taken into account. Appendix B reports on the alliance composition.
In order to create a fair playground for the empirical comparison of the different measures, we set for all model a unique minimum connecting time of 1 hour for all kinds of connections. Maximum connecting times, if any, are directly taken from the author's original works and are reported in table 3. The mathematical elaborations of the different models can be found in appendix A.

The majority of models work on a single day flight scheduling. We choose to consider an average week day in a typical autumn week, Thursday 18th September 2008. For the number of connectivity patterns model (Budde et at. 2008) we needed to extend the period since to distinguish patterns of connections from a statistical point of view, the connections must happen at least twice in the period. Employing a single day period would have resulted in limiting the analysis to flights with a daily frequency higher than 1. For this reason, the chosen period is the week from Monday 15th to Sunday 21st September 2008. The result of this model is the number of connections on Thursday 18th September 2008, which belong to statistically significant patterns recognized over the week.

The WCN and Bootsma models also employ other connecting times, between the minimum and maximum, to weigh their respective measures. Again, in these cases we take the values from the author's original work.

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[1] Innovata is a provider of Scheduled Reference Services in partnership with IATA. The SRS airline schedules database contains data from over 892 airlines worldwide.

Model	Min. conn. Time (mct)	Max. connecting time (MCT)	Period	Routing Factor limit
Weighted connectivity	60’	European: 180 min Interc.: 720 min	1 day	1.4 * flying times
Netscan	60’	No MCT	1 day	No
Bootsma connectivity	60’	European: 180’ Europe-Interc.: 300’ Interc.-Interc.: 720’	1 day	No
WCN – Weighted Connectivity Number	60’	European: 120’ Europe-Interc.: 180’ Interc.-Interc.: 180’	1 day	1.5 * distances
Doganis and Dennis connectivity	60’	90’	1 day	No
Number of connection patterns	60’	No MCT	7 days	No
SPL – Shortest Path Length	No mct	No MCT	1 day	No
QPL - Quickest Path Length	60’	No MCT	1 days	1.25 * distances

Table 3. Minimum and maximum connecting times, considered periods and routing factor limits for the models.

The QPL model does not have a connecting time upper limit. Since it only includes the quickest paths from origin to destination, even if the related waiting times in intermediate airports are long, completing the connections results in the minimum travel time. However, since the quickest trip must conclude within 24 hours of travel time, there is a indirect limit on connecting times. For this reason, connections requiring to wait 24 hours in intermediate airports are not taken into account.

The Netscan model does not have a maximum connecting time either, but in this case the quality of the connection decreases as the connecting time increases. However, in practice no one-stop connections have connecting times exceeding 4 hours.

The last column of table 3 indicates whether the models employ same restrictions on the connections’ routing factors. The QPL model employs a specific routing factor limit of 1.25. This limit is defined as the ratio between the flying distance to complete the connection divided by the great circle distance between the origin and the destination airports. The WCN model employs also a distance-based routing factor limit of 1.5. It also employs an intermediate routing factor limit of 1.2 to distinguish good connections with routing factors from 1 to 1.2 and poor connections with routing factor from 1.2 to 1.5. The weighted connectivity model takes into account a routing factor limit of 1.4 based on flying time. It is defined as the ratio between flying times of two direct flights to complete the connection and the estimated direct flying time between departure and arrival airports. The Netscan model does not have a routing factor upper limit but the connection importance decreases with the increase of the routing necessary to connect origin and destination. However, in practice the maximum routing factor of Netscan does not exceed 150%.

We consider all European airports with at least one scheduled flight on Thursday 18th September 2008 resulting in a sample of 485 airports. Table 4 reports the list of the 28 countries included and the number of airports considered for each country.

Country	**N° of airports**	**Country**	**N° of airports**
Austria	6	Latvia	2
Belgium	3	Lithuania	3
Cyprus	3	Luxembourg	1
Czech Republic	3	Malta	2
Denmark	9	Netherlands	5
Estonia	3	Norway	49
Finland	20	Poland	11
France	57	Portugal	16
Germany	39	Slovakia	5
Greece	38	Slovenia	2
Hungary	2	Spain and Canary Islands	41
Iceland	9	Sweden	40
Ireland	9	Switzerland	6
Italy	40	United Kingdom	61

Table 4. *List of the countries included and the related number of airports.*

Table 5 summarizes the main characteristics of the sample. The number of airlines operating is 224, offering almost 2.5 million seats per day.

Main characteristics of the dataset	
Number of airports	485
Number of countries	28
Number of airlines	224
Number of flights	17.105
Number of direct routes (one way)	5.216
Number of seats offered (x1000)	2,471,640

Table 5. *Characteristics of the dataset.*

4. Results: network centrality

This section reports the results of the comparison among the eight different connectivity models. Each model can provide a measure of centrality and also a measure of accessibility.

Top of the ranking

This first part of the analysis deals with the measurement of centrality of the European airport population. Table 6 and 7 show the results and the related rankings for the first thirty European airports and also the rankings for the three size-related measures (offered seats, number of destinations and number of flights). The different measure values cannot be directly compared among the different models since they have different assumptions in terms of maximum connecting times and weigh the connections in different ways. However, it does not surprise that among the first six measures belonging to the "local" typology, the Bootsma's yields the highest score since the Bootsma model assumes the longest maximum connection times of all models.

It is surprising how similar many measures perform in general in terms of their ranking: Frankfurt airport comes on the top for five out of eight measures. In the other three measures, Paris Charles De Gaulle is the leading airport. Munich, Amsterdam, London Heathrow and Madrid often come after those two airports.

Interestingly, London Heathrow, the most important airport in terms of offered seats, second for number of flights and fourth in terms of number of destinations, does not come always on the top places. It ranks third for the first two measures (WCN and Netscan) and for the SPL measure but comes only fifth in the WCN ranking, sixth in the Doganis and Dennis's and QPL, seventh in the number of connection patterns. A possible explanation is that Heathrow has evolved from a traditional hub airport with an extensive local feedering network to a "super-gateway" airport which mainly connects high-density routes but without a pronounced wave-system structure and a dominant hub-carrier. For this reason, when considering a measure related to the number of connections, the role of Heathrow weakens with respect to other leading European airports as Frankfurt and Paris Charles De Gaulle, since the latter offer a greater number of destinations and approximately the same number of flights.

	Weighted connectivity		**Netscan**		**Bootsma connectivity**		**WCN**		**Doganis and Dennis connectivity**		**Number of connection patterns**	
Rank	Airport	Value	Airport	Value	Airport	Value	Airport	Value	Airport	Value	Airport	Value
1	FRA	20,262	CDG	3,931	FRA	39,996	FRA	11,149	CDG	9,778	CDG	12,617
2	CDG	19,824	FRA	3,224	CDG	39,068	CDG	10,579	FRA	8,840	FRA	11,979
3	LHR	14,691	LHR	2,463	MUC	25,923	AMS	7,113	MUC	7,596	AMS	8,642
4	AMS	11,431	AMS	1,971	LHR	25,651	MUC	6,579	AMS	5,954	MUC	6,291
5	MUC	8,411	MAD	1,348	AMS	23,316	LHR	6,183	MAD	4,769	VIE	5,955
6	MAD	6,865	MUC	1,072	MAD	17,112	MAD	4,753	LHR	4,262	MAD	5,186
7	FCO	3,972	FCO	614	VIE	11,701	VIE	3,513	VIE	3,784	LHR	5,178
8	VIE	3,823	ZRH	573	FCO	11,545	FCO	3,411	FCO	3,709	FCO	4,656
9	ZRH	2,865	VIE	436	ZRH	6,827	ZRH	2,386	ZRH	2,584	ZRH	3,027
10	CPH	1,626	LIS	245	CPH	5,826	CPH	1,494	CPH	1,757	BRU	1,774
11	HEL	1,070	CPH	231	ARN	4,606	OSL	1,080	LYS	1,715	CPH	1,752
12	BCN	1,038	HEL	188	OSL	4,580	ARN	1,062	HEL	1,380	DUB	1,727
13	ARN	995	ARN	134	DUS	4,091	HEL	1,040	OSL	1,380	PRG	1,670
14	LIS	989	ORY	97	HEL	3,837	PRG	863	ARN	1,297	HEL	1,598
15	PRG	763	LGW	96	ORY	3,797	LYS	840	ORY	1,209	ATH	1,528
16	OSL	709	PRG	88	BRU	3,062	DUS	736	DUS	1,122	STN	1,499
17	BUD	603	DUS	82	BCN	2,854	BCN	717	PRG	967	LIS	1,366
18	BRU	576	BRU	82	PRG	2,717	BRU	692	BRU	880	DUS	1,240
19	DUS	566	OSL	76	LYS	2,342	LIS	599	BCN	826	BCN	1,186
20	LGW	556	DUB	69	LGW	2,307	WAW	529	WAW	652	ARN	1,139
21	ORY	540	BCN	68	WAW	2,170	BUD	518	LIS	647	LYS	1,132
22	WAW	494	WAW	59	LIS	2,155	ATH	484	STN	634	LGW	1,081
23	ATH	462	ATH	57	STN	2,139	LGW	449	LGW	593	WAW	935
24	MXP	390	BUD	44	ATH	1,793	ORY	420	ATH	567	BUD	926
25	DUB	385	MXP	39	DUB	1,613	STN	379	PMI	437	PMI	925
26	LYS	204	KEF	32	HAM	1,482	PMI	271	DUB	414	MXP	739
27	TXL	165	MAN	29	TXL	1,376	MXP	267	BUD	406	ORY	663
28	MAN	156	STN	22	MXP	1,280	DUB	264	HAM	390	OSL	583
29	STN	154	PMI	22	BUD	1,243	TXL	190	TXL	361	MAN	569
30	PMI	126	OPO	16	PMI	919	HAM	173	MXP	283	GVA	422

Table 6. *Centrality or hub-connectivity measures for the first six models.*

As explained in the methodology section, our analysis takes into account only interline transfers among carriers of the same alliance or online transfers within non-allied carriers. This implicates that airports that have low dominance by a single alliance rank lower in the ranking. Only when alliances have a large share in the total number of flights at an airport and operate a well-developed wave-system, they will meet the conditions for offering a large amount of connecting flights. For example, London Stansted ranks between the 20th and 30th position in all the connectivity measures even if it ranks eight in terms of number of destinations. The airport is visited by a large amount of low-cost carriers, is mainly oriented towards Europe and none of the carriers operates a wave-system at Stansted.

	SPL		QPL		Offered seats		No. of routes		No. of flights	
Rank	Airport	Value	Airport	Value	Airport	Value	Airport	Value	Airport	Value
1	FRA	68,086	FRA	2,591	LHR	128	FRA	202	CDG	733
2	CDG	53,946	MUC	2,045	CDG	116	CDG	196	LHR	668
3	LHR	51,898	CDG	1,773	FRA	109	AMS	187	FRA	652
4	AMS	42,080	AMS	1,639	MAD	90	LHR	154	MUC	595
5	MAD	40,492	MAD	1,441	AMS	86	MAD	143	MAD	592
6	VIE	33,524	LHR	1,423	FCO	79	MUC	140	AMS	566
7	MUC	32,618	VIE	1,175	MUC	71	VIE	132	FCO	504
8	BCN	24,200	CPH	992	LGW	50	STN	126	VIE	388
9	FCO	22,812	ZRH	953	ORY	49	LGW	124	BRU	366
10	ZRH	20,790	FCO	889	OSL	45	BRU	123	CPH	365
11	CPH	19,402	DUS	867	DUB	45	BCN	122	ARN	358
12	LIS	16,548	ARN	859	ZRH	44	FCO	122	DUS	338
13	ARN	14,622	OSL	741	BRU	44	DUB	118	OSL	330
14	LYS	14,192	BRU	673	CPH	44	ZRH	102	ZRH	328
15	OSL	13,936	PRG	636	BCN	43	CPH	96	ORY	325
16	HEL	13,298	BCN	615	VIE	43	DUS	95	BCN	324
17	LGW	13,058	LYS	591	STN	43	MXP	92	LGW	322
18	PRG	12,942	HAM	581	ARN	42	ORY	92	HEL	289
19	STN	10,244	TXL	573	DUS	41	PRG	90	ATH	267
20	WAW	10,154	HEL	548	ATH	37	ARN	89	DUB	264
21	DUS	10,000	STR	499	MXP	33	ATH	89	MXP	249
22	NCE	9,676	MXP	497	HEL	32	GVA	73	STN	245
23	BRU	9,548	WAW	468	TXL	30	MAN	73	HAM	229
24	BUD	9,394	ORY	441	PMI	29	HEL	71	PRG	224
25	DUB	9,100	MAN	372	PRG	26	LIS	71	TXL	224
26	ORY	8,800	LIS	370	HAM	26	OSL	71	MAN	215
27	LCY	8,472	GVA	368	LIS	26	WAW	68	LYS	195
28	MXP	8,226	HAJ	336	MAN	24	BUD	63	PMI	185
29	MRS	7,364	LCY	335	LIN	23	PMI	63	GVA	183
30	CFE	6,724	DUB	314	GVA	22	LYS	62	LIS	178

Table 7. Centrality or hub-connectivity measures for the shortest path length and quickest time and rankings based on offered seats ('000), number of destinations and number of flights.

Value and rank correlation between the measures

Table 8 reports the connectivity matrix among the different connectivity measures and the size-related offered seats, number of routes and number of flights. The lower triangular matrix shows the correlation between the measures values. The first six centrality values, belonging to the "local" type, are strongly correlated to each other. The highest correlation is between the Bootsma's model and the WCN model and approximates 100%. When considering rankings, the correlation between the Bootsma's and WCN decreases to 92%. However, when comparing the relative rankings in table 6, one observes that several airports have different rankings. For example, Amsterdam is third in the WCN ranking and only fifth in Bootsma's. The upper triangular matrix of table 8 shows the correlation between the airports rankings: it is usually lower than the correlation between values.

		1	2	3	4	5	6	7	8	9	10	11
1	Weighted connectivity	1	0.72	0.68	0.79	0.74	0.64	0.65	0.58	0.58	0.56	0.57
2	Netscan	0.99	1	0.77	0.87	0.81	0.76	0.76	0.65	0.65	0.65	0.64
3	Bootsma connectivity	0.98	0.97	1	0.92	0.98	0.94	0.89	0.87	0.88	0.88	0.89
4	WCN	0.98	0.96	1.00	1	0.94	0.87	0.84	0.78	0.77	0.77	0.78
5	Doganis and Dennis connectivity	0.94	0.92	0.98	0.99	1	0.92	0.89	0.84	0.85	0.84	0.86
6	Number of connection patterns	0.95	0.94	0.97	0.98	0.98	1	0.90	0.82	0.88	0.89	0.86
7	SPL	0.90	0.88	0.94	0.93	0.93	0.94	1	0.79	0.81	0.82	0.80
8	QPL	0.84	0.81	0.91	0.90	0.93	0.91	0.94	1	0.88	0.86	0.92
9	Offered seats	0.82	0.80	0.86	0.85	0.86	0.87	0.93	0.92	1	0.94	0.96
10	No. of destinations	0.69	0.67	0.76	0.75	0.78	0.80	0.87	0.88	0.94	1	0.95
11	No. of flights	0.76	0.74	0.83	0.81	0.85	0.84	0.91	0.94	0.98	0.96	1

Table 8. Correlation matrix for the eight measures of centrality or hub connectivity and the three size-related measures (offered seats, number of destinations and number of flights).The lower triangular matrix reports the correlation among measures values and the upper one the correlation among measures rankings.

Table 8 also shows the correlation between the hub connectivity measures and three the size-related variables, offered seats, number of destinations and flights. The most correlated size-related variable is usually offered seats, followed by the number of flights. Correlation values on the upper triangular matrix are often lower. In other words, size-related rankings and connectivity rankings do not coincide, even if their related values are significantly correlated. The first six 'local' connectivity measures are only partially related to the three size variables whose correlation value ranges from 69% to 84%. The two 'global' connectivity measures, SPL and QPL, show higher correlations. The highest correlation value is 94% between the QPL model and the number of flights. It decreases to 92% when looking at the rankings.

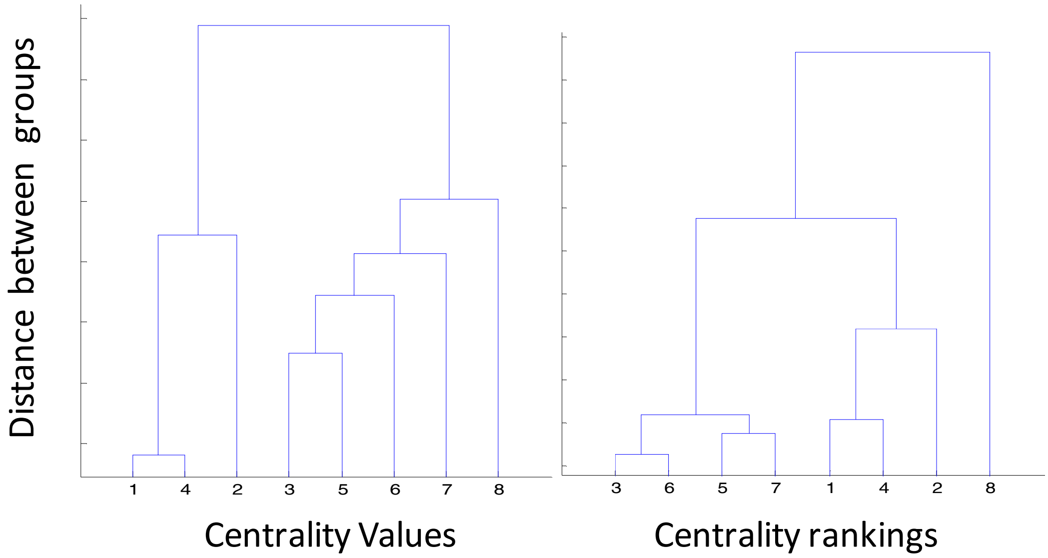

Figure 2. Dendrogram of a cluster analysis on the eight centrality measures. The left-side relates to centrality values; the right-side to centrality ranking. The numbers refer to the connectivity measures in table 8.

Centrality clustering

Figure 2 shows the dendrogram related to the values and rankings of the eight centrality measures. A dendrogram is a diagram which shows the interrelationships between the different measures, as well as estimates of when they can be brought together. It illustrates the results of the clusters produced by a clustering algorithm. Here the numbers at the bottom represent the different measures, numbered as in table 8. The height of each joint ∩ represents the distance between two measures or measures' groups being clustered.

From the left-side of figure 2, we can observe two clusters of measures that yield similar centrality values. The first cluster of measures with similar values, is that composed of the local measures that take into account connection quality (Weighted connectivity/Netscan/WCN) in terms of connecting times and routing factors: the first two by devising a continuum weighting formula and the latter but a discrete four-level weighting system (0, 0.25, 0.5 and 1) depending on connecting times and routing factors reaching certain thresholds.

The second cluster consists of the Bootsma/Doganis and Dennis/Number of Connection Patterns. All these three measures are similar in the sense that count the number of connections (or connection patterns) in a given time window. The two network-based measures, SPL and QPL, are much more difficult to classify and are more correlated to the measures in the second cluster. This two network-based measures consider only shortest or quickest paths passing through intermediate airports but they do not have a weighting mechanisms as the measures in the first cluster.

Looking at the centrality rankings, from the right-side of figure 2, there is difference with respect to centrality values. We still find the two cluster related to the weighted and un-weighted measures but in this case the SPL approach (7) results in rankings much more similar to those of the un-weighted local measures.

When looking at both centrality values and rankings, the least correlated measure, which is more difficult to cluster with the others, is the QPL. In fact, looking at the dendrogram in figure 2, the QPL measure clusters at a greater height than any other measure. It is also confirmed by the lower correlation coefficients between QPL and the other centrality measures, shown in table 8.

Conclusions

The comparison of the network centrality outcomes of the various connectivity measures yields interesting results. First of all, most 'local' and 'global' connectivity measures perform quite equally in terms of value correlation, but show remarkable differences with traditional size-based measures. Secondly, differences are much larger in terms of the rankings than in terms of the absolute values of the various connectivity measures. Finally, we can identify a number of clusters, which broadly mirror the theoretical dimensions of connectivity measures described earlier

5. Results: network accessibility

The second part of the empirical analysis deals with comparing the connectivity measures in terms of accessibility. Whereas the measures previously reported regard network centrality as the importance of a specific airport in making one-stop connections between the origin and destination airport, the measurement of network accessibility quantifies how well one can travel from a specific airport to the rest of the airports. In other words, centrality takes the perspective of the intermediate hub airport, whereas accessibility takes the perspective of the traveller in a connectivity analysis.

	Weighted connectivity		Netscan		Bootsma connectivity		WCN		Doganis and Dennis connectivity		Number of connection patterns	
Rank	Airport	Value	Airport	Value	Airport	Value	Airport	Value	Airport	Value	Airport	Value
1	CDG	5,533	LHR	1,663	CDG	9,755	LHR	3,386	LHR	2,733	CDG	2,275
2	LHR	5,358	CDG	1,660	LHR	8,961	CDG	3,386	CDG	2,730	FRA	2,132
3	AMS	4,209	FRA	1,310	FRA	8,156	AMS	2,714	FRA	2,628	AMS	1,964
4	FRA	4,180	AMS	1,270	AMS	7,523	FRA	2,677	AMS	2,376	LHR	1,874
5	FCO	2,402	MAD	923	MUC	6,384	MUC	1,872	MUC	2,182	FCO	1,525
6	MUC	2,260	FCO	915	FCO	5,408	FCO	1,853	MAD	1,823	BCN	1,472
7	MAD	2,148	MUC	886	ZRH	5,229	MAD	1,836	FCO	1,809	DUS	1,408
8	ZRH	1,860	ZRH	600	DUS	5,080	BCN	1,608	DUS	1,790	MAD	1,403
9	DUS	1,805	BRU	591	MAD	4,730	ZRH	1,568	ZRH	1,727	ZRH	1,397
10	BRU	1,751	BCN	589	BCN	4,556	DUS	1,542	BCN	1,688	MUC	1,376
11	BCN	1,718	VIE	573	CPH	4,453	BRU	1,375	CPH	1,589	BRU	1,347
12	MAN	1,459	DUS	570	HAM	4,211	CPH	1,374	MXP	1,530	MXP	1,270
13	MXP	1,437	ARN	560	VIE	4,119	MXP	1,319	VIE	1,494	CPH	1,230
14	ARN	1,415	CPH	542	TXL	4,075	ARN	1,296	HAM	1,428	VIE	1,154
15	CPH	1,404	LGW	527	MXP	4,013	VIE	1,271	BRU	1,415	ATH	1,096
16	LGW	1,389	MXP	470	BRU	3,905	HAM	1,246	ARN	1,387	GVA	1,079
17	VIE	1,349	OSL	450	ARN	3,734	TXL	1,166	TXL	1,385	HAM	1,031
18	HAM	1,340	ATH	434	GVA	3,260	MAN	1,114	OSL	1,277	ARN	1,025
19	DUB	1,243	MAN	434	OSL	3,216	OSL	1,064	GVA	1,174	MAN	1,006
20	TXL	1,232	DUB	405	STR	3,204	GVA	1,018	PRG	1,133	TXL	981
21	GVA	1,092	HEL	404	MAN	2,948	PRG	945	STR	1,103	PRG	971
22	OSL	1,065	TXL	390	PRG	2,896	STR	914	NCE	1,036	DUB	927
23	STR	1,023	PRG	386	NCE	2,763	HEL	907	MAN	1,018	VCE	868
24	PRG	949	HAM	381	LIN	2,520	DUB	899	HEL	905	OSL	836
25	ATH	915	GVA	350	LYS	2,310	LGW	886	WAW	891	STR	831
26	HEL	877	ORY	349	WAW	2,309	LIS	869	TLS	883	LIS	822
27	EDI	841	LIS	319	DUB	2,306	ATH	859	LYS	877	NCE	778
28	LIS	753	LYS	295	TLS	2,279	EDI	796	VCE	870	LYS	751
29	LYS	746	NCE	286	HEL	2,258	NCE	756	LIS	867	WAW	742
30	NCE	729	EDI	283	HAJ	2,230	LIN	731	ATH	836	HEL	721

Table 9. *Measurement of accessibility for the first six models.*

All the models previously described can be employed to measure network accessibility, even though most of the original papers only apply them to network centrality. The accessibility measure is computed as the sum of direct (non-stop) and indirect (one-stop) connectivity (Veldhuis, 1997).

For the first thirty European airports, Table 9 and 10 show the accessibility measures derived for the eight models, the related rankings and also the rankings for the three size-related measures (offered seats, number of destinations and number of flights).

	SPL				QPL				No. seats		No. routes		No. flights	
Rank	**Code**	**SPL**	**No.**	**Value**	**Code**	**QPL**	**No.**	**Value**	**Code**	**Value**	**Code**	**Value**	**Code**	**Value**
1	CDG	1.7	577	384	FRA	408	426	118	LHR	128	FRA	202	CDG	733
2	FRA	1.7	568	378	MUC	427	420	114	CDG	116	CDG	196	LHR	668
3	AMS	1.8	569	370	CDG	408	437	113	FRA	109	AMS	187	FRA	652
4	MAD	1.8	595	364	AMS	416	431	112	MAD	90	LHR	154	MUC	595
5	FCO	1.8	578	350	VIE	443	388	106	AMS	86	MAD	143	MAD	592
6	LHR	1.8	550	346	CPH	454	404	104	FCO	79	MUC	140	AMS	566
7	MUC	1.9	542	332	MAD	436	404	103	MUC	71	VIE	132	FCO	504
8	VIE	1.9	558	332	DUB	464	408	102	LGW	50	STN	126	VIE	388
9	BRU	1.9	575	331	ARN	479	382	100	ORY	49	LGW	124	BRU	366
10	BCN	1.9	548	328	FCO	460	409	98	OSL	45	BRU	123	CPH	365
11	MXP	2.0	570	321	BRU	440	415	97	DUB	45	FCO	122	ARN	358
12	LGW	2.1	585	320	ZRH	447	394	93	ZRH	44	BCN	122	DUS	338
13	DUB	2.0	557	318	DUS	444	397	93	BRU	44	DUB	118	OSL	330
14	CPH	2.0	553	312	LHR	428	414	90	CPH	44	ZRH	102	ZRH	328
15	MAN	2.1	590	310	BCN	467	387	89	BCN	43	CPH	96	ORY	325
16	PRG	2.0	556	309	PRG	483	375	87	VIE	43	DUS	95	BCN	324
17	ZRH	1.9	530	306	ATH	534	378	87	STN	43	MXP	92	LGW	322
18	NCE	2.0	577	306	HAM	476	391	87	ARN	42	ORY	92	HEL	289
19	DUS	2.0	537	304	MXP	464	386	86	DUS	41	PRG	90	ATH	267
20	ARN	2.0	544	304	LYS	499	385	86	ATH	37	ARN	89	DUB	264
21	ATH	2.1	557	302	GVA	481	388	85	MXP	33	ATH	89	MXP	249
22	GVA	2.0	558	299	NCE	506	378	85	HEL	32	MAN	73	STN	245
23	BUD	2.1	557	291	TXL	475	397	83	TXL	30	GVA	73	HAM	229
24	LIS	2.0	534	290	HEL	543	366	81	PMI	29	OSL	71	TXL	224
25	WAW	2.1	553	287	STR	489	392	78	PRG	26	LIS	71	PRG	224
26	TXL	2.1	549	286	MAN	485	375	78	HAM	26	HEL	71	MAN	215
27	MRS	2.2	569	285	STN	252	186	76	LIS	26	WAW	68	LYS	195
28	HAM	2.0	533	285	OSL	525	352	75	MAN	24	BUD	63	PMI	185
29	LYS	2.1	538	284	WAW	509	350	75	LIN	23	PMI	63	GVA	183
30	AGP	2.2	562	282	BUD	525	348	72	GVA	22	LYS	62	LIS	178

Table 10. *Measurement of accessibility for the shortest path length and quickest time models and rankings based on offered seats ('000), number of destinations and number of flights.*

When looking at various measures, London Heathrow comes back on top positions. Three out of six "local" models in table 9 put Heathrow in the first place, and the other three in second place, confirming its role of gateway to reach the final destinations. On the other hand, considering the two global models of table 10, Heathrow only comes sixth in the SPL model, and fourteenth in QPL model. The latter models respectively consider the average minimum number of steps and the average quickest travel times to reach any other world-wide destination. Considering these measures, Heathrow is at a disadvantage since it focuses mainly on intercontinental destinations. As a consequence, the paths starting from Heathrow to European airports involve a higher number of steps and longer travel times than its main competitors Paris Charles De Gaulle and Frankfurt (that have a more developed European network). Furthermore, when taking into account travel time and European destinations, it is less competitive than those airports because of its peripheral position.

From the differences in the results between local and global connectivity measures follows that both types of measures essentially evaluate different things: local measures analyze the absolute accessibility available to the consumer at that airport with a maximum of one transfer, regardless of the destinations served. On the other hand, global measures analyze accessibility available to the consumer relative to the all airports theoretically available to the consumer with any number of steps.

		1	2	3	4	5	6	7	8	9	10	11
1	Weighted connectivity	1	0.96	0.98	0.98	0.98	0.93	0.93	0.94	0.92	0.86	0.92
2	Netscan	0.99	1	0.95	0.97	0.96	0.91	0.90	0.93	0.96	0.93	0.98
3	Bootsma connectivity	0.96	0.97	1	0.98	0.99	0.94	0.95	0.94	0.91	0.85	0.91
4	WCN	0.98	0.99	0.99	1	0.99	0.93	0.93	0.95	0.92	0.88	0.94
5	Doganis and Dennis connectivity	0.94	0.95	0.99	0.98	1	0.94	0.93	0.94	0.92	0.86	0.92
6	Number of connection patterns	0.92	0.94	0.98	0.97	0.98	1	0.93	0.91	0.90	0.87	0.87
7	SPL	0.59	0.63	0.69	0.68	0.72	0.74	1	0.94	0.88	0.84	0.86
8	QPL	0.74	0.78	0.84	0.83	0.87	0.88	0.92	1	0.89	0.88	0.91
9	Offered seats	0.95	0.98	0.93	0.95	0.92	0.90	0.62	0.77	1	0.94	0.96
10	No. of destinations	0.88	0.93	0.91	0.92	0.92	0.92	0.72	0.87	0.94	1	0.95
11	No. of flights	0.93	0.98	0.95	0.96	0.95	0.93	0.67	0.83	0.98	0.96	1

Table 11. *Correlation matrix for the eight measures in terms of accessibility and the three size-related measures (offered seats, number of destinations and number of flights). The lower triangular matrix reports the correlation among measures values and the upper one the correlation among measures rankings.*

Table 11 reports the connectivity matrix among the eight accessibility measures and the three size-related variables. In this case the less correlated measures to airport size are the SPL model and the QPL model. They have also a low correlation to the other six accessibility measures. Correlations based on values, shown in the lower triangular matrix of table 11 is often lower than that computed on rankings, in the upper triangular matrix.

Accessibility clustering

Figure 3 shows the dendrogram related to the values and rankings of the eight centrality measures. Here the numbers at the bottom represent the different measures, numbered as in table 11. Looking at the left-side of the figure, the Netscan values (2), and the WCN values (4) can be grouped together very easily, as also shown by the high correlation index between them. Also the Bootsma (3) and the Doganis and Dennis (5) connectivity values can be clustered together. The two network-based measures, SPL (7) and QPL (8) can also be part of a group. It is much more difficult to classify the weighted connectivity (1) and the number of connection patterns (6). With less precision we can group them with the Bootsma connectivity and Doganis and Dennis connectivity.

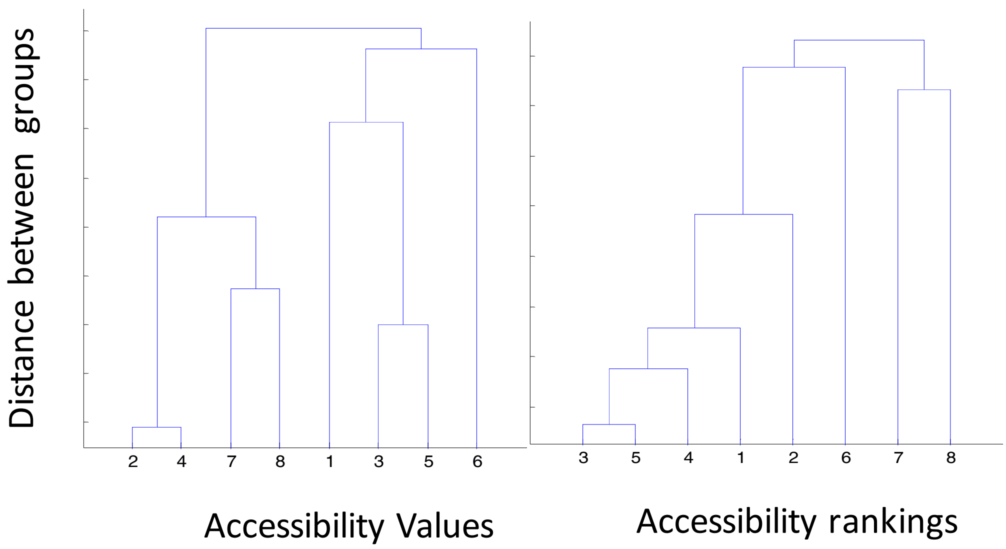

Figure 3. Dendrogram of a cluster analysis on the eight accessibility measures. The left-side relates to centrality values; the right-side to centrality ranking. The numbers refer to the connectivity measures in table 11.

Conclusions

Looking at the correlation structure of the different accessibility ranking, two groups emerge. The first includes all the six local measures; the second includes the two global measures, the SPL and QPL. In the case of accessibility ranking, there is a higher correlation between the local measures that do and do not (or only in a discrete way) take into account connection quality. The reason may be that when looking at accessibility there is less variance among different airports than in the case of centrality. As a consequence, all measures tend to be more correlated to each other. This very important difference between centrality and accessibility measures is considered in the next section.

When looking at both accessibility values and rankings, the least correlated measure, which is more difficult to cluster with the others, is the number of connection patterns.

6. Bringing the different perspectives together

Table 12 and table 13 report statistics on the eight models, grouped by their related rankings. Averages and medians significantly drop from the first ten airports class to the others, meaning that centrality is strongly concentrated. After the first fifty airports, average and median of different centrality measures tend to zero as the airlines at these airports do not offer temporal coordination of flights and, as a result, connecting opportunities for the passengers.

Considering accessibility statistics, averages and medians decrease in a smoother trend from the first ten airports to the other groups. Even in the group of the least connected airports, accessibilities are significantly positive. Looking at the ratio between standard deviations and averages, centrality values show a much higher dispersion around the average than accessibility values for all the airports groups. It accounts for the very different correlation figures between centrality values and centrality rankings, as reported in table 8.

Rank	Var.	Weighted connectivity	Netscan	Bootsma connectivity	WCN	Doganis and Dennis connectivity	Number of connection patterns	SPL	QPL	No. seats	No. routes	No. flights
First 10	Average	9.377	1.588	20.697	5.716	5.303	6.531	39.045	1.492	82.246	153	543
	Median	7.638	1.210	20.214	5.468	4.516	5.571	37.008	1.432	82.451	142	579
	St. Dev.	0,70	0,76	0,56	0,54	0,48	0,52	0,37	0,34	0,34	0,19	0,23
From 11 to 50	Average	303	40	1.458	330	466	673	7.687	366	24.504	66	193
	Median	119	15	823	173	254	419	6.678	302	21.406	62	178
	St. Dev.	1,07	1,30	0,91	0,97	0,96	0,81	0,57	0,57	0,49	0,37	0,44
For 51 to 100	Average	9	0	112	18	36	58	1.009	62	7.313	26	63
	Median	7	0	94	14	34	63	936	50	7.426	26	64
	St. Dev.	0,73	0,76	0,51	0,62	0,48	0,35	0,58	0,49	0,25	0,19	0,22
For 101 to end	Average	0	0	4	0	1	3	22	3	784	4	8
	Median	-	-	-	-	-	-	-	0	310	2	5
	St. Dev.	3,10	8,06	2,09	2,87	2,25	2,08	2,41	1,89	1,30	1,09	1,09

Table 12*. Average, median and standard deviation to average for the eight measures in terms of centrality and the three size-related variables by the ranking groups.*

Rank	Var.	Weighted connectivity	Netscan	Bootsma connectivity	WCN	Doganis and Dennis connectivity	Number of connection patterns	SPL	QPL	No. seats	No. routes	No. flights
First 10	Average	3.151	1.041	6.578	2.244	2.149	1.683	351	107	82.246	153	543
	Median	2.331	919	5.896	1.862	2.003	1.499	348	105	82.451	142	579
	St. Dev.	0,45	0,38	0,27	0,31	0,19	0,19	0,06	0,06	0,34	0,19	0,23
From 11 to 50	Average	824	306	2.429	784	892	749	281	73	24.504	66	193
	Median	721	281	2.195	719	835	693	279	72	21.406	62	178
	St. Dev.	0,47	0,44	0,38	0,39	0,37	0,35	0,08	0,16	0,49	0,37	0,44
For 51 to 100	Average	213	88	744	243	286	255	222	45	7.313	26	63
	Median	180	82	654	223	272	258	217	44	7.426	26	64
	St. Dev.	0,36	0,26	0,34	0,31	0,32	0,24	0,08	0,14	0,25	0,19	0,22
For 101 to end	Average	21	10	79	27	33	28	68	11	784	4	8
	Median	8	6	31	13	16	11	56	7	310	2	5
	St. Dev.	1,40	1,20	1,34	1,32	1,27	1,32	0,98	0,94	1,30	1,09	1,09

Table 13*. Average, median and ratio between standard deviation and average for the eight measures in terms of accessibility by the ranking group.*

Figure 4 shows the distributions of the average size-related measures, as well as the results from the connectivity measures both from an accessibility (consumer) and centrality (hub) perspectives. The connectivity results have been standardized to one for all the European airports included in this analysis[2]. Interestingly, centrality distribution lies under size distribution whereas accessibility distribution lies above size distribution. As remarked above, centrality measures on average decrease more than proportionally with respect to size, passing from the most to the least central airports. In other words, above a size threshold, hub connectivity increases more than proportionally than size due to the connectivity multiplier characteristic of hub-operations.

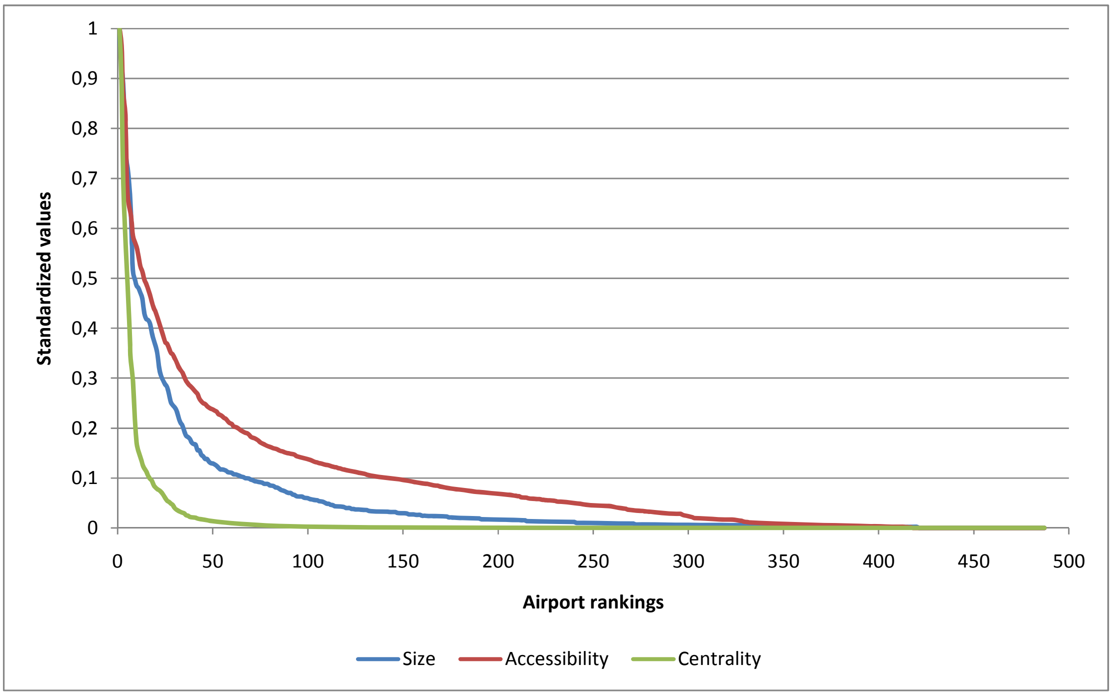

Figure 4. Distribution comparison of average size-related variables, centrality measures and accessibility measures standardized to one.

On the other hand, accessibility decreases less than size, passing from the most to the least connected airports. A small airport can have good accessibility values if well-connected to a few very central hub airports.

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[2] The standardized measures are obtained by dividing each airport's measure by its maximum. Then, for each airport ranking, it was computed the average of the different standardized values. These steps were repeated for the eight centrality measures, the three size measures and the eight accessibility measures.

In essence, with respect to centrality of airports, traditional size related measures seem to overestimate the importance of airports as hubs. However, due to the strong exponential relationship between size and number of hub connections, size variables alone, such as frequency and capacity, do not accurately measure the performance of hubs and their centrality in the network. With respect to accessibility, it is the other way around: traditional size related measures such as frequency and capacity underestimate the accessibility of airports. They do not take into account that having one daily frequency to one very central hub airport which offers a multitude of unique connections beyond the hub is far more valuable for the consumer than a single daily frequency to a non-hub airport.

7. Conclusions

In this paper we analyze various connectivity models that have been employed in the academic literature to measure airport centrality and accessibility. We assessed the measures in terms of included variables, underlying models and empirical results and compared them with traditional size-based measures (frequency, capacity, number of destinations).

Our analyses show that there are good reasons to use connectivity measures instead of traditional size-based measure for both accessibility and centrality analyses. In the current air transport market, carriers compete both directly and indirectly because of the widespread use of hub-and-spoke systems. We have shown empirically that, as a consequence, traditional size-based measures tend to overestimate the importance of airports as connecting hubs but underestimate the accessibility available to the consumer at a certain airport. A minor regional airport can reach an acceptable level of accessibility to the rest of the network if it has just a few flights to one of the major hubs. On the other hand, big airports do not always have a proportionally high centrality in the network. Not surprisingly, the correlation between the traditional sized based measures such as frequency, seats, routes is much higher than the correlation between traditional sized based measures on the one hand and connectivity measures on the other.

For both practitioners and academics, the question rises which connectivity measures should be used in what circumstances. From our analyses follows that the choice for an appropriate connectivity measure depends very much on the objective of the research. A number of factors play a role.

First of all, the acceptable level of information loss in terms of connection quality. The more detailed the analysis is, the lower the acceptable loss of information should be. Quick analyses at a very aggregate level may do with Dennis, WCn and Bootsma type of local connectivity models. However, in more in-depth studies local measures with a continuous measurement of connection quality may be required, such as the Netscan and WNX models. This is in particular true for studies on the impact of flight schedule coordination on connectivity, analyses at the individual OD market level and studies on connectivity at small airports. As expected from theoretical point of view, these local continuous measures perform empirically quite similar, looking for example at the rank correlation of airport connectivity.

Secondly, the number of steps required. The local connectivity models allow to analyze connections with a maximum of one hub transfer (two steps). However, there may be good reasons to include connections with more than two steps. This in particular true for ultra-long haul markets and markets between very small airports. Although most local models can, in theory, be extended to include >2-step connections, at present only the global QPL and SPL models allow to include connections with more than one transfer.

Thirdly, does the researcher aim to perform a ‘size’ or ‘best in class’ analysis? Apart from routing and connection time conditions, the global models (QPL/SPL) add another criterion for a connection to be classified as viable: being the shortest or quickest connection for a particular origin-destination market among all possible connections in that market. In contrast, most local models count each possible connection in that market, regardless if it is the quickest or shortest. The exception is the Budde model, which is the only local model where a statistical condition is applied. As a result, the Budde model allows for distinguishing between planned connections (statistically significant patterns) from ‘random’ connections (not significant patterns).

Finally, the complexity allowed in performing the connectivity analysis may play a role. Local continuous models and in particular global models require more data, time and technical skills from the researcher than local binary and discrete models do.

A future development of this work will address the issue of connectivity determinants. Besides airport’s size, other variables play a role in determining an airport’s centrality to the network, such as the geographical position and the degree of schedule coordination.

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Appendix A- Elaboration of the connectivity measures

Hub connectivity models

All the eight measures of hub connectivity have the same underlying principles. They can be computed following a two steps procedure. The hub connectivity measure of the intermediate airport i, shown in the left-side of figure 5, is computed as follows:

1) identify the connections from the generic airport k to the generic airport j passing through airport i that meet some defined conditions which vary from measure to measure. We call those conditions "cut-point" conditions and the resulting connections "viable" connections.
2) after indentifying the viable connections, the measure can be obtained applying the following expression:

   $$\text{Hub connectivity measure} = \sum_{1}^{n} f(c_{j-i-k})$$

   Where n is the number of viable connections and $f(c_{j\text{-}i\text{-}k})$ is a function of the characteristics of the generic viable connection j-i-k that we call weighting function. It also depends on the specific measure applied.

Accessibility models

The six local measures of accessibility have the same underlying principles. They can be computed following a two steps procedure. The accessibility measure of an airport i, shown in the right-side of figure 5, is computed as follows:

1) identify in any airport j, directly linked to airport i, all the connections starting from airport i and going onwards to the generic airport k that meet some defined conditions, varying from measure to measure. Again, we call those conditions "cut-point" conditions and the resulting connections "viable" connections.
2) after indentifying the viable connections, the measure can be obtained applying the following expression:

   $$\text{Accessibility measure} = d + \sum_{j=1}^{m} \sum_{1}^{n_j} f(c_{i-j-k})$$

   The first term d is the direct connectivity, measured as the number flights from airport i. The second term refers to indirect connectivity, or onward 2-step connectivity, where m is the number of airports with incoming flights from airport i, and n_j is the number of viable connections indentified in the intermediate airport j; $f(c_{i-j-k})$ is a function of the characteristics of the generic viable connection j-i-k that we call weighting function. It also depends on the specific measure applied.

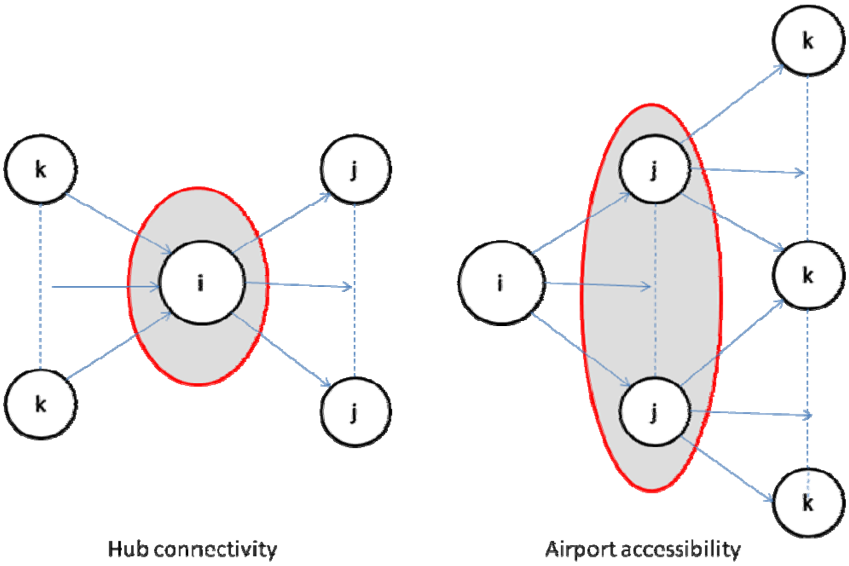

Figure 5. Hub connectivity and airport accessibility measures.

Measures profiles

In order to compute all the eight hub connectivity measures and the six local accessibility measures, one only requires to know the cut-point conditions and the particular form of the weighting function, that will be reported in the following measures profiles. The remaining two accessibility measures related to SPL and QPL will be considered at the end of this appendix

Weighted connectivity

Measure	Weighted connectivity	
Main reference	Burghouwt, G. and J. de Wit (2005)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60‘ for all connections - maximum connecting time (MCT) of 180’ for EU connections - maximum connecting time (MCT) of 720’ for intercontinental connections - maximum routing factor (R) of 1.4 based on flight times	
Weighting function for every viable connection	f=WI= $\frac{2.4*TI+RI}{3.4}$; WI: weighted indirect connection; TI=1-$\frac{1}{MCT-mct}T$; TI: transfer index; T: connection transfer time; MCT maximum connecting time for the connection; mct: minimum connecting time for the connection; RI=$1-(2*\frac{R}{2}-2*\frac{1}{2})$; RI: routing index; R: routing factor; R=IDT/DTT IDT: actual in-flight time; DTT: estimated in-flight time of the direct connection based on the great circle distance	
Software	Microsoft Access	Medium complexity

Netscan

Measure	Netscan	
Main reference	Veldhuis (1997)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60’ for all connections	
Weighting function for every viable connection	f=QUAL= $1-\frac{PTT-NST}{MAXT-NST}$; QUAL: quality index; NST: non-stop travel time (hours); PTT=FLY+3*TRF; PTT: Perceived travel time (hours); TRF: Connection transfer time (hours); FLY: Flying time (hours); MAXT=(3-0.075*NST)*NST; MAXT: Maximum perceived travel time (hours)	
Software	Microsoft Access	Medium complexity

Bootsma connectivity

Measure	Bootsma connectivity	
Main reference	Bootsma (1997)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60’ for all connections - maximum connecting time (MCT) of 180’ for EU connections - maximum connecting time (MCT) of 300’ for connections from (to) EU to (from) intercontinental airports - maximum connecting time (MCT) of 720’ for connections from and to intercontinental airports	
Weighting function for every viable connection	f=1	
Software	Microsoft Access	Low complexity

WCN

Measure	WCN – Weighted Connectivity Number	
Main reference	Danesi (2006)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60’ for all connections - maximum connecting time (MCT) of 120’ for EU connections - maximum connecting time (MCT) of 180’ for all other connections	
Weighting function for every viable connection	f=tau*delta; tau: connection time weight; delta: routing factor weight; tau= $\left\{\frac{\text{if} \cdot CT_{EU} < 90' \cdot \text{or} \cdot CT_{INT} < 120' \Rightarrow \text{tau} = 1}{\text{otherwise} \cdot \text{tau} = 0.5}\right.$; CT_{EU}=Connecting transfer time for European connections; CT_{INT}= Connecting transfer time for all other connections; delta= $\left\{\frac{\text{if} \cdot RF < 1.2 \cdot \Rightarrow \text{delta} = 1}{\text{otherwise} \cdot \text{delta} = 0.5}\right.$; RF: routing factor defined as the ratio between the direct distance and the flights distance;	
Software	Microsoft Access	Medium complexity

Doganis and Dennis connectivity

Measure	Doganis and Dennis connectivity	
Main reference	Doganis and Dennis (1989)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60' for all connections - maximum connecting time (MCT) of 90' for all connections	
Weighting function for every viable connection	f=1	
Software	Microsoft Access	Low complexity

Number of connections patterns

Measure	Number of connections patterns	
Main reference	Budde, A., J. de Wit and G. Burghouwt (2008)	
Applications	Hub connectivity and airport accessibility	
Cut-point conditions	- minimum connecting time (mct) of 60' for all connections - the connection must be recognized as a statistically significant patterns (see below for more information)	
Weighting function for every viable connection	f=1	
Software	Matlab	High complexity

Further notes on the number of connections patterns measure

This methodology has originally been developed for behavioural research. It was originally conceived by Magnus Magnusson (2000), a psychologist, to recognise patterns in the occurrence of events.

The algorithm is based on the following principle. If two events occur in succession, (event A followed by B) and do so at least twice within a given timeframe, the program tests the null hypothesis that these events are distributed independently (by chance) and have a constant probability per time unit NB/T (where NB = the number of points of B and T = the observation period in time units). Obviously, in case of hub schedules, events (departures and arrivals) will rarely be distributed by chance and significance levels will have to be set accordingly high. After setting a significance level, the methodology finds the interval within which event A is followed significantly more often by event B than can be expected by chance. The critical interval research algorithm is analysed in Magnusson (2000) at p.108-109 and the statistical test at p.107. Whenever an event A is followed by event B within a critical interval at least twice within the given timeframe, a pattern (AB) is found. Arrivals and departures can be conceptualised as events. A high quality indirect connection can be conceptualised as a pattern because it consists of two events that occur repeatedly and in close temporal proximity. The inclusion of a flight in a departure/arrival pattern we term pattern participation. An efficiently designed hub schedule will generate a maximum of high quality indirect connections (patterns) out of a minimum of arrivals and departures (events). A highly connective flight will have a high degree of pattern participation.

SPL

Measure	SPL – Shortest Path Length	
Main reference	Guimerà et at. (2005)	
Applications	Hub connectivity	
Cut-point conditions	- The connection must lie on the shortest path, in terms of number of steps, from origin to destination	
Weighting function for every viable O-D connection	f=1	
Software	Matlab	High complexity

Further notes on the SPL hub connectivity measure

In order to quantify an airport role as an intermediate step between airports that are not directly connected, graph theory has developed the SPL hub connectivity measure, known as Betweenness centrality (Freeman, 1977).

Guimerà et al. (2005) define the Betweenness of airport i as the number of shortest path lengths (SPL) where airport i is an intermediate node. Betweenness expresses the centrality of the airport. In many cases, a given pair of airports is connected by several minimal paths with the same number of steps. The Betweenness centrality simply counts all the shortest path lengths that transit through airport i, including equivalent alternatives.

QPL

Measure	QPL – Quickest Path Length	
Main reference	Malighetti et at. (2008)	
Applications	Hub connectivity	
Cut-point conditions	- minimum connecting time (mct) of 60' for all connections - maximum routing factor (R) of 1.25 based on distances - the connection must lie on the quickest path, in terms of travel time, from origin to destination	
Weighting function for every viable O-D connection	f=1 R=[O-D direct distance]/[in-flight distance]	
Software	Matlab	Very high complexity

Further notes on the QPL hub connectivity measure

The problem of the quickest path may be tackled by applying the time-dependent minimum path approach. For more information on these methods, see Miller-Hooks and Patterson (2004). Optimal travel times incorporate both flight time and waiting time at any intermediate airports. The latter may be influenced by several factors, such as the presence of dedicated facilities to manage transfer passengers, airport congestion, and airport size. As said before, in this paper we assume a minimum connecting time of 60 minutes for all airports. This period is acceptable for European connections, but should be lengthened if our analysis is extended to intercontinental flights. We do not exclude any routes on the basis of their connecting times, since the "shortest" path between two airports (in terms of the number of flights required) is always the quickest. If we were to exclude these routes, some of the airports would no longer have no longer a feasible connection.

This analysis also depends on the starting time of each flight. For each pair of airports this model calculates the shortest travel time QPL_{ijt} from airport i to airport j, starting at a specified time t. The day is divided into 96 units of fifteen minutes, so that starting times range from 00:00 to 23:45 (Brussels time). Itineraries ending after midnight are not taken into account. Thus, for every possible combination of two airports, the model computes the shortest travel times for all flights leaving as early as 00:00 and concluding before midnight of the next day. The minimum travel time for airports i and j is then simply QPL_{ij}=mint(QPL_{ijt}).

In order to evaluate hub connectivity, the optimal path from airport i to airport j is defined as the path that 1) lasts the minimum travel time QPL_{ijt} and 2) involves the fewest possible steps. For example, if there are two connections from A to B lasting for 5 hours, A-C-D-B and A-E-B, only the latter will be defined as optimal.

Shortest and quickest path accessibility models

The network-based models do not express accessibility in just one value. Both the SPL shortest path length and the QPL quickest travel time report a first value indicating how many airports can be reached by departing from a specific airport and a second value indicating how long is the average path to reach the connected airports. The latter is the average number of steps for the SPL model and the average travel time for the Malighetti et al. model. However, to rank airports based on accessibility those variables must be jointly considered. To that purpose, for the shortest path length approach an accessibility index is defined as follows:

$$\text{Accessibility}_{SPL} = \sum_{j \in N_i} \frac{1}{SPL_{i,j}}$$

Where N_i represents the set of airports that can be reached from airport i and $SPL_{i,j}$ is the shortest path length, in terms of number of steps, from airport i to airport j. The index represents the accessibility connection in terms of the equivalent number of one-step connections. For example, if an airport can reach only three other airports with SPL respectively equal to 1, 2 and 2, the equivalent number of one-step connections is 2 (1/1+1/2+1/2) since n-step connections weigh 1/n of single step connections.

Analogously, an accessibility index for the Malighetti et al.'s model can be defined as follows:

$$\text{Accessibility}_{QPL} = \sum_{j \in N_i} \frac{60}{QPL_{i,j}}$$

Where again N_i represents the set of airports that can be reached from airport i and $QPL_{i,j}$ is the quickest travel time, in minutes, from airport i to airport j. The index represents the accessibility connection in terms of the equivalent number of one-hour connections.

Appendix B – Alliance composition

One World	SkyTeam	Star Alliance
American Airlines	AeroMexico	Air Canada
American Eagle Airlines	Aeroméxico Connect	Air Canada Jazz
Executive Air	Air France	United Airlines
Chautauqua Airlines	Brit Air	Lufthansa
Trans States Airlines	Cityjet	Air Dolomiti
British Airways	Régional	Augsburg Airways
BA CityFlyer	Delta Air Lines	Contact Air
Comair	Delta Connection	Eurowings
GB Airways	Delta Shuttle	Lufthansa CityLine
Loganair	Korean Air	Scandinavian Airlines System
Sun Air	Alitalia	Thai Airways International
Cathay Pacific Airways	Alitalia Express	Air New Zealand
Dragonair	CSA Czech Airlines	Air Nelson
Qantas Airways Limited	KLM Royal Dutch Airlines	Eagle Airways
JetConnect	KLM Asia	Mount Cook Airline
QantasLink	KLM Cityhopper	All Nippon Airways
Eastern Australia Airlines	Northwest Airlines	Air Nippon
Southern Australia Airlines	Northwest Airlink	Air Japan
Sunstate Airlines	Continental Airlines	Air Nippon Network
National Jet Systems	Continental Connection	Air Central
Jetstar Airways	Continental Express	Air Next Co.,Ltd.
Jetstar Asia Airways	Continental Micronesia	Ibex Airlines
Iberia Airlines of Spain	Aeroflot Russian Airlines	Hokkaido International Airlines
Air Nostrum	China Southern Airlines	Star Flyer Inc.
Finnair	Air Europa	Skynet Asia Airways Co.,Ltd.
LAN Airlines	Copa Airlines	Singapore Airlines
LAN Argentina	Kenya Airways	Austrian Airlines Group
LAN Express		(Austrian Airlines)
LAN Ecuador		(Tyrolean Airways/Austrian Arrows)
LAN Peru		(Lauda Air)
Japan Airlines Corporation		Asiana Airlines
Japan Asia Airways		British Midland Airways/bmi
JALways		BMI Regional
Japan Transocean Air Co.,Ltd.		Spanair
JAL Express Co.,Ltd.		LOT Polish Airlines
J-AIR		EuroLOT
Hokkaido Air System		US Airways
Japan Air Commuter		America West Airlines
Ryukyu Air Commuter		TAP Portugal
Skymark Airlines Inc.		South African Airways
Malev Hungarian Airlines		Swiss International Air Lines
Royal Jordanian Airlines		Swiss European Air Lines
Royal Jordanian Xpress		Air China
		Shanghai Airlines
		Adria Airways
		Blue1
		Croatia Airlines
		Turkish Airlines