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Accessibility Measures and Flight Schedules: An Application to the European Air Transport

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Abstract

This paper evaluates differences in accessibility patterns in air transport for 82 major European cities. We use information on flight frequencies to compute four different partial indicators and compare them to conventional accessibility measures without frequencies. In addition, principal component analysis is used to synthesize the partial indicators. We find out that a synthesis of different accessibility indicators, which include flight schedule information, interestingly does not show significant changes in the accessibility patterns amongst cities. Differences, however, still exist, if partial indicators are taken into account.

Keywords: Accessibility measures, flight schedule, schedule delay, air transport.

1. Introduction

Accessibility is a concept of evaluating the mobility of individuals in space. Because of their simplicity, conventional indicators have been and are still widely used to quantify the accessibility of regions and cities. Over the years a huge amount of literature has accumulated with respect to accessibility measurement (for reviews see e.g. Weibull 1976, Vickerman et al. 1999, Rietveld / Bruinsma 1998, Handy / Niemeier 1997, Hansen 1959, Pirie 1979). However, if one considers transport systems as a whole, traditional accessibility indicators may need to be modified. In air transport for instance, physical infrastructure (airports) is not the only factor which plays a decisive role for accessibility because their existence alone does not guarantee the passengers' potential interaction in space. In fact, the choices of airlines to serve certain destinations (from an airport in question) together with the choice of hub-and-spoke vs. point-to-point operations play a major role for accessibility. In addition, existing literature (e.g. Martín et al. 2004) shows heterogeneities in partial accessibility indicators and underlines the need to use synthetic approaches in order to derive one single indicator. Closing this gap, this paper analyses accessibility patterns in air transport for 82

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European cities by incorporating flight schedule information for partial as well as for synthetic indicators. In doing so, the main idea of air transport as a whole system presented above is employed in the partial and synthetic analysis, resulting in the incorporation of schedule delay in accessibility measurement. The integration of European air transport schedule data leads to much more representative indicators with different empirical findings, which are subsequently presented.

Section 2 provides a brief discussion of the conventional accessibility measures, especially their pros and cons and tests their applicability to air transport in general. Furthermore, it reviews certain approaches to synthesize the different partial indicators.

Section 3 shows the data, comments on implementation issues and gives the empirical results.

Finally section 4 concludes.

2. Conventional accessibility indicators

Usually conventional indicators are employed to measure spatial accessibility. Such indicators are mainly developed from the point of view of economic geography. They differ, however, from the more modern approach of individual accessibility measurement (e.g. Kwan 1998, Miller 1999) or non-parametric approaches (Schulz / Bröcker 2007). All conventional indices are based on two functions: the potential function and the distance decay function. The first function is based on the concept of transport as derived demand, so that individuals can reach cities and regions with means of transportation to be able to consume at the desired destination (e.g. leisure time facilities, products, work, and institutions of education). Regional GDP and population seem to be adequate potentials to be achieved and are therefore integrated in most of the analyses using such indicators. The second one (distance decay function) devaluates the potential function and reflects the actual influence of a city's potential on the accessibility patterns, which decreases the further the destination is away from an origin. Hence, the distance decay function provides information on actual distance, or on travel time, or travel costs.[1]

2.1 Partial indicators

A different treatment of the two above mentioned functions leads to four different partial indicators, notably the potential indicator, the daily accessibility, the location indicator and the relative network efficiency indicator. In the following we will briefly describe these indicators.

2.1.1 Potential indicator

The gravity-based potential indicator measures the economic potential, which is accessible from the city (or region) in question, given that nearby cities are more important for economic activities than ones located further away. The potential function is defined as the aggregation of economic attractiveness of the analysed cities, e.g. GDP, population or consumers, and influences the potential indicator positively. The distance decay function (also generalized travel cost function) reflects travel time, distance or actual travel costs. This implies negative effects on the potential indicator.

[1] In order to avoid a value-of-time-discussion, it is practical to use time instead of cost measures.

The two functions together are a further application of the law of gravity: with increasing generalized travel costs the impact of the economic potential decreases. It can be easily shown, that this measure is utility based since it reflects the individual choice of destination (Bröcker 2006). High index values indicate a great economic potential reachable from the origin (discounted by generalized travel costs) and therefore a high accessibility. For the ease of understanding, potential indicators are usually interpreted in relation to their mean or median.

In the subsequent empirical analysis we use regional GDP data (NUTS 3) for the economic potential. t_{ij} denotes the travel time between two airports and β the degree of its devaluation. For β we choose the value of unity, which is often also used in other empirical analyses.[2]

Thus, the potential indicator P_i of a city can be defined as:

$$P_i = \sum_{j=1}^{n} \frac{GDP_j}{{t_{ij}}^{\beta}} . \tag{2.1}$$

The so called self-potential is furthermore included in (2.1) and is considered as the economic potential of the city in question and therefore of "itself" (Stewart 1947 or Pooler 1987, who describes the self-potential "as a measure of a population's influence on itself", p. 270). To take the self-potential of a city i into account and to consider the distance decay within the city as well (because the individual has to travel from the city centre to the airport), the inner distance d_{ii} of a city is measured as two thirds of the radius of the city i (e.g. Schulz / Bröcker 2007, Rietveld / Bruinsma 1998):

$$d_{ii} = \frac{2}{3} * \sqrt{(O_i/\pi)} \tag{2.2}$$

where O_i denotes the surface of the city, which is assumed to be circular and all zones in that city would be used in the same way (Rietveld / Bruinsma 1998, Schulz / Bröcker 2007). The hypothetical speed for the travel time within a city is 30 kilometers per hour as usually assumed in engineering studies for private transport.

2.1.2 Daily accessibility

Daily accessibility indicators use a travel time threshold. The number of accessible inhabitants or the aggregated GDP within this threshold are considered to be accessible.[3] This corresponds with the notion that such measures are constructed in order to answer the question of how many inhabitants or income is accessible within one working day. The most common time threshold used in literature is four hours. That is, daily accessibility accounts for a business round trip to a city within one day with sufficient time at the destination for activities or a meeting. Therefore, the potential of the cities with a longer travel time than the defined threshold b is not added to the accessibility DA_i of the considered city. The indicator is easy to interpret: the higher the

[2] If local or regional accessibility is measured, than the distance decay parameter can also be estimated from data of commuter flows (e.g. Schulz / Bröcker 2007).

[3] This may appear at first glance to be arbitrary. However, as Bröcker (2006) shows, daily accessibility indicators are a further application of the economic potential index, notably for a Box-Cox specification of generalized travel costs.

number of e.g. inhabitants that can be reached from the origin, the higher is the accessibility of that origin.

In order to account for air transport specific characteristics, we, however, assume a time threshold of three instead of four hours. This is due to access time to get to the airport or the city centre as well as the check-in and -out time for passengers. In this context the daily accessibility index includes also elements of the quality of connections from the respective airport to regional short distance airports. NUTS 2 population data will account for the achievable potential and therefore for the catchment area of the airport. Formally, the daily accessibility indicator DA_i is as follows:

$$DA_i = \sum_j^n Pop_j * \delta_{ij} \qquad (2.3)$$

with

$$\delta_{ij} = \begin{Bmatrix} 1, \; if \;\; t_{ij} < b = 3 \\ 0 \; else \end{Bmatrix} \qquad (2.4)$$

where δ_{ij} is a binary variable, t_{ij} is the actual travel time between origin i and destination j and b is the defined time budget of three hours.

2.1.3 Location indicator

The so called weighed average travel time indicator determines the average travel times, travel costs or distances from one origin to all other destinations in the dimension of minutes, Euros or kilometers. In addition, travel times, costs or distances, e.g. t_{ij}, between the airports of the cities i and j are weighted by the corresponding regional or local GDP (respectively population) of the destination j. Although easy to interpret (the higher the indicator in e.g. minutes, the lower the accessibility), the indicator reflects the locational disadvantage of peripheral cities much stronger than the rest of the indicators. This, however, has nothing in common with the quality of infrastructure or the flight schedules. It may therefore occur, that despite poor performance of this index, airport infrastructure and flight supply are still very good. Furthermore, a distance decay function is not included, hence cities located far away are not devaluated as in the potential indicator or daily accessibility. This implies, that more distant cities contribute to an individuals' utility in the same way as cities close-by (Gutiérrez 2001). One may therefore conclude that the use of the location index may lead to distorted results. We, however, share the opinion, that locational disadvantages cannot be disregarded in such analyses, since a city's location is a given fact and affects the passengers' utility, e.g. in form of travel times.

In this study the GDP (NUTS 3) is used as the potential of the cities. The shortest travel time between two airports is used for calculating the location indicator L_i as accessibility measure:

$$L_i = \frac{\sum_{j=1}^n t_{ij} * GDP_j}{\sum_{j=1}^n GDP_j}. \qquad (2.5)$$

2.1.4 Network indicator

The relative network efficiency indicator NE_i is a well-known modification of the location indicator. Here the quality of connections between the airports is measured by comparing the actual travel time t_{ij} with a hypothetical optimal travel time $\hat{t}_{ij}$. To take the latter into account the straight line distance between i and j is usually divided by the possible speed in air transport of about 600 kilometers per hour. Additionally, the actual (shortest) travel time between origin and destination airport is weighted by the GDP (NUTS 3) of destination j (Martín et al. 2004):

$$NE_i = \frac{\sum_{j=1}^{n} \frac{t_{ij}}{\hat{t}_{ij}} GDP_j}{\sum_{j=1}^{n} GDP_j}. \quad (2.6)$$

2.2 Applicability of the conventional accessibility indicators to air transport

The indices discussed above are not free of conceptual problems. In particular in the case of air transport the problem of self-potential has to be reviewed. Since in air transport an individuals' utility is not derived by staying at the origin, it is not clear whether it is beneficial to generate accessibility patterns which are based on the self-potential. Certainly, the demand for transport services is derived demand, but air transport connections are also important for further purposes e.g. for tourism. Therefore, the inclusion of the self-potential in air transport accessibility measurement may lead to an overestimation of bigger cities and an underestimation of smaller ones. On the other hand the use of self-potential in our calculations leads to the consideration of predominantly business trips and neglects tourists.[4] Exactly this is in line with the scope of this paper, since the application of schedule delay reflects more the utility of business passengers than tourists.

The second issue arises by analysing partial accessibility indicators including flight frequencies. The common potential indicator takes GDP or population numbers into account. It is natural to expect, that airlines utilize the information on GDP (respectively population numbers), when they design their flight schedules.[5] For this reason a positive correlation between economic potential and flight schedules can be expected. Therefore, one could argue that the use of the potential indicator is sufficient and contains all relevant information, also the information related to flight frequency. This would, in fact, be true, if airlines could freely choose their destinations and frequencies, as they, for instance, do in the United States, where most of the airports are not slot-controlled.[6] In contrast to the United States this choice is not totally free in Europe. It depends rather upon the availability of slots. Especially "grandfather rights" may distort the airlines' desired frequencies. For this reason, we expect that particularly at capacity constraint airports the positive correlation mentioned above is not a priori given. From this perspective the use of schedule delay is fully justified.

The definition of the area of analysis is a third challenge in accessibility measurement. According to the formulation of the partial indicators, geographic effects like periphery-

[4] Note that for tourists in many cases exist also charter flights, which are not included in our data set.
[5] In fact, all models on frequency choice use variables describing the economic potential (e.g. Brueckner 2010 and Brueckner / Flores-Fillol 2006).
[6] An exemption takes place for six major airports (IATA, 2010).

centre differences influence the accessibility patterns, whereas cities in the centre usually have higher accessibility indices than cities in the periphery. Therefore, the definition of borders regarding the study area could somehow define the resulting accessibility patterns (especially for the daily accessibility indicator and location indicator). To generate interpretable accessibility patterns a sufficiently large area of analysis should be chosen. In this study we define the whole of Europe as our area of analysis. In addition, we hypothesize that in air transport geographical effects do not play such a major role due to the very high travel speed.

2.3 Synthesis methods

The computation of different conventional accessibility indicators is in several cases convenient. It is especially useful to calculate different indices, since each of them answers a different question with respect to accessibility. Exactly this identity, however, reveals the heterogeneity of the indices and results in different rankings of the considered cities or regions (Martín / Reggiani 2007). Thus, a global accessibility index, containing the relevant information of the partial indices, is necessary in order to derive a unique accessibility ranking order.

In this respect Martín et al. (2004) as well as Martín and Reggiani (2007) used two synthesis techniques notably Data Envelopment Analysis (DEA) and Principal Component Analysis (PCA). Although both approaches generate different absolute effects, the relative intervals of the accessibility results for the cities derive similar rankings for both synthesis techniques (e.g. Zhu 1998, Martín / Reggiani 2007).

The PCA is a multivariate statistics technique, which enables the dimension reduction of extensive data sets by the so called "principal components" without considerable loss of information. This method was used by Martín and Reggiani (2007) to generate accessibility indices for 88 European cities with application to the high-speed rail transport which contain the information of the heterogeneous partial accessibility indicators (potential indicator, daily accessibility and location indicator). They constructed a global accessibility index for each city for three different scenarios (respective status of the European high-speed rail network in 1996, 2005 and 2015) to reveal changes in the accessibility patterns (changes in the respective rankings based on the global accessibility index). Their results show no noticeable changes for already highly (in the centre of Europe) or low (peripheral cities in Italy, Spain or the south of France) accessible cities. Changes, however, were revealed for cities with "intermediate" accessibility patterns. In addition, DEA is best known for its application in production theory based on the work of Charnes et al. (1978). Martín et al. (2004) used this synthesis method to construct a global accessibility index as well, including the three above mentioned indices plus the network indicator to show the effects of the high-speed train connection between Madrid, Barcelona and the French border in two scenarios (with and without the high-speed train line in the year 2005). The area of analysis was represented by 58 European cities covering enough Spanish cities to highlight the effects of the new line. In the scenario without the high-speed connection high DEA values are revealed for cities with connection to other high-speed rail lines (e.g. Madrid, Valladolid and Barcelona). As Martin et al. (2004) show the high-speed connection enhances accessibility especially for regions and cities along the new connection. However, the DEA approach may lead to theoretical difficulties, since the classification of some of the indices as inputs or outputs seems to be arbitrary. Its use is therefore not perfectly justifiable. In addition, since both methods seem to derive equivalent rankings (Martín / Reggiani 2007), the DEA method will not be applied in this analysis.

The PCA[7] is e.g. used by Hesse et al. (2012) to examine accessibility patterns for German cities regarding air transport (amongst other transport modes). To our knowledge, PCA has not been applied yet for European air transport accessibility. The partial accessibility indicators (per city) build the data set for the PCA analysis. To get only one unique indicator, measuring the accessibility of the cities and generating a benchmark, each partial indicator has to be weighted. The weights explain how strong the influence of each conventional indicator on the global index is (Zhu 1998) and can be computed by identifying the underlying principal components. Here, methods similar to regression analysis are employed. The principal components finally extracted, explain the highest possible fraction of data variance (Jolliffe 2002). Applying the weights to each partial indicator of the respective city leads to a new synthetic ranking of the cities, where the relative differences between the cities are of importance and not the absolute numerical differences. The inclusion of an additional city in the sample requires a new calculation of all indices, because the benchmarking is only valid for one specific data set.

In the following we carry out our empirical analysis. We compute the four described indicators for the above mentioned sample and synthesize them by using PCA. In doing so, we include information of flight schedules. For this purpose we extend conventional indicators by including the city pair's schedule delay.

3. Empirical analysis

The integration of flight schedule data in accessibility measures is very important to generate more realistic mobility patterns. This is, in particular, more important for air transport than for other transport modes for two reasons. First, in contrast to road transport, waiting time is important for accessibility in air transport since trip makers are not atomistic. Therefore, their utility depends on airline schedules. Second, compared to the rail sector, public service obligations play a minor role in air transport. Due to public service obligations, rail operators have limited choices in many cases with respect to frequency. Taking schedules into account, when measuring accessibility in rail transport, would more or less lead to taking political factors into consideration, for local governments interfere in the allocation of concessions.

For air transport the choice whether to serve a city-pair or not, or the choice of flight frequency is a matter of the individual airlines' decision. Policy makers have in most cases no influence on them.[8] Accessibility is in this case the result of the airlines' decision to serve certain routes with a certain frequency or even the result of the airlines' business model (hub-and-spoke vs. point-to-point).

For this reason it is important to take flight schedules into account. In addition, in several cases, an airport serves more than one city. This also makes it important to account for access time (travel time to the airport).

[7] For an in depth treatment of the PCA see e.g. Washington et al. (2003).

[8] Policy makers may, however, influence these factors indirectly, if for instance a publicly owned airport gives certain pricing conditions for expanding routes, or for higher flight frequencies.

3.1 Methodology

Rietveld and Bruinsma (1998) already used schedule information to construct an adjusted travel time and thereby modified the gravity based potential indicator. The modified travel time $\bar{t}_{ij}$ between the airports of the cities i and j contains the actual flight time RT_{ij} between the airports of the cities i and j including possible transfer times and waiting times at the gates, the time penalty S_{ij} caused by the flight schedules and the time penalty I_{ij} caused by the check-in or check-out procedures:

$$\bar{t}_{ij} = RT_{ij} + S_{ij} + I_{ji}\,. \qquad (3.1)$$

The relevant component is the time penalty S_{ij} related to flight schedules. The schedule delay or "frequency delay" (Douglas and Miller 1974) results because passengers have a desired departure time and want to fly without a delay. It is therefore defined as the difference between the favourite and the real time of departure and describes the mean of minimum (that is zero) and maximum waiting time. Hence, the delay S_{ij} decreases with flight frequency:

$$S_{ij} = \frac{E}{4 * F_{ij}} \qquad (3.2)$$

where E denotes the time period in question and F_{ij} the flight frequency between the cities i and j.

The passengers' preferred time of departure is assumed to be distributed uniformly over a circular period of time, so that each individual passenger takes the average schedule delay into account. A stochastic delay component as shown by Douglas and Miller (1974) will not be taken into account, as it is very challenging to generate data which contain the passengers' probability of missing a flight.

3.1.1 Modification of the conventional accessibility indicators

Travel times, especially for flight connections via another airport, vary considerably for each observed connection among the 82 cities, because of different connecting times at the airport in between the departure and destination airport, different changeover airports, or numbers of changeovers. As from now on the travel time for n flights from a departure airport via other airports to the corresponding destination airport is denoted as t_{ij}^{V} and will be defined as follows:

$$t_{ij}^{V} = \frac{t_{ij}^{V1} + t_{ij}^{V2} + \dots + t_{ij}^{Vn}}{n} \qquad (3.3)$$

where $V_k,\ k = 1, \dots, n$ denotes the number of the different via-connections. Besides the average travel time for via-connections the travel time for the direct connection between airports t_{ij}^{D} is defined as the shortest travel time for this connection. The adjusted travel time RT_{ij} is therefore a combination of the two travel time components weighted by the number of frequencies:

$$RT_{ij} = t_{ij}^{D} * \frac{D_{ij}}{F_{ij}} + t_{ij}^{V} * \frac{V_{ij}}{F_{ij}} \tag{3.4}$$

where D_{ij} and V_{ij} represent number of direct flight connections respectively the number of via-connections between the airports of the cities i and j. The total number of frequencies F_{ij} can therefore be written as:

$$F_{ij} = D_{ij} + V_{ij} \,. \tag{3.5}$$

F_{ij} is important in order to calculate the schedule delay component showed in (3.2). For our analysis the partial indicators will be modified by using the adjusted travel time $\bar{t}_{ij}$ in the decay function. Handy and Niemeier (1997) suggest as well the use of travel time rather than distance in the decay function, because travel time is a highly influential variable for individual mode-choice behaviour.[9]

A last issue for our analysis is the use of check-in and check-out times I_{ij}. Due to the similar security regulations in Europe it is fair to assume that check-in and -out time is more or less the same for all considered airports. For this reason it can be omitted.

The described modifications in the indicators can therefore be summarized as follows:

- The Potential Indicator uses the adjusted travel time $\bar{t}_{ij}$ in the power function as decay function;
- The Daily Accessibility uses the adjusted travel time $\bar{t}_{ij}$ for the time threshold of 3 hours;
- The Weighted Average Travel Time uses the adjusted travel time $\bar{t}_{ij}$ instead of the shortest travel time to devalue the potential of the cities;
- The Network Efficiency uses the adjusted travel time $\bar{t}_{ij}$ instead of the shortest travel time to be compared with the optimal travel time $\hat{t}_{ij}$. The latter is defined as the fastest possible connection between two airports.

3.1.2 *Database*

82 European cities of the EU-27 with more than 300,000 inhabitants and airports with more than 2 million passengers p.a. build the sample.[10]

The first step in the data collection process implied the gathering of information on:

- NUTS 3 population of all 82 cities (Eurostat 2011a) with an airport, mainly serving as a criterion to rank cities;
- GDP (per capita) (Eurostat 2011b) of the corresponding NUTS 3 regions of the airports;
- Inhabitants of the corresponding NUTS 2 regions (Eurostat 2011a);
- Surface of all 82 cities in square kilometers (Eurostat 2011c);
- Airports, which were listed in Flugplan (2011) as origin or destination airport of the city-pairs in question.

[9] This view is also shared by Anas et al. (1998).

[10] In some cases we also include some additional, regional important airports (although they do not fulfill the mentioned criteria). These are the major airports of Luxemburg, Norway, Switzerland, Estonia, Lithuania, Malta, Slovenia and Slovakia as well as the airports of Dresden and Leipzig in Saxony (Germany).

For analysing the frequencies an appropriate timeframe had to be selected to assess the connections on all routes between all considered cities. For this purpose an average week (168 hours) is chosen.

Within the European network an increasing number of airports, especially in Central Europe, cannot be served at night due to noise regulations. Thus, the time window between midnight and 6 a.m. can be regarded as less relevant for European connections and will therefore be excluded from the weekly schedule within this study. For all seven days a total of 126 hours is the subsequent possible flight period. The adjusted travel time $\bar{t}_{ij}$ can therefore be defined as:

$$\bar{t}_{ij} = \frac{126}{4 * F_{ij}} + RT_{ij} \,. \qquad (3.6)$$

The week between August 8th and 14th 2011 as a representative time framework was selected. Travel times, frequencies and numbers of stopovers (involving also carriers and clearing of code-sharing) come from Flugplan (2011).

Table 1 shows the descriptive statistics of this data.

Table 1: Descriptive statistics.

	Mean	*Min.*	*Max.*	*Standard deviation*
Travel time without frequencies t_{ij}	213.6	35.0	640.2	102.8
Distance d_{ij}	1,533.0	82.0	6,868.0	815.0
Total schedule delay $\sum S_{ij}$ (per city i)	3,064.8	1,923.6	8,380.2	1,140.0
Average schedule delay $\bar{S}_{ij}$ (per city i)	37.0	23.0	102.0	14.0
Direct connections D_{ij}	759	59	4,076	761.1
Via connections V_{ij}	4,395	1,769	6,104	825.7
Frequencies F_{ij}	5,154	1,874	7,559	1,176.2
Shortest adjusted travel time $\bar{t}_{ij}$	348.0	63.6	1290.0	120.0

Source: Own calculations. (Note: The dimension of time / distance data is minutes / kilometers.)

3.1.3 *Analysis design and expectations*

The empirical analysis below shows which factors will influence the relative changes between the first scenario including frequencies (scenario A) and the second scenario without frequencies (scenario B).

Special attention will therefore be paid to the shift in accessibility patterns between indicators with and without the modified travel time. The adjusted weighted travel time leads to higher travel times between almost all cities. For airports with frequent direct connections to most destinations we do not expect significant changes as their travel time will remain at the lowest level, whereas for cities which are directly connected to many cities but with low frequency we expect to observe substantial changes. The adjusted travel times will increase extensively for connections where the actual travel times are based on a direct connection once a week and numerous indirect (and therefore far reaching) connections.

In addition, it is expected that airports in the central regions of Europe will become even more accessible due to schedule delay modifications while peripheral regions might seem to become more remote. Furthermore, we will test whether findings can hold with the synthetic index.

The two scenarios will be compared in the empirical analysis as follows: Scenario A covers the measurement of the modified accessibility indicators (including schedule delay and the adjusted travel time) as well as a synthesis of the partial indicators. The same data set is used to derive the conventional accessibility indices and global accessibility patterns (without schedule delay) in scenario B. The results are compared to scenario A. The partial indicators are presented first, before analyzing the synthetic accessibility patterns. In order to save space we only show detailed results of the economic potential and the daily accessibility[11] as well as the synthesis measures.

3.2 Empirical results of the partial indicators

The integration of the adjusted travel time $\bar{t}_{ij}$ into the partial indicators generates different influences on each of the indicators, which therefore present diverse accessibility patterns. First the results of the economic potential and the daily accessibility are discussed in detail (the location and network indicator show analogous results) before the findings of the synthesis (including all four conventional indicators) are presented.

The economic potential indicator in scenario A shows a high accessibility of major airports with hub function. This explains the ranking of London, Paris, Frankfurt and Amsterdam. But also cities with lower frequencies but with a high share of connections to the aforementioned airports show high economic potential. Milan, Brussels, Zurich and Berlin belong to this group of central cities. Table 2 (left column) shows the first and last ranked cities.

The ranking shows that several aspects can contribute to the centrality of airports, expressed in economic potential. A high level of self-potential, a high level of frequencies, a high number of direct connections to high-potential cities or even a high number of services to hub airports, where good connections assure further connections to most places in the network.

Table 2: Economic potential.

Including frequencies (A)			*Without frequencies (B)*			*B vs. A*
Rank	*City*	*Millions of euros*	*Rank*	*City*	*Millions of euros*	*Change of rank*
1	London	1,759,817	1	Brussels	2,231,882	+5
2	Frankfurt/M.	1,452,790	2	London	2,145,436	-1
3	Munich	1,381,120	3	Frankfurt/M.	2,108,769	-1
4	Paris	1,311,100	4	Munich	2,063,361	-1
5	Amsterdam	1,265,246	5	Dusseldorf	2,054,468	+4
6	Brussels	1,230,217	6	Amsterdam	1,952,572	-1
7	Zurich	1,143,642	7	Stuttgart	1,886,682	+10
8	Berlin	1,123,958	8	Hamburg	1,837,017	+3
9	Dusseldorf	1,109,145	9	Zurich	1,817,802	-2
10	Milan	1,090,480	10	Paris	1,815,788	-6
…			…			
41	Dresden	704,732	40	Leipzig	1,289,566	+4

[11] Further results on the location and network indicator can be delivered upon request.

…			…			
44	Leipzig	683,798	47	Dresden	1,221,620	-6
…			…			
73	Vilnius	509,789	73	Istanbul	947,189	-23
74	Valletta	506,067	74	Bratislava	941,933	+5
75	Izmir	493,897	75	Tallinn	911,089	+1
76	Tallinn	490,767	76	Vilnius	894,014	-3
77	Antalya	483,336	77	Izmir	797,218	-2
78	Ankara	467,537	78	Antalya	763,742	-1
79	Bratislava	419,683	79	Varna	691,150	+2
80	Las Palmas	408,466	80	Ankara	687,218	-2
81	Varna	384,924	81	Las Palmas	572,619	-1
82	Adana	373,125	82	Adana	56,930	-

Source: Own calculations.

An exceptional position can be identified for London. With a 129 percent deviation to the average economic potential London is the most accessible city in the study including flight schedule data. The role of London as a major hub airport with the largest share and highest total number of direct connections together with the highest self-potential among the surveyed cities leads to this result.

An interesting finding is the impact of self-potential on total potential. London derives in first position 41% of its economic potential from itself. The next higher figure is Brussels with about 28%.

To analyse the importance of including schedules into accessibility measures, we compare the already computed partial indicators (scenario A) with those without frequencies (scenario B) resulting in the changes in the according ranks (table 2, right column). Furthermore, we present the normalized (in percent) deviation to the average value. We receive a similar overall picture for both approaches (figure 1).[12] Most obvious is the first rank of Brussels in the ranking while Paris only achieves rank ten.

Changes in the rankings seem to be below average for larger cities. This is because they extract a high share of their accessibility from self-potential; this applies especially for London, Paris and Istanbul.

On the whole in scenario B we can observe a decreasing significance of self-potential because of the lower travel times in this scenario. Therefore, in scenario B even more remote cities have an impact on the economic potential of all cities compared to scenario A. The average value of economic potential in scenario B is about 73 Percent higher than in A. As can be seen in figure 1 the distribution of the potential values is more balanced in B than in A.

[12] Small differences, however, still exist.

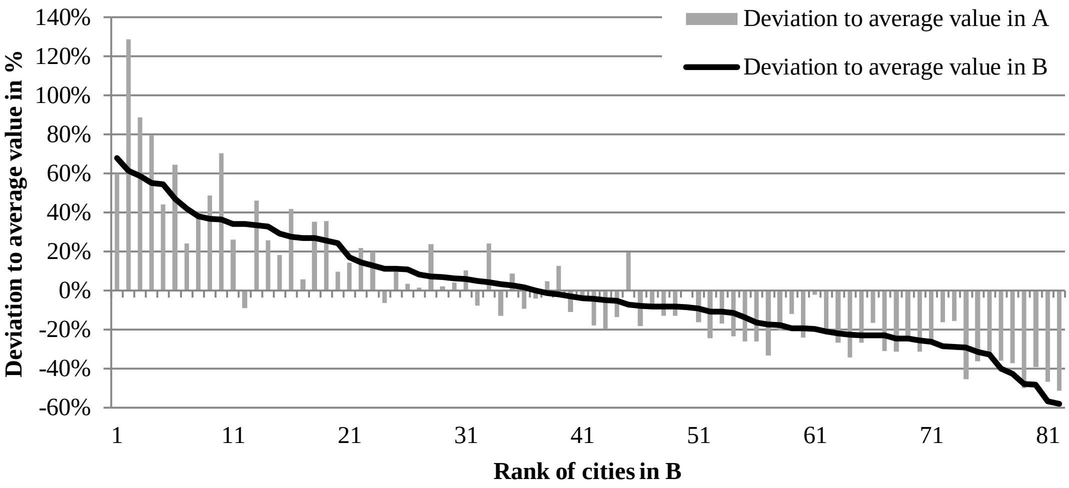

Figure 1: Economic potential.
Source: Own calculations. (Note: The indicators are normalized, in percent.)

The key factor of the daily accessibility indicator is the time-threshold. Only destinations which are accessible within this time frame are included in the calculation. In this study we used three hours of flight time.

Under this condition only few connections are relevant for daily accessibility. From a total of 6,724 possible connections in the database, only 540 connections (about 8%) are within the three hour time frame and therefore considered when calculating the daily accessibility indicator. This number stems from the time requirements for indirect connections, where transfer times are added to the total actual travel time. In addition to this, the schedule delay generates higher adjusted travel times for almost all connections. On average about 37 minutes are added to the actual travel time of each city pair. For connections from and to Varna the schedule delay amounts to about 96 minutes on average, for Dortmund even 102 minutes have to be added as a frequency delay. Connections with a large share of via-connections derive in general low rankings.

Because of the low number of the connections entering the index only a low number of inhabitants can be reached; on average about 27 million inhabitants from each city are accessible. This makes only 24 cities accessible above average. Between Paris (rank one), with about 105 million, and Valetta (rank 82), with only about 400,000 inhabitants accessible, a wide gap is observed.

This indicator shows a small group of about 16 highly accessible cities followed by a large group of peripheral cities with below average accessibility (table 3, left column). Cities at the end of the ranking, like Valetta, Bratislava and Las Palmas, draw their potential only from their own NUTS 2 region; in terms of actual air travel no accessibility is generated.

Table 3: Daily accessibility.

Including frequencies (A)			*Without frequencies (B)*			*B vs. A*
Rank	*City*	*Number of inhabitants*	*Rank*	*City*	*Number of inhabitants*	*Change of rank*
1	Paris	105,275,000	1	Paris	240,013,000	-
2	London	100,084,000	2	Milan	232,799,000	+5

3	Munich	98,051,000	3	Munich	230,596,000	-
4	Rome	93,637,000	4	London	228,991,000	-2
5	Frankfurt/Main	88,336,000	5	Amsterdam	224,732,000	+1
6	Amsterdam	82,502,000	6	Frankfurt/Main	219,281,000	-1
7	Milan	80,776,000	7	Rome	219,158,000	-3
8	Madrid	79,507,000	8	Brussels	217,485,000	+8
9	Barcelona	71,082,000	9	Prague	207,560,000	+6
10	Zurich	61,084,000	10	Barcelona	204,347,000	-1
…			…			
21	Istanbul	31,502,000	14	Berlin	181,524,000	-3
…			…			
31	Ankara	21,617,000	25	Hamburg	145,298,000	-13
…			…			
42	Izmir	18,887,000	49	Gdansk	109,244,000	+19
…			…			
44	Antalya	18,028,000	66	Istanbul	76,480,000	-45
…			…			
53	Dresden	14,865,000	68	Dresden	74,540,000	-15
…			…			
62	Leipzig	9,043,000	71	Bremen	72,444,000	-4
…			…			
73	Salonika	5,867,000	73	Vilnius	58,290,000	+1
74	Vilnius	5,727,000	74	Leipzig	55,290,000	-12
75	Bristol	4,812,000	75	Dortmund	48,838,000	+3
76	Sofia	4,737,000	76	Tallinn	45,644,000	-4
77	Katowice	4,708,000	77	Izmir	40,213,000	-35
78	Dortmund	3,782,000	78	Las Palmas	32,226,000	+2
79	Varna	3,116,000	79	Antalya	30,973,000	-35
80	Las Palmas	2,059,000	80	Ankara	25,336,000	-49
81	Bratislava	600,000	81	Adana	25,336,000	-27
82	Valletta	409,000	82	Varna	15,000,000	-3

Source: Own calculations.

Most connections with less than three hours adjusted travel time can be reached from Munich (28 connections). Frankfurt, Amsterdam and London are each connected with 25 destinations. Due to the limited number of valid connections, smaller cities which are close to hub airports or well connected to cities with a high potential reach a remarkably high position in the ranking. A small independent network seems to exist for example in Turkey where Ankara, Izmir and Antalya provide each other with high potential of population and good direct connections. Although in all other accessibility indicators these three cities perform under average, in the modified daily accessibility they show a high performance.

The elimination of schedule delay in B leads to an increase of connections, which enter the daily accessibility formula. These are now almost 2,800 (41.6%) connections. Travellers from Paris reach more than 240 million inhabitants in the network, compared to only 105 million in scenario A. The influence of schedule delay becomes more obvious within this indicator (table 3, right column). At the end of the ranking Varna can still draw potential from seven destinations within 3 hours. Overall the relative impact of self-potential is reduced compared to scenario A because more cities with their potential become accessible. In scenario A for instance Bratislava´s and Valetta´s accessibility consists only of the self-potentials (100%). This differs in scenario B, where the share of their self-potential is below one percent.

On average 126 million inhabitants are accessible, which is more than could be reached from Paris in scenario A. Now 40 cities have an over average accessibility. This leads to a more balanced distribution of accessibility values (figure 2). Still, deviations of about 90% of average values are observable between the top and bottom ranks. This indicates that the strict cut-off time threshold supports highly differentiated accessibility patterns. The inclusion of schedule delay shows such differences more clearly.

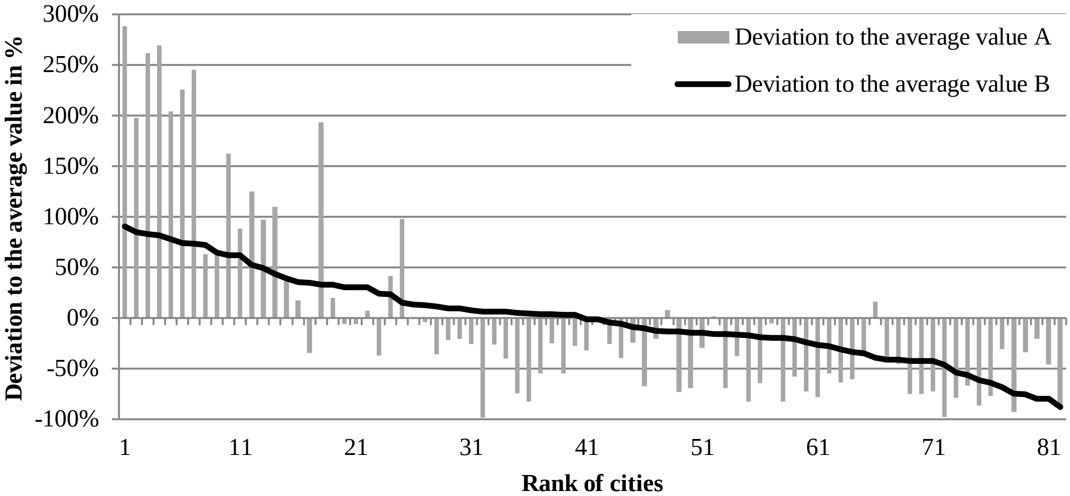

Figure 2: Daily accessibility.
Source: Own calculations. (Note: The indicators are normalized, in percent.)

As a result of this part of the analysis the inclusion of flight frequency information shows major differences in the accessibility patterns, especially for the daily accessibility indicator and the network efficiency indicator. These differences are also evident for the first half of the economic potential ranking, whereas they do not clearly exist for the location indicator. From these results we can therefore argue, that the use of frequencies when calculating partial indicators leads not only to different results but also gives a more accurate picture of the accessibility patterns. In addition, the inclusion of schedule delay derives a more utility oriented measurement method, which (in contrast to other pure utility oriented measurement concepts, e.g. choice models) is much more easily applicable. Both criteria (applicability and theoretical-utility foundation) suggest therefore that in particular the potential indicator adjusted with flight frequency information may be sufficient enough for accessibility measurement.

3.3 Composition of the partial indicators: synthesis results

The heterogeneity of the partial indicators is obvious, as shown in the analysis above. Spearman's rank correlation coefficients for scenario A (with schedule delay) and B (without flight schedule data) in table 4 confirm this.

Table 4: Spearman's rank correlation coefficient.

	Scenario A				*Scenario B*			
	P_i	DA_i	L_i	NE_i	P_i	DA_i	L_i	NE_i
Economic Potential P_i	1				1			
Daily Accessibility DA_i	.769**	1			.782**	1		
Location Indicator L_i	-.965**	-.789**	1		-.962**	-.869**	1	
Network Efficiency NE_i	-.060	-.297**	.053	1	-.232*	-.556**	.378**	1

Source: Own calculations. (Note: Significant at **99% and *95%.)

Subsequently the results of the synthesis with principal component analysis (PCA) for scenario A and B are presented and discussed.

Based on PCA the cities' global accessibility index can be constructed as a linear combination by applying the parameters of the principal component analysis to the value of each indicator as described in section 2.3 (also shown by Martín and Reggiani 2007). Equation (3.7) shows the results for scenario A:

$$PCA_i = 0.349\ P_i + 0.342\ DA_i - 0.329\ L_i - 0.130\ NE_i\ . \quad (3.7)$$

Figure 3 and table 5 contain the results normalized to the interval (0;1). The mean of the new index is 0.343. Thus, 33 of the 82 cities are ranked above average and 49 are below 0.343. Not surprisingly London, Paris, Frankfurt/Main and Munich are the leading airports in this analysis, given the high rankings concerning the partial indicators. Remarkably all German cities with a major airport (besides Frankfurt/Main and Munich also Berlin, Hamburg, Dusseldorf, Stuttgart, Cologne/Bonn and Hannover are included) are in the top 25 of the ranking and above average. Dresden and Leipzig are in the central ranking and more accessible than some capitals of European countries (e.g. Luxembourg, or Sofia).

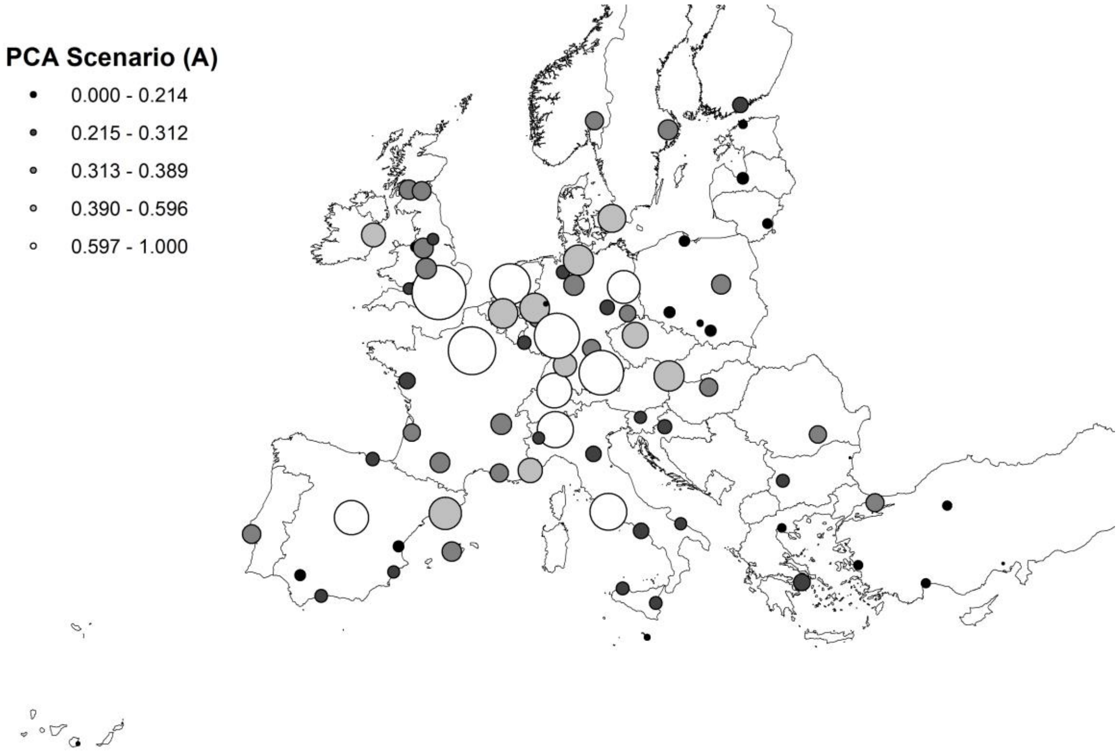

Figure 3: Synthesis results including frequencies (A).
Source: Own calculations.

The same approach is used to derive a global accessibility index without schedule data. PCA results yield:

$$PCA_i = 0.312\, P_i + 0.325\, DA_i - 0.318\, L_i - 0.186\, NE_i\,. \quad (3.8)$$

As the parameters indicate, the differences between scenario A and B will obviously not be too large, presumably because the synthesis method accounts for some differences in the heterogeneous indicators. Furthermore table 5 shows the transformed PCA-indices for scenario B with a mean of 0.551 and the changes in the according ranks. Hence, 36 cities (three more than in scenario A) are ranked above average in scenario B. Of course London and Paris stay at the positions one and two because of their high share of economic potential and direct connections. The high economic potential is also evident for Munich in comparison to Frankfurt/Main. Munich's position in the European ranking is not surprising since it confirms the multihub strategy followed by Lufthansa and the significance of Munich for continental flights.[13] Interesting results can be seen e.g. for Brussels, Luxembourg and Valletta which gain 11, 22 and respectively 34 ranks or e.g. for Istanbul and Athens which fall back 26 and 25 ranks by omitting flight frequencies. In general, peripheral located cities seem to reach very low accessibility scores, which seem to be even lower than in scenario A.

[13] Also Zurich as the third Lufthansa hub performs over average.

Table 5: Synthesis Results.

Including frequencies (A)			*Without frequencies (B)*			*B vs. A*
Rank	*City*	*PCA index A*	*Rank*	*City*	*PCA index B*	*Change of rank*
1	London	1.000	1	London	1.000	-
2	Paris	0.889	2	Paris	0.983	-
3	Frankfurt/Main	0.836	3	Munich	0.960	+1
4	Munich	0.826	4	Brussels	0.960	+11
5	Amsterdam	0.751	5	Frankfurt/Main	0.948	-2
6	Rome	0.677	6	Amsterdam	0.940	-1
7	Milan	0.674	7	Dusseldorf	0.888	+7
8	Zurich	0.650	8	Milan	0.870	-1
9	Madrid	0.636	9	Zurich	0.837	-1
10	Berlin	0.608	10	Prague	0.834	+7
11	Barcelona	0.595	11	Berlin	0.816	-1
12	Hamburg	0.562	12	Stuttgart	0.795	+8
13	Vienna	0.555	13	Vienna	0.789	-
14	Dusseldorf	0.549	14	Rome	0.782	-8
15	Brussels	0.546	15	Barcelona	0.767	-4
16	Copenhagen	0.514	16	Hamburg	0.765	-4
17	Prague	0.471	17	Copenhagen	0.743	-1
18	Nice	0.451	18	Bonn	0.739	+4
19	Dublin	0.436	19	Cologne	0.735	+2
20	Stuttgart	0.434	20	Dublin	0.725	-1
21	Cologne	0.389	21	Lyon	0.704	+2
22	Bonn	0.388	22	Nice	0.704	-4
23	Lyon	0.385	23	Manchester	0.671	+3
24	Birmingham	0.383	24	Budapest	0.664	+10
25	Hannover	0.381	25	Palma/Mallorca	0.663	+4
26	Manchester	0.369	26	Madrid	0.653	-17
27	Stockholm	0.368	27	Bologna	0.641	+19
28	Toulouse	0.366	28	Luxembourg	0.637	+22
29	Palma/Mallorca	0.355	29	Toulouse	0.628	-1
30	Warsaw	0.354	30	Nuremberg	0.625	+8
31	Glasgow	0.352	31	Edinburgh	0.611	+2
32	Lissabon	0.348	32	Marseille	0.583	+3
33	Edinburgh	0.345	33	Warsaw	0.576	-3
34	Budapest	0.338	34	Oslo	0.572	+3
35	Marseille	0.338	35	Neapel	0.562	+9
36	Istanbul	0.337	36	Stockholm	0.553	-9
37	Oslo	0.331	37	Bordeaux	0.544	+2
38	Nuremberg	0.328	38	Hannover	0.540	-13
39	Bordeaux	0.325	39	Lisbon	0.531	-7
40	Bucharest	0.317	40	Malaga	0.529	+14
41	Dresden	0.312	41	Valencia	0.521	+24
42	Athens	0.305	42	Bristol	0.514	+20
43	Nantes	0.301	43	Valletta	0.513	+34
44	Neapel	0.289	44	Bucharest	0.513	-4
45	Helsinki	0.282	45	Alicante	0.503	+14
46	Bologna	0.281	46	Zagreb	0.497	+2
47	Leipzig	0.268	47	Krakow	0.494	+17

48	Zagreb	0.260	48	Gdansk	0.494	+20
49	Bremen	0.249	49	Bremen	0.490	-
50	Luxembourg	0.246	50	Ljubljana	0.487	+6
51	Bilbao	0.245	51	Birmingham	0.482	-27
52	Sofia	0.242	52	Nantes	0.481	-9
53	Catania/Sicily	0.240	53	Bilbao	0.475	-2
54	Malaga	0.238	54	Liverpool	0.465	+15
55	Palermo	0.235	55	Riga	0.459	+8
56	Ljubljana	0.230	56	Sofia	0.450	-4
57	Turin	0.228	57	Catania/Sicily	0.449	-4
58	Bari	0.227	58	Turin	0.448	-1
59	Alicante	0.222	59	Helsinki	0.446	-14
60	Leeds	0.216	60	Palermo	0.423	-5
61	Bradford	0.216	61	Sevilla	0.421	+5
62	Bristol	0.214	62	Istanbul	0.416	-26
63	Riga	0.212	63	Katowice	0.416	+13
64	Krakow	0.206	64	Glasgow	0.412	-33
65	Valencia	0.202	65	Salonika	0.409	+9
66	Sevilla	0.202	66	Bari	0.409	-8
67	Wroclaw	0.196	67	Athens	0.407	-25
68	Gdansk	0.194	68	Wroclaw	0.393	-1
69	Liverpool	0.187	69	Dresden	0.391	-28
70	Vilnius	0.180	70	Leipzig	0.367	-23
71	Antalya	0.170	71	Leeds	0.358	-11
72	Ankara	0.163	72	Bradford	0.358	-11
73	Izmir	0.161	73	Tallinn	0.304	+2
74	Salonika	0.157	74	Vilnius	0.295	-4
75	Tallinn	0.149	75	Antalya	0.226	-4
76	Katowice	0.115	76	Izmir	0.215	-3
77	Valletta	0.108	77	Bratislava	0.209	+5
78	Dortmund	0.082	78	Dortmund	0.192	-
79	Las Palmas	0.067	79	Ankara	0.134	-7
80	Adana	0.046	80	Las Palmas	0.103	-1
81	Varna	0.028	81	Varna	0.097	-
82	Bratislava	0.000	82	Adana	0.000	-2

Source: Own calculations.

Due to the fact that three more cities are ranked above average in B compared to A we can conclude, that the approach with flight schedule data reveals some differences in the accessibility patterns. However, these differences may at first glance not be strong enough. Figure 4 offers a comparison for both approaches.

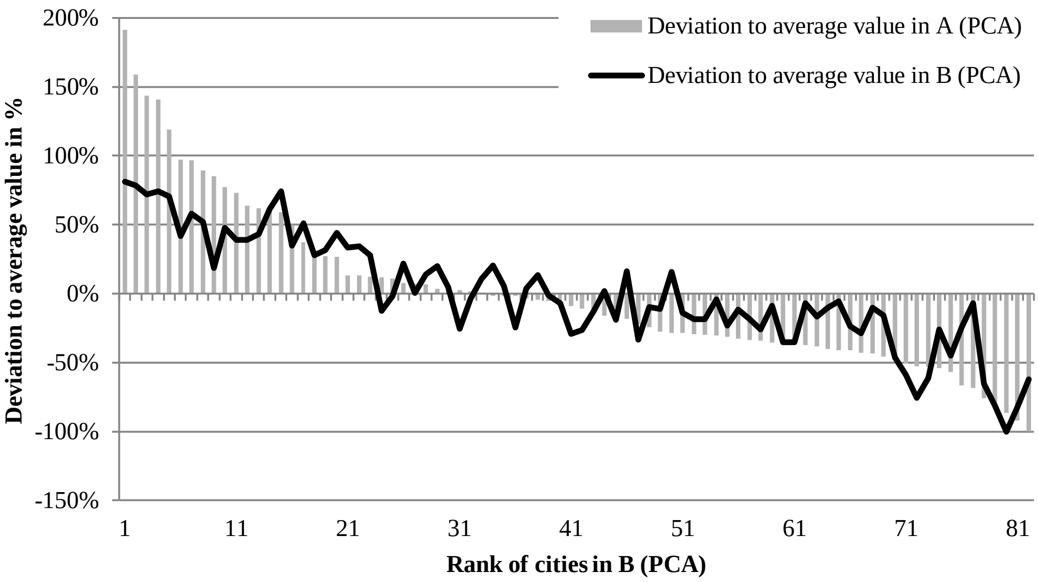

Figure 4: Comparison scenario B to A.
Source: Own calculations.

The Spearman's rank correlation coefficient for comparing the order of the synthesis rankings in A and B results in 0.88 and therefore reveals a high correlation between the actual orders of the rankings in the two approaches to measure global accessibility. Given the higher degree of complexity and additional data requirement, it is questionable whether incorporating frequency information in accessibility measurement can give additional insights, when computing synthetic indicators. One may therefore argue that synthetic methods possibly eliminate existing differences in accessibility patterns. Still, some interesting differences can be observed, especially in the central ranking positions. Major differences may be seen in the cases of Brussels, Luxembourg or Istanbul. In addition, the higher dispersion of accessibility values (figure 4) may reveal possible existing differences and results in more authentic accessibility patterns. For this reason we still consider the use of flight frequency information to be practical.

4. Conclusions

In this paper we analysed the accessibility patterns for 82 cities for the European air transport sector. We used four well-known conventional indicators, which have already been applied in relevant accessibility literature (e.g. Rietveld / Bruinsma 1998, Gutiérrez 2001, Martín et al. 2004, Martín and Reggiani 2007). Their use gives a more comprehensive picture of accessibility, since each of them answers a different question related with the quality of connections and infrastructure and therefore considers different aspects (e.g.travel time, geographical distance or economic potential of cities). Additionally, we modified these four indicators by entering time penalties (as already shown by Rietveld / Bruinsma 1998 for the potential indicator), which result out of the airlines' decision for frequency. The comparison of the partial indicators with and without flight schedule data show major differences especially for the daily accessibility, the potential indicator and the network efficiency. Therefore, the use of frequencies and schedule delay gives a more accurate picture of the accessibility patterns within Europe.

In addition to the conventional accessibility measures, we employed the synthesis method presented by Martín / Reggiani (2007) in order to synthesize partial accessibility indicators to a global index by performing principal component analysis. This paper adds therefore to the existing literature the implementation of schedule delay into the conventional accessibility indicators combined with a synthesis of these partial indices and its application in air transport. The comparison of both scenarios (with and without schedule delay) showed only minor changes in the synthetic accessibility rankings, although partial indicators reveal major differences. This result questions the adequacy of synthetic methods, especially PCA. Due to the fact, that the derived principal components represent only a share of data variance interesting differences in accessibility patterns among cities may be a part of the residuals and therefore not included in the global index. For this reason PCA seems not to account for all differences in accessibility patterns of cities. We therefore still advocate the parallel use of partial indicators depending on the research question. The results of this paper still depend on the selection of the cities representing the area of investigation. Since we selected only 82 European cities we do not cover the whole European territory. However, since the airports in our sample represent a high share of all passenger flows in Europe we still expect similar results to analyses with extended data sets.

In addition, we advocate the inclusion of accessibility measures (like the ones presented in this paper) as outputs to efficiency and productivity analyses of airports. The reason for this may be found within the field of the political economy. Standard approaches follow the notion of airports to be profit maximizing entities. Given, that the majority of European airports are not (or only partly) privatized, policy makers may directly influence their pricing policy and therefore, they may not be interested in profit maximization but rather in the maximization of the accessibility of the airport in question. This may give interesting insights on the overall performance of private vs. publicly owned airports.

Finally, accessibility measurement is the first stage of analysis. Investments in transport infrastructure change accessibility patterns, but the measurement itself is not sufficient enough to assess the necessity of the investment, since knowledge on the optimal infrastructure level is needed. This in turn would speak for the consideration of the indicators presented in this paper in models of economic growth.

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