Modeling the European Air Transportation Network considering inter-airport coordination

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***Abstract*—The air transportation network is essential to ensure mobility and connectivity between important metropolises and regions in Europe. Within the overall system, full-service network carriers operate sub-systems consisting of hub and spoke airports. These airlines enable various connections from different destinations by a low number of routes via the hub. Due to increasing traffic volumes in recent years, the system has become more congested, and several hub airports operate at their capacity limits. This has downstream effects on the hub airlines' operation performance. Capacity expansions are needed to handle the additional traffic efficiently. To assess the impact of these measures, local performance developments and propagation effects into the whole air transportation system should be considered. In this study, a simulation of relevant European airports is used to analyze network behavior under capacity enhancements for selected hub airports and airlines. Airports are rated based on flight delays and queue times at runways. The rate of reached flight connections is used to evaluate the performance of full-service network carriers. The results underline the dependency of airlines on the corresponding hub airport operations. A 10% capacity increase at London Heathrow decreases in- and outbound delay by 42% and 80% and improves the rate of successful flight connections from British Airways by approx. 10%. Significant propagation effects for carriers using London Heathrow as a spoke airport cannot be observed due to the complex large airline networks and the resulting low importance of one spoke airport for the overall network service quality.**

***Keywords*—Air traffic network, Capacity management, Airport performance, Airline performance, Benefit propagation**

I. INTRODUCTION

Europe is one of the major regions in terms of aviation traffic volume besides North America and Asia [1]. In 2019, the last complete unaffected year from the significant impact of the COVID-19 pandemic, over nine million departures were operated, and more than one billion passengers were carried. The recent years are characterized by steady growth in Instrument Flight Rules (IFR) movements and handled passengers [2]. In parallel, EUROCONTROL, as responsible central management unit of the European aviation network, monitors an unsatisfying increase in delay and lower service qualities partly resulting from a saturation of available capacities at airports and airspaces. The capacity of an aviation system is determined by several input factors [3]. This includes for airports e.g., the available runway configuration, expected weather influences, and the available Air Traffic Control (ATC) equipment. Airspace capacities depend e.g., on the traffic complexity, the airspace design, and separation standards. An airport consists of many sub-systems, each limited by a maximum capacity. The determination of these capacities is a complex procedure that requires the use of different methods, including mathematical models and observation results during daily business. The most constraining sub-system limits the overall airport capacity (bottleneck) [4]. If the demand exceeds the available capacity, the system becomes congested, which results in disadvantageous delays [5]. Increasing delays leads to higher costs e.g., for missed connections from transfer passengers, and could impact subsequent operations of an airline [6]–[8]. The management of the scarce resources in Europe is the responsibility of the Network Manager (NM) [9].

EUROCONTROL predicts a traffic increase of 53% more flight events until 2040 compared to the traffic values in 2017 [10]. However, the forecast did not consider the impact of COVID-19, which will probably lead to overestimated development figures. Other crises and demand decreases (e.g., during the financial crisis in 2007) have shown the fast recovery potential of the air transportation system [11]. Further, EUROCONTROL and the European Commission defined challenging service quality and performance level for the European aviation system [12,13]. It will not be possible to achieve these performance targets with the currently available capacities while maintaining high safety standards [14]. Challenging aspects are the variety of connections and the coupled air/ground processes within the air transportation network [15]–[17]. These can lead to downstream effects of capacity lacks on non-direct participated network systems and could impact the entire operating day and cause a massive impact on air traffic performance.

A. *Status quo*

To increase the capacity of an airport, a wide range of measures is available, which can be divided into two major categories. The first one includes investment options like the physical extension at an airport [18]. This covers, e.g., the construction of new runways/terminals, improved taxiways (Rapid Exit Taxiways (RETs) and End-Around Taxiways (EATs)), or upgraded ATC equipment. As proved in several types of research, new infrastructure has a hugely beneficial effect on the airport capacity [19]–[21]. However, regional political constraints and the structural landscape around the airport can complicate or avoid physical airport expansions due to the significant consequences on third parties [18]. Since infrastructure enhancing measures have a major impact on the whole airport system and the vicinity environment, the planning, assessment, and implementation is a time-consuming process and is based on future traffic forecasts [22]. Structural extensions can be over- or undersized when the forecasts are inaccurate. Hence, investment options are connected with unavoidable risk. The second group of measures includes non-investment opportunities, which contains improved procedures and processes to handle the air traffic [18]. This includes e.g., improved usage of slots for runway occupying activities, the reduction of safety distances due to wake turbulence, or a traffic shift to nearby less congested airports to relax the traffic load.

Local capacity enhancements or disturbances are directly linked to propagation effects within a network, which are analyzed from two perspectives in previous researches. The first examines the impact of a single aircraft on airline performance. Therefore, the well-known Delay Multiplier (DM) is a commonly used evaluation tool, which describes the ratio between an initial delay and the resulting downstream delay within the network [23]–[25]. This occurs due to the usage of aircraft and flight crews for further flight cycles and transfer passengers who need to reach their follow-up flight. For evaluation of DMs, delay trees are an appropriate instrument since these also illustrate the complex airline linkages. Flights associated with high DMs are network critical. Airlines should be aware of these flights and intervene if the operation is adversely affected. The magnitude of the DM depends on multiple factors. Flights departing in the morning hours tend to have higher DMs than flights in the later hours due to a larger number of connected flights [23,24,26]. Most air traffic activities are stopped in the late evening because of night flight bans, which allows the air transportation system to recover from disruptions. The flight schedule structure of an airline depends on the used business model. This leads to different initial conditions for the propagation of delays. Full-Service Network Carrier (FSNC) operate a hub-and-spoke or multi-hub-and-spoke system where the hub is used as a central transfer airport [27,28], which allows the connection of multiple destinations with a low amount of flight routes. In the last decade, worldwide alliances and joint ventures of FSNCs have been established to get access to other regions of the world, reduce the competition on the market, and overcome regional administration barriers [29,30]. Low Cost Carrier (LCC) are using a decentralized point-to-point network to link two destinations without any transfer procedures [31]. However, LCC operate base airports to enable centralized maintenance and customer service activities. Flights from a hub-and-spoke network tend to lower DMs compared to point-to-point network flights under the same initial delay conditions [25,32]. Further, more flights are adversely affected in a point-to-point system, and the recovery process from the initial delay needs more flight cycles compared to a hub-and-spoke network. FSNC have various instruments at their hub airport to absorb delays (e.g., spare flight aircraft or crews). Robust scheduling of airline resources can prevent an airline from the adverse effects from delay propagation [33].

B. *Focus and structure of the document*

In our contribution, we want to analyze the effect of local capacity improvements on the performance of FSNC and the corresponding hub airport. In a first step, major European network carriers and alliances are described, and a method to identify possible designed flight connections is presented. Further, a simulation considering important European airports is implemented to determine the network performance during a busy air traffic volume period.

II. Data analysis and simulation setup

Based on two data sets provided from EUROCONTROL, a simulation of relevant European network airports is executed. The data includes post-operation information for more than 3.2 million reported flight events during the summer period between July and September 2019. Table I shows the relevant information used for the model development. Based on the data, relevant airports are extracted, and the basic simulation logic is implemented. Detailed information about the setup are explained by the authors in a previous study [34]. In the following, a summary of the central simulation elements and extensions resp. adjustments are explained.

TABLE I. Used data set information for the development of the model.

Information	Description	Example
ADEP	Departure airport	EDDF
ADES	Destination airport	EGLL
SOBT/AOBT	Scheduled/Actual time for Off-Block at the departure airport	11:20:00
Taxi-out duration	-	00:12:36
STA/ATA	Scheduled/Actual time of arrival	12:40:00
Taxi-in duration	-	00:08:00
Aircraft type	ICAO designator for used aircraft	A320
Aircraft registration	-	DAIFT
Airline designator	3 digit ICAO code for an airline	DLH

A. *Basic simulation logic*

The model considers 212 relevant European airports located in 41 countries, where the NM is responsible for Air Traffic Flow and Capacity Management (ATFCM) activities (NM area). Each of them is represented by the available number of runways used for take-off or landing procedures. To ensure safe operations, separation distances between two consecutive starting or landing aircraft are defined based on the wake turbulence category of the used aircraft type. Further, only one aircraft operating on a runway is allowed. This processing time equals the Arrival Runway Occupancy Time (AROT) or Departure Runway Occupancy Time (DROT). These safety time buffers are limiting the runway capacity. The airports are connected via flights. A flight schedule from a busy weekday during the summer period is used as simulation input, which includes 35,098 flights and 58,478 movements operated at the 212 network airports. Flights to other airports are handled by a dummy airport, which has infinite capacity. This prevents the network from external disruptions triggered by non-network airports. Airlines are using aircraft for multiple flight legs during an operating day resulting in flight cycles. A general example is shown in Fig. 1. The cycle is described by four timestamps for the off-block, departure, arrival, and in-block event. Between these timestamps, processes need to be executed (taxi-out, flight, taxi-in, turnaround).

The process times are determined stochastically based on the reported times within the data set. Since the runway capacity is limited at airports, additional waiting times can occur at the origin airport (additional taxi-out time) or at the destination airport (additional Arrival Sequencing and Metering Area (ASMA) time) if the runway is not approved for use. To investigate the effect of enhancing runway capacity on the airport and FSNC performance, the time-based separation distances are decreased in 5% steps up to 30%. This reduction leads to a comparable increase in capacity if the runway is under pressure. The baseline scenario does not consider any capacity enhancements. Every scenario is executed 10 times, and each run takes about 1 hour of processing time using an Intel(R) Core(TM) i7-1065G7 CPU processor. The simulation is implemented using a Python programming platform. Propagation effects occur only if flights from an airline are connected. Therefore, a data-driven spatial method for determining designed flight connections based on the airline flight schedule is developed.

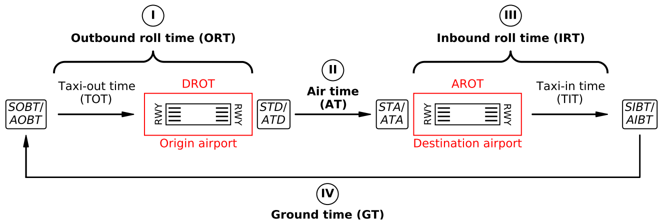

Figure 1. Principle of the general flight cycle.

B. *Definition of designed flight connections from FSNC*

The business model from FSNC airlines equals a hub-and-spoke network to connect a variety of airports via a central transfer airport. This allows passengers to access the entire network of an FSNC by only one transfer. Selected relevant FSNC with a hub airport located in Europe are shown in Table II.

FSNC	Hub airport location	Traffic share at business days (median) [%]
Lufthansa	Frankfurt a.M.	62
	Munich	59
British Airways	London	52
KLM	Amsterdam	57
Air France	Paris	44
Iberia	Madrid	59

TABLE II. OVERVIEW OF FSNC LOCATED IN EUROPE.

The number of hub airports differs depending on the FSNC. E.g., Lufthansa uses Frankfurt a.M. and Munich airport as a hub, whereas British Airways maintains only London Heathrow as a transfer option. The particular hub airline predominates the traffic volume at the corresponding hub airport. In Frankfurt a.M. 62% of flights are operated by Lufthansa airlines at the median weekday within the data set period. This results in a high dependence between the FSNC and the corresponding hub airport performance. Every FSNC can only generate the benefits of the hub-and-spoke network when the connectivity between flights is ensured. If the hub airport operation is staggering or unreliable, the FSNC suffers from unstable conditions. To mitigate this effect, hub airlines are directly involved in airport decision-making and future development resolutions. E.g., Lufthansa operates a dedicated area at Frankfurt a.M. Airport (EDDF) and is a shareholder in the airport operator company (Fraport AG) [35]. European FSNC are characterized by a dense network of short- and medium-haul flights within Europe combined with several long-haul flights to major metropolises located in the rest of the world. Co-operations, joint ventures, and alliances between airlines are arranged to enhance the offered network for the customers. Lufthansa maintains a strong collaboration with United Airlines, which is one of the important FSNC in the USA. This enables advantages for both parties, as transferring to flights of the respective airline partner is feasible, and access to the network is provided. Table III gives an overview of three major airline co-operation groups that have emerged in recent decades.

Airline group	Included passage airlines	Joint-venture airlines
Lufthansa group	Lufthansa, Lufthansa CityLine, Air Dolomiti, Swiss, Austrian Airlines, Brussels Airlines, Eurowings	United Airlines, Air Canada, All Nippon Airlines, Singapore Airlines, Air China
IAG group	British Airways, British Airways CityFlyer, Sun Air, Iberia, Iberia Express, Vueling Airlines, LEVEL, Aer Lingus	American Airlines, Finnair, Japan Airlines, Qatar Airways, China Southern Airlines
Air France-KLM group	Air France, Air France Hop, Transavia France, KLM, KLM Cityhopper, Transavia	Delta Air Lines, Alitalia, Virgin Atlantic, China Southern Airlines, Xiamen Airlines

TABLE III. MAJOR AIRLINE GROUPS IN THE AVIATION WORLD [36]–[38].

Since it is challenging to obtain holistic information on transfer passengers because this involves sensitive airline data subject to confidentiality (International Air Transport Association (IATA) and several Global Distribution Systems (GDSs) provide selected transfer data at some cost), a three-step approach is used to identify the intended flight connections as input to the simulation [39]. The general logic of a transfer flight between an Origin and Destination (O&D) looks as follows:

$$\text{Origin (O)} \xrightarrow{\text{Flight 1 (F1)}} \text{Hub} \xrightarrow{\text{Flight 2 (F2)}} \text{Destination (D)}$$

Two flights are needed to connect the O&D. F1 carries the passenger from the origin to the hub airport. After the transfer process at the hub, F2 is used to finish the journey and reach the final destination. The applied principle is explained using an example flight operated by Lufthansa from EDDF to Stockholm Arlanda Airport (ESSA) as F2 and a general scenario for a long-haul O&D via EDDF.

1) Determining the transfer time horizon: A designed flight connection from a FSNC is characterized by a transfer at the hub airport. This process includes the entrance into the airport terminal, an optional id card control as well as a security check, and the boarding pass control at the departure gate [40]. In addition, there could be a long distance to cover between the arrival gate of F1 and the departure gate of F2. It may even be necessary to switch between two terminals at the hub airport. These activities are time-consuming and form a required time buffer for a passenger and his luggage to reach a connecting flight, which is represented by the Minimum Connecting Time (MCT) [41]. The MCT varies between different airports and is mainly depending on the size. In addition to this minimum transfer time, the airlines aim at planning connections as time-effective as possible to keep travel times short. To represent this criterion, a maximum transfer time of 3 hours is used as an assumption. Longer stopovers at hub airports are possible, but the corresponding flights are not handled as a designed flight connection within the simulation logic. Finally, the period for planned connections can be determined using the Scheduled Off-Block Time (SOBT) of F2 and Scheduled Time of Arrival (STA) of F1 for all flights of an FSNC. The transfer time between F1 and F2 ($\mathrm{TT}_{\mathrm{F1} \rightarrow \mathrm{F2}}$) equals the difference from the SOBT from the second flight leg and the STA from the first flight leg (1).

$$\mathrm{TT}_{\mathrm{F1} \rightarrow \mathrm{F2}} = \mathrm{SOBT}_{\mathrm{F2}} - \mathrm{STA}_{\mathrm{F1}} \tag{1}$$

A F1 has a designed connection with F2 if the $\mathrm{TT}_{\mathrm{F1} \rightarrow \mathrm{F2}}$ is within the transfer time limits (2).

$$\text{connection} = \begin{cases} \text{Yes} & \text{if } \mathrm{MCT}_{\mathrm{Hub}} \leq \mathrm{TT}_{\mathrm{F1} \rightarrow \mathrm{F2}} \leq 3 \text{ hours} \\ \text{No} & \text{else} \end{cases} \tag{2}$$

This algorithm is applied for every flight of an airline group and the corresponding hub airports shown in Table II and III. 103 connections fulfill the time-based criteria for the example flight from EDDF to ESSA. The corresponding 80 airports are shown in Fig. 2 (left).

2) Definition of the excluded area - part 1: The time-based criteria for the classification of flight connections don't consider the geographical position from the O&D airports. This allows the definition of flights from two closed located airports as designed flight connections. In the worst-case, the O&D airports are located in the same city, which results in a highly uncommon journey route. Usually, these short-haul trips are traveled by other transportation modes (e.g., high-speed trains or long-distance buses). To exclude unusual routing with closely located airports, a distance- and an angle-based criterion is applied.

In a first step a Lower Distance Boundary (LDB) and a Upper Distance Boundary (UDB) is determined to limit the excluded area around the destination airport. The basis is the orthodromic distance between the hub and destination airport ($\mathrm{d}_{\mathrm{Hub} \rightarrow \mathrm{D}}$). The location of both airports is characterized by a longitudinal (λ) and a latitudinal (ϕ) coordinate in degrees. Equation (3) is used to calculate $\mathrm{d}_{\mathrm{Hub} \rightarrow \mathrm{D}}$ in kilometres. LDB and UDB are determined by subtraction resp. addition of 600 km as a threshold value from $\mathrm{d}_{\mathrm{Hub} \rightarrow \mathrm{D}}$.

$$\begin{aligned} \mathrm{d}_{\mathrm{Hub} \rightarrow \mathrm{D}} = {} & \arccos(\sin(\phi_{\mathrm{Hub}}) \cdot \sin(\phi_{\mathrm{D}}) + \cos(\phi_{\mathrm{Hub}}) \\ & \cdot \cos(\phi_{\mathrm{D}}) \cdot \cos(\lambda_{\mathrm{Hub}} - \lambda_{\mathrm{D}})) \cdot 6.378 \text{ km} \end{aligned} \tag{3}$$

The distance borders for the example flight are shown in Fig. 2 (left). EDDF and ESSA are located about 1,220 km apart from each other, which results in a LDB of 620 km and an UDB of 1,820 km. To further restrict the excluded area around the destination airport, an angle-based limitation is used. The basis is the location of the destination in reference to the hub airport and the north direction (N). These three points form the angle $\theta_{\mathrm{N,\ Hub,\ D}}$ shown in Fig. 2 (left). The angle border in the negative direction of rotation is called Negative Angle Boundary (NAB). The Positive Angle Boundary (PAB) equals the border in the positive direction of rotation. Both are determined similarly to the distance limits by subtracting or adding the threshold value of 30°. Equation (4) shows the determination of $\theta_{\mathrm{N,\ Hub,\ D}}$ using the scalar product.

$$\theta_{\mathrm{N,\ Hub,\ D}} = \arccos\left(\frac{\overrightarrow{\mathrm{P}_{\mathrm{Hub}}\mathrm{P}_{\mathrm{N}}} \cdot \overrightarrow{\mathrm{P}_{\mathrm{Hub}}\mathrm{P}_{\mathrm{D}}}}{\left|\overrightarrow{\mathrm{P}_{\mathrm{Hub}}\mathrm{P}_{\mathrm{N}}}\right| \cdot \left|\overrightarrow{\mathrm{P}_{\mathrm{Hub}}\mathrm{P}_{\mathrm{D}}}\right|} \right) \tag{4}$$

LDB, UDB, NAB, and PAB create a sector around the destination airport which corresponds to the excluded area. If an origin airport is located in this area, the resulting O&D is defined as uncommon and is not considered in the simulation. Fig. 2 (left) shows the excluded area in red for the example flight. Flights from seven departure airports (ESSA included) are neglected due to the close distance to ESSA. In this special case, this also affects seven flights, which leads to 96 remaining valid leg 1 flights for the example case.

3) Definition of the excluded area - part 2: The explained method for determining the excluded area works well for the European area but has issues with increasing distance from the hub to origin and destination airports. Fig. 2 (right) shows a scenario for F2 from EDDF to New York John F. Kennedy Airport (KJFK). The resulting excluded area around KJFK becomes significantly larger than for ESSA. This results from the exponential expansion of ellipses with increasing distances between hub and destination airport. The curious shape of the excluded area arises due to the equirectangular projection of the map and the resulting deformation. The sector includes several major airports located at the upper US east coast

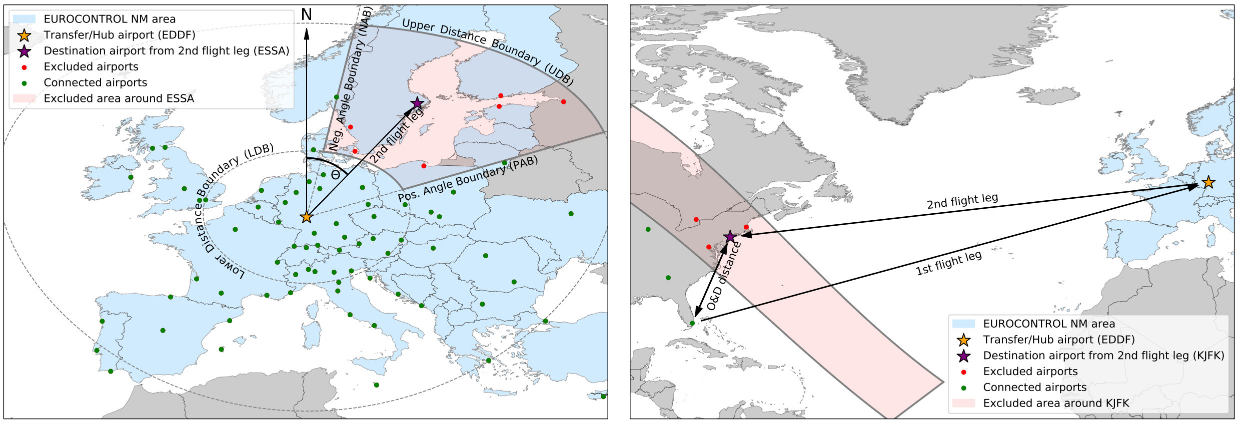

Figure 2. Evaluation method to identify designed flight connections by FSNC airlines.

(e.g. Washington Dulles Airport (KIAD) or Boston Logan Airport (KBOS)), but airports located in the southeast area (e.g., Atlanta Airport (KATL) or Miami Airport (KMIA)) are handled as valid connection to KJFK via EDDF. In practice, however, it is not a viable route. To prevent this unintentional declaration, a second distance-based criterion is applied for long-haul O&Ds if both airports are more than 3,000 km apart from the hub airport. In this case a Detour Factor (DF) is determined to precise the valid O&D definition. For this purpose the distance between origin and destination ($d_{\mathrm{O}\rightarrow\mathrm{D}}$), origin and hub ($d_{\mathrm{O}\rightarrow\mathrm{Hub}}$) as well as between hub and destination airport ($d_{\mathrm{Hub}\rightarrow\mathrm{D}}$) is calculated using the corresponding airport coordinates and the adjusted equation for the determination of the orthodromic distance (3). The definition of the DF for an O&D ($\mathrm{DF}_{\mathrm{O\&D}}$) is given in (5).

$$\mathrm{DF}_{\mathrm{O\&D}} = \frac{d_{\mathrm{O}\rightarrow\mathrm{Hub}} + d_{\mathrm{Hub}\rightarrow\mathrm{D}}}{d_{\mathrm{O}\rightarrow\mathrm{D}}} \tag{5}$$

The identification of valid long-haul O&Ds is based on a threshold value for the DF. If the distance sum from both flight legs exceeds the distance between origin and destination airport by more than 45% (DF = 1.45), the corresponding O&D is excluded (6).

$$\text{O\&D valid} = \begin{cases} \text{Yes} & \text{if } \mathrm{DF}_{\mathrm{O\&D}} \leq 1.45 \\ \text{No} & \text{else} \end{cases} \tag{6}$$

For the shown case in Fig. 2 (right) with KMIA as origin, EDDF as hub, and KJFK as destination the DF equals 7.94 and therefore the O&D is declined. This method prevents long-haul O&Ds from and back to the same region of the world. The DF threshold value is a result from a set of example O&Ds with EDDF as hub airport shown in Table IV. Green highlighted cells show possible O&Ds using the defined threshold DF value of 1.45.

Table V shows the results for the evaluation of designed flight connections from major FSNC airlines. Lufthansa operates the highest amount of outbound hub-flights (500) and overall potential connections (31,110). The highest determined value of valid feeder flights equals 102 for two Lufthansa flights departing at 8 PM. However, it should be stated that a designed flight connection describes only a possible link between two flights. If the O&D is not booked from any passenger, the successful connection of those flights has no impact on the transfer performance from the airline. The number of connecting flights is comparatively low for early morning flights because only a limited number of arriving flights have arrived at the hub airport before them.

DF		Destination (D)								
		WSSS	RJTT	OMDB	ZBAA	VIDP	KLAX	MMMX	SBGL	FACT
Origin (O)	WSSS	-	3.71	2.59	4.02	3.94	1.39	1.19	1.26	2.03
	RJTT	3.71	-	1.79	8.2	2.64	2.12	1.67	1.02	1.27
	OMDB	2.59	1.79	-	2.16	5.02	1.06	1	1.21	1.86
	ZBAA	4.02	8.2	2.16	-	3.65	1.7	1.39	1	1.33
	VIDP	3.94	2.64	5.02	3.65	-	1.2	1.07	1.12	1.67
	KLAX	1.39	2.12	1.06	1.7	1.2	-	7.55	1.86	1.16
	MMMX	1.19	1.67	1	1.39	1.07	7.55	-	2.49	1.38
	SBGL	1.26	1.02	1.21	1	1.12	1.86	2.49	-	3.11
	FACT	2.03	1.27	1.86	1.33	1.67	1.16	1.38	3.11	-

TABLE IV. DF FOR SELECTED O&DS VIA EDDF (GREEN = ACCEPTED O&DS; RED = DECLINED O&DS).

FSNC	Hub airport location	Outbound flights (F2) (group airlines included)	Feeder flights (F1)			
			min	max	avg	sum
Lufthansa	Frankfurt a.M.	500	8	102	62	31,110
	Munich	391	4	74	46	17,799
British Airways	London	368	1	44	27	9,837
KLM	Amsterdam	389	8	89	53	20,842
Air France	Paris	363	1	45	22	7,899
Iberia	Madrid	369	1	52	21	7,570

TABLE V. CONNECTIVITY STATUS FROM FSNC AIRLINE GROUP OUTBOUND FLIGHTS DEPARTING AT THE CORRESPONDING HUB AIRPORT.

C. *Unimpeded process times*

The data set from EUROCONTROL includes taxi-out and flight times, which are used as simulation input for the stochastic determination of the process times. Fig. 3 shows the mean and standard deviation for taxi-out times for EDDF (left) and EGLL (right), depending on the number of aircraft taxiing on the apron. The number of taxiing aircraft is counted

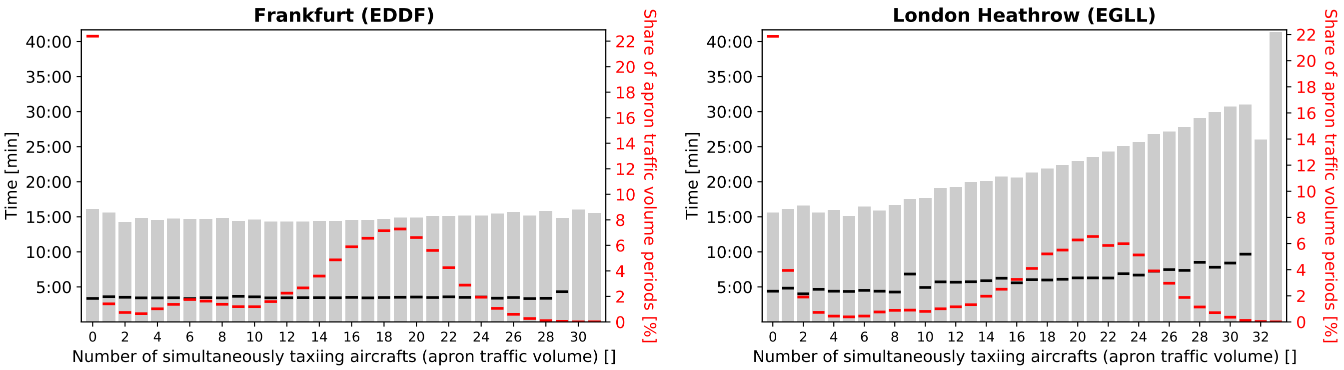

Figure 3. Mean taxi-out times (grey) and standard deviations (black) based on apron traffic for EDDF and London Heathrow Airport (EGLL).

in 5-minute steps, representing the current traffic volume on the apron. The red lines show the share of periods for all observed traffic volume conditions. Standard deviations are not calculated for high traffic volumes on the apron because this condition occurs only rarely. High percentages for low traffic volumes result from the night hour time periods. The average taxi-out time considers all flights starting their taxi-out process under the same initial apron traffic volume. For EDDF the taxi-out times are stable with increasing apron traffic, which indicates that the apron design of the airport can absorb the resulting congestion. The taxi-out times at EGLL are steadily increasing due to congestion effects if a threshold of simultaneously taxiing aircraft is exceeded. Stable roll time parameters can be monitored with lower traffic volumes on the apron. The transition point indicates the amount of manageable aircraft by the apron infrastructure. Every additional aircraft leads to a loss in quality and an increase in taxi-out time due to congestion effects. The threshold value depends on the apron size as well as the design and differs between airports.

Taxi-out times for lower apron traffic volumes vary due to different taxi-out distances depending on the gate position and active runway configuration. For the simulation, the use of an unimpeded taxi-out time without queue times is necessary. The simulation creates additional waiting times for departures and arrivals on its own due to the exclusive use of a server (runway) by only one flight. An unimpeded taxi-out time doesn't consider any additional times due to congestion effects on the apron. Fig. 3 indicates the increase of mean taxi-out time for EGLL if more than seven aircraft are simultaneously moving on the apron. Analysis of other network airports shows that even when more than five flights are taxiing, interactions occur amongst them. We assume that an unaffected taxi operation at all network airports is guaranteed when the apron traffic volume does not exceed this threshold. The used taxi-out parameters considered in the simulation are calculated based on flights that started their taxi procedure meeting this apron traffic volume criterion.

A similar approach is used to determine the flight times between an O&D for a specific aircraft type. Fig. 4 exhibits the distribution of reported flight times from EGLL to EDDF flown by A320neo. The red line shows the corresponding normal distribution. Due to the consideration of outliers, the curve runs flat. Comparably low flight times are results from e.g., advantageous wind conditions. Holdings around the departure airport due to congestion effects, necessary re-routings, or severe weather can be reasons for high travel times. Flight times outside the 2σ are located in the outlier area and are excluded, which results in a better shaping curve (green). Valid flight times for the simulation are within the 3σ interval calculated using the parameters from the green curve to avoid extremely short or long times due to the natural behavior of the normal distribution.

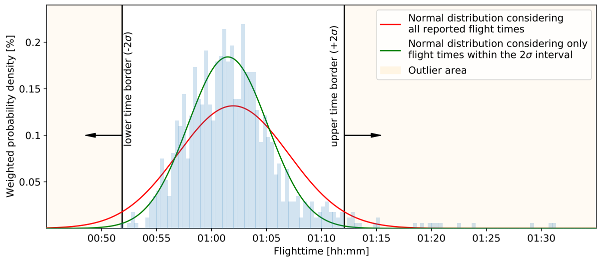

Figure 4. Distribution of reported flight times from EGLL to EDDF for flights using A320neo aircraft.

The reported values of taxi-in times for an airport are constant, but they differ from airport to airport. A study using open-source data for London Gatwick Airport (EGKK) indicates a lower dependence of taxi-in times on apron traffic volumes [42]. Hence, these fixed values are used for the simulation. The turnaround time is calculated using an assumption based on the wake turbulence category from the used aircraft type. Therefore reference aircraft for medium (A320neo), heavy (A350-900), and super (A380-800) categories are specified, and the indicated *full servicing turn round time* (A320neo: 44 min [43]; A350-900: 61 min [44]) resp. the *typical turn-round time - standard servicing via main deck and upper deck* (A380-800: 90 min [45]) is used as expected value (μ). The corresponding assumed standard deviation equals 10% of μ. Based on the resulting normal distribution, the turnaround times are generated within the simulation. An expected turnaround time of 20 minutes and a standard deviation of 2 minutes is assumed for light aircraft.

III. SIMULATION RESULTS

The simulation is executed considering capacity enhancements for two major European airports (EDDF and EGLL), which serves as hub for a FSNC. Fig. 5 shows the results for the following four performance indicators for both airports:

- **Inbound delay**: Difference between Actual Time of Arrival (ATA) and STA of arrival flights
- **Outbound delay**: Difference between Actual Off-Block Time (AOBT) and SOBT of departure flights
- **additional taxi-out time**: queue time at the runway from departing flights
- **ASMA additional time**: queue time at the runway from arriving flights

The results exhibit low delay figures for EDDF and manageable additional waiting times at the runways for the baseline case. Capacity enhancement measures don't show a significant improvement for the performance of EDDF since the delay is not a result of traffic congestion at this airport. On the other hand, EGLL is characterized by high delays and queue times at the runway. In contrast to EDDF, a capacity increase leads to a significant improvement in airport performance. 10% more capacity reduces the inbound delay by 10,832 minutes (-42%), the outbound delay by 2,884 minutes (-80%), the additional taxi-out time by 7,815 minutes (-33%), and the ASMA additional time by 8,931 minutes (-56%). However, a saturation effect can be observed for high rates of capacity enhancements. This indicates structural delay from a too-tight flight schedule or created at other network airports.

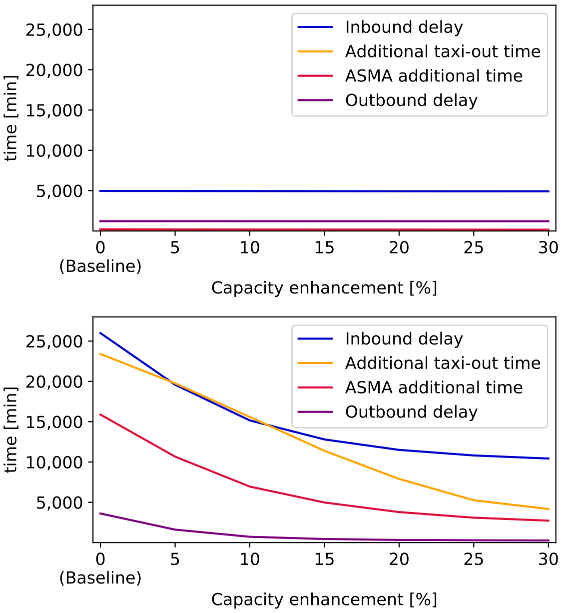

Figure 5. Development of the airport performance indicators from EDDF (top) and EGLL (bottom) under increasing capacity.

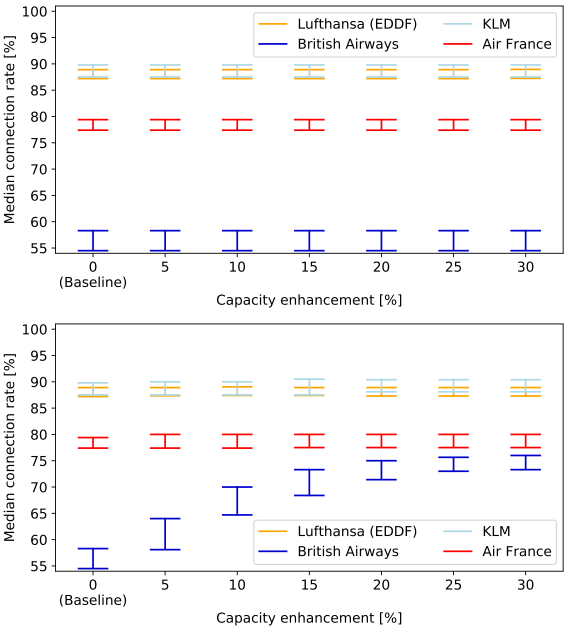

Figure 6. Median connection rate of major FSNC under increased capacity at EDDF (top) and EGLL (bottom).

To investigate the improvements for FSNC the connection rate is analyzed, which equals the ratio between fulfilled flight connections and the number of defined flight connections from a FSNC outbound flights at the hub airport. A feeder flight is connected successfully with the outbound flight if the in-block time from the feeder occurs before the off-block time from the outbound flight minus the MCT of the hub airport. Fig. 6 shows the range of median connection rates for all 10 simulation runs for increased capacity at EDDF (top) and EGLL (bottom). Between 87% and 90% of feeder flights arrive in time to catch the outbound flight of the median Lufthansa flight. This ratio does not improve by increasing capacity at EDDF. The missed connections occur majorly due to disturbances at the spoke airports. The median connection ratio of other FSNC is also not improving significantly when the capacity of EDDF is enhanced. For British Airways, a connection rate of 55% up to 60% can be observed. The comparable low ratio reasons from the high congestion at EGLL. Suppose the capacity at EGLL is enhanced, the median connection rate increases significantly. Similar to airport performance, a saturation effect and lower growth occur at higher rates of capacity increase. A 10% capacity increase at EGLL leads to a similar increase in fulfilled flight connections for the median flight from British Airways. This underlines the importance of the hub airport performance for the resident FSNC. However, no measurable effect can be observed for other FSNCs. The median connection rates are stable and independent of the improved performance at EGLL. The airport is only one spoke in the network for the other FSNC. Lufthansa serves 136 further spoke airports from EDDF on the simulated operation day. The capacity enhancement at EGLL improves primary the direct flights to this airport. Benefits to downstream flight events using the same resources for a flight are possible if the flight is delayed in the baseline scenario and the planned ground buffer is insufficient and exceeded. Nevertheless, Lufthansa operates 24 flights between EDDF and

EGLL in the used simulation flight schedule. In comparison to the overall number of 900 Lufthansa flights via EDDF the improvement potential is limited. An enhanced spoke airport has not a quantifiable impact on the Lufthansa connection rates since the operated networks are too comprehensive.

IV. DISCUSSION AND CONCLUSION

FSNC are essential providers of inner-European and intercontinental connections via a hub airport. To offer a wide range of O&D linkages, a seamless transfer between the first and second flight leg is essential. A simulation of one operation day from relevant airports of the European air transportation network is used to investigate the development of flight connection rates from FSNC under increased local airport capacity. The results exhibit the importance of the hub airport performance for FSNC. A 10% increased capacity at EGLL leads to significantly less delay and waiting time at the airport resources compared to the baseline scenario. Simultaneously the ratio of successfully reached designed flight connections from British Airways increased by the same percentage. The growth rates slightly decrease with steady capacity enhancements, leading to a natural saturation in airport delay figures and connection rates. To overcome these barriers, other measures like flight schedule adjustments are necessary. Other FSNC connection rates (which serves EGLL as spoke airport) do not improve significantly from the capacity increase. The direct connections to EGLL are positively affected by the airport improvement, but propagation effects on downstream airline flights are not observed. The large expansion of FSNC networks and the high number of operated flights during an operation day leads to a negligible effect of improved connections to only one spoke airport.

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