USING SCHEDULED DELAYS TO MEASURE AN AIRPORT'S SCHEDULING PERFORMANCE

D. Kösters, D. Klingebiel
Dept. of Airport and Air Transportation Research, RWTH Aachen University, Germany

Abstract

Airport coordination including the allocation of airport slots is the relevant instrument to control and to manage operational infrastructure access to congested European airports. Therefore an airport's scheduling performance is related to the feasibility of realizing operational airport infrastructure access as requested and as resulting from airport coordination and slot allocation decisions. To quantify and to measure airport scheduling performance, 'scheduled delays' had been defined as a quality criterion.

The definition of scheduled delays as performance indicator allows a retrospective performance analysis of the airport coordination process. Indicating a low quality of service during scheduling and thus an airport's incapability and insufficiency to cope with the slot demand, scheduled delays can be used as a parameter to address airport capacity and airport design issues. Empirical studies of airport coordination data at five German airports show that average scheduled delays per allocated slot will rise if slot utilization and thus system load increases.

Besides a retrospective performance analysis additional benefit results from predicting scheduled delays. Future developments may be forecasted, as well as different input parameters' impact on the airport scheduling performance may be analyzed. Additionally actual airport scheduling results can be benchmarked towards the prognosis. Such usage and application of scheduled delays require precise modeling of the initial slot coordination process and of the aforementioned relation between slot utilization and scheduled delays in particular.

Therefore within the paper at hand a deterministic model approach is introduced to calculate scheduled delays depending on the level of slot utilization by the initial slot demand. This model allows a first estimation on the amount of scheduled delays as resulting from conflict resolution within the initial slot coordination. Due to incompleteness of available airport coordination data no model calibration could be realized so far. Even so validation shows sufficient model accuracy for certain levels of slot utilization. The impact on airport scheduling performance of both varying declared capacity restrictions and diversified slot demand patterns can be demonstrated and analyzed using the model.

1. INTRODUCTION

'Access and equity' had been determined as one of eleven global ATM performance areas [1]. The feasibility to access required infrastructure elements during operations is to be evaluated. At major European airports the operational infrastructure access is controlled and managed by allocating airport slots. An airport slot is required for every take-off and every landing and thus can be considered as a temporarily specified operations permit for the airport infrastructure [2]. In the EU airport slots are allocated within the so called airport coordination following Council Regulation 95/93 [3]. Thus airport coordination is in the center of airport scheduling activities which form the basis of ATM months before operations [4]. It decides on the feasibility to realize operational infrastructure access as requested.

Airport coordination is to avoid operational overloads by balancing capacity and demand at a strategic planning stage. Here airport capacity is defined as the declared number of airport slots being available for allocation [5]. During airport coordination excess demand may occur if the number of airport slot requests exceeds the number of available slots. Resolution of given conflicts include both rescheduling (proposing alternative slot times) and rejecting slot requests [6]. For such cases operational airport access cannot be realized as requested by an airline.

Described coordination results are used to evaluate the feasibility of accessing the airport infrastructure as requested. Being defined as the difference between requested and allocated slot times, scheduled delays allow measuring an airport's scheduling performance [7]. ATM performance in terms of 'access and equity' is quantifiable. Scheduled delays will occur if an airport does not cope with the slot demand in the strategic planning phase. Thus, considering scheduled delays allows integrating the performance area 'access and equity' when addressing airport capacity and airport design issues. An airport's capability to accommodate the given demand may be discussed using scheduled delays as performance indicator.

Besides a retrospective analysis of historical data additional benefit would arise from precise knowledge on the interrelationship between slot demand (measured as the utilization of available slots) and scheduling performance (measured as scheduled delays). Future developments may be forecasted, as well as different input parameters' impact on the airport scheduling performance may be analyzed. In addition, actual airport scheduling results can be benchmarked towards a scheduled delay prognosis. Therefore, within the paper at hand a model approach is defined which allows to determine and thus to forecast scheduled delays depending on the level of slot utilization. The initial conflict resolution during the airport coordination is modelled.

The paper at hand consists of 4 parts. Chapter 2 focuses on this research topic's background. Airport coordination according to Council Regulation 95/93 is introduced. Parameters required to discuss an airport's scheduling performance are defined: Scheduled delays as performance indicator as well as the interrelationship between scheduled delays and slot demand / slot utilization. In chapter 3 a deterministic model to calculate scheduled delays is introduced; given capacity restrictions and initial slot requests (slot demand) are used as model input parameters. Model validation then is described in chapter 4. Finally, chapter 5 focuses on the usage of this model approach. Exemplarily the impact on the airport scheduling performance (scheduled delays) of both varying capacity restrictions and diversified daily demand patterns is demonstrated.

With airport coordination data being available for German coordinated airports (schedule periods summer 2005 and winter 2005/2006) analysis and modeling within this research project are based on the relevant developments at those airports: DUS/ Düsseldorf, FRA/ Frankfurt, MUC/ Munich, STR/ Stuttgart, TXL/ Berlin-Tegel. Because airport coordination in Germany follows Council Regulation 95/93 precisely it may be assumed that this paper's research results are transferable to any airport being slot-coordinated according to this regulation.

2. BACKGROUND

2.1. Airport Coordination

Airport coordination in the EU and thus in Germany is an administrative process which is based on Council Regulation 95/93. The latter has endorsed the IATA Worldwide Scheduling Guidelines [8]. A national airport coordinator is responsible for allocating airport slots. Although the Regulation specifies relevant procedures precisely, remaining tolerances result in national and local particularities. The following summary corresponds to slot allocation procedures at German coordinated airports.

Article 2 of the Regulation defines the term slot as 'the permission given by a coordinator in accordance with this Regulation to use the full range of airport infrastructure necessary to operate an air service at a coordinated airport on a specific date and time for the purpose of landing or take-off as allocated by a coordinator in accordance of this Regulation'. Practically, a slot is the right to use the airport infrastructure with an aircraft at a particular time – it is a temporally specified operations permit. The slot time defines the moment of leaving or arriving at the aircraft stand (on block, off block) and is equal to the published flight time usually. At German airports during coordination a 10 minutes time span is used as smallest coordination unit. With flights being scheduled in full 5 minutes steps, 2 adjacent slot times will be combined and considered within one 10 minutes coordination interval.

2.1.1. Coordination Paramaters – Declared Capacity

Airport coordination parameters – predominantly an airport's declared capacity – are relevant input parameters for the slot allocation process. The declared capacity describes a maximum number of slots per unit of time (block period) that can be allocated by the coordinator. Declared capacity values may differentiate between arrival (ARR), departure (DEP) and total movements (TOT). The duration of blocks may vary as well; in addition, several blocks with different duration may be superposed to control the concentration of flights within a certain time period. While 60 minutes values determine the maximum number of slots, 30 and 10 minutes values are optionally used to control the concentration of flights. This objective is achieved by applying rolling blocks (10 minutes steps) in addition. The use of declared capacity values for the whole season means a fixing of the seasonal airport infrastructure capacity at an early stage. The determination of the declared capacity shall take into account all relevant technical, operational and environmental constraints as well as any changes thereto. It tries to maximize the use of available airport capacity whilst keeping the quality of service during operations at locally acceptable levels.

2.1.2. Initial Slot Request, Coordination and Slot Allocation

About 5 months before the start of a scheduling season (winter or summer) airlines have to provide details on their planned schedules for the upcoming season to the responsible coordinator. As conflicts may exist at the initial slot request deadline (multiple booking of slots) a balancing of capacity demand and supply is required within the so called initial coordination. Coordinators may retime (reschedule) slot requests to meet capacity restrictions. Then alternative slot times – for the same day usually – are proposed. Second best option to resolve conflicts is a complete rejection of slot requests. The latter is inevitable if no adequate rescheduling proposal is available.

The initial coordination of slots is carried out using administrative priority criteria as described in Article 8 of the Regulation. The key rule specifies that a series of slots will be assigned to an airline for the upcoming season again if it had been used at least 80% in the previous equivalent season (winter or summer). This rule is known as use-it-or-loose-it rule, 80/20 rule or grandfather rights. Lower priority is granted to airlines that comply with conditions for being considered as new entrant at that specific airport. After processing all slot requests the airport coordination office informs the airlines about the results at the initial slot allocation. A coordinated schedule becomes available which meets all relevant capacity restrictions and which represents a feasible reference program for operations.

2.1.3. Post Initial Allocation Activities

Airport coordination continues after the initial slot allocation. Right after it the worldwide IATA Schedules Conference takes place. Representatives of airlines and airports as well as airport coordinators may negotiate slots, arrange slot amendments and alternatives and exchange slots (between airlines) in this conference. Schedules adjustments are carried out through bilateral discussions between airlines and coordinators. Due to the presence of worldwide airlines and coordinators the schedules conference is the main opportunity for schedules adjustments particularly if there is more than one airport/coordinator affected.

Council Regulation 95/93 allows for various ways to fine tune schedules. Schedules adjustments may continue not only until the start of the season but until the days of operations. While the aforementioned order of priorities is applied to meet capacity restrictions at the initial allocation, all additional schedule adjustments, slot requests and returns follow a first-come-first-served-strategy, e.g. by using waiting lists.

2.2. Performance Indicator: Scheduled Delays

A parameter to measure ATM performance in terms of 'access and equity' is to be based on the relevant developments during airport coordination. It needs to allow quantifying the feasibility to access the airport infrastructure as requested, building a basis to discuss the operational airport access with regard to a performance and quality aspect.

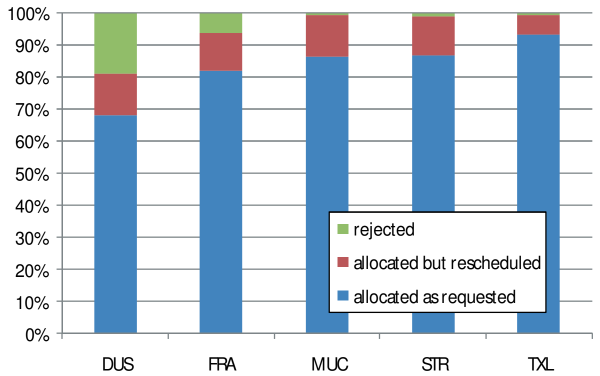

FIG. 1. Initial allocation: Proportion of rejected, allocated but rescheduled, allocated as requested slots

Conflict resolution which is required in periods of excess slot demand impacts on the feasibility to access airport infrastructure. If the number of slot requests exceeds the number of slots being available, slot requests will be coordinated by either a rescheduling (proposal of alternative slot time) or a complete rejection (cp. figure 1 for the proportion of requested slots being rejected, allocated but rescheduled and allocated as requested at German coordinated airports in scheduling seasons summer 2005 and winter 2005/2006). For such cases operational infrastructure access cannot be realised as requested: A different access time has to be accepted, or access is denied completely. Differences occur between internally planned schedules and allocated slots.

Variations described are to be considered by the indicator. To allow the quantification of such variations scheduled delays had been defined. Scheduled delays measure the difference between initially planned / requested and actual / allocated slot times. Being 'hidden' in schedules they remain abstract only. Scheduled delays are calculated as follows:

$$(1)\quad \delta_{s,i} = \left| t_{all,i} - t_{req,i} \right| [\text{min}]$$

with

$\delta_{s,i}$	Scheduled delay of allocated slot i
$t_{all,i}$	Allocated slot time of allocated slot i
$t_{req,i}$	Requested slot time of allocated slot i

Depending on the method of conflict resolution slot times may be postponed or may be brought forward. Scheduled delays measure the absolute value of differences between requested and allocated slot times only. Within this paper scheduled delays are measured at the initial allocation only and thus resulting from the initial coordination. In general the performance indicator may be determined at any stage of airport coordination which continues until the days of operations.

Equation (1) focuses on the rescheduling of slot requests but disregards slot rejections. Integrating the latter also is required to measure the feasibility to access an airport's infrastructure and thus to indicate the scheduling performance completely. Following the logic of this scheduling performance model approach a slot rejection would be equal to being delayed infinitely.

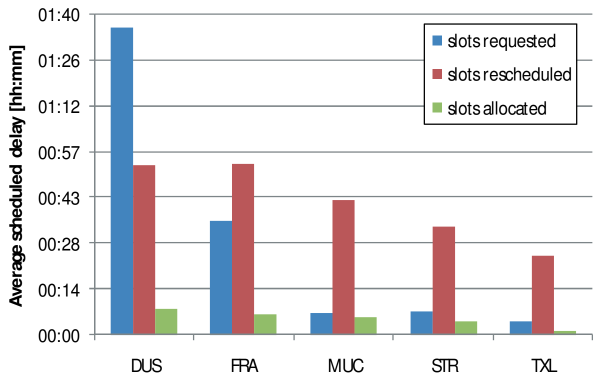

FIG. 2. Average scheduled delays of requested, rescheduled and allocated slots

Figure 2 displays average scheduled delays of requested, rescheduled and allocated slots at German coordinated airports in summer 2005 and winter 2005/2006. In theory, slots that are completely rejected suffer from infinite scheduled delays. To integrate rejected slots in the computation of scheduled delays for requested slots, instead of those infinite scheduled delays a standard value is used per definition: 8 hours. This value represents the required temporal shift to displace a slot being requested in the centre (2 pm) of the daytime period (6 am – 10 pm) from this time to the curfew hours out of consideration (10 pm – 6 am). This standardised value is used as scheduled delay for all slots being rejected.

2.3. Slot Utilization and Scheduled Delays

An airport scheduling performance may be analyzed using scheduled delays as performance indicator only. Analogous to common operational delay analyses several statistical parameters (average delay per slot, proportion of delayed slots, delay variability, delay maxima etc.) allow to evaluate the feasibility to access the airport infrastructure as requested. Nonetheless, additional information would be useful to address airport capacity and airport design issues by the use of scheduled delays, the interdependency between slot utilization (both system load – slot demand – and process output – slots allocated) and scheduled delays (scheduling performance / quality) in particular. Relevant parameters to discuss this relation are introduced in the current chapter. Additionally results of an empirical analysis of the airport coordination at German coordinated airports are demonstrated.

Conflict resolution within the initial coordination is restricted to single days of operations – slot requests will not be rescheduled to precedent or following days usually. Therefore, the interdependency between slot utilization and scheduled delays focuses on complete days of operations (Daytime hours 06:00 to 22:00 LT). Slot demand per day (process input) and slots allocated per day (process output) will be put into relation to the number of slots being available for allocation at that particular day. This allows calculating daily slot utilization ratios. Finally, average scheduled delays per day build the counterpart required to demonstrate the interdependency between slot utilization and performance / quality indicator.

Declared capacity values of an airport form the basis of calculating the daily slot supply as the total number of slots being available at one day. Here following formula symbol is used for an airport's declared capacity values:

(2) $C_{i,z,k}$ [Slots / time interval]

with

C	Declared capacity value
i	Type of flight movement (ARR, DEP, TOT)
z	Duration of time interval (10, 30, 60 min)
k	Temporal position of time interval

		10min			30min			60min			Slot supply
	[Local Time]	ARR	DEP	TOT	ARR	DEP	TOT	ARR	DEP	TOT	06:00 – 22:00
TXL	06:00 – 22:00			8						40	640
DUS	06:00 – 21:00			10						40	635
	21:00 – 22:00			10						35	
FRA	06:00 – 14:00	9	9	16	23	25	43	41	43	80	1296
	14:00 – 21:00	9	9	16	23	25	43	42	45	82	
	21:00 – 22:00	9	9	16	23	25	43	42	50	82	
MUC	06:00 – 22:00	12	12	15				58	58	89	1424
STR	06:00 – 22:00	6	6	8				30	30	40	640

TABLE 1. Declared capacities at German coordinated airports; max. number of available slots (slot supply) – Source: Airport Coordination Germany (FHKD)

Table 1 depicts the number of slots being available for allocation purposes and declared capacities at German coordinated airports in summer 2005 and winter 2005/2006 scheduling season.

60 minutes declared capacity values for total movements are used to calculate the daily slot supply (daytime hours from 06:00 to 22:00 LT). 10 minutes and 30 minutes values control the slot demand concentration, but do not limit the maximum slot supply. Therefore, the latter is calculated as follows:

(3) $\Phi_{\mathrm{TOT},d} = n_d * C_{\mathrm{TOT},60}$ [Slots / day]

with

$\Phi_{\mathrm{TOT},d}$	Number of available slots (total movements) at day d
n_d	Number of daytime hours at day d

Figure 3 displays the daily slot supply $\Phi_{\mathrm{TOT,d}}$ at German coordinated airports in the period under investigation.

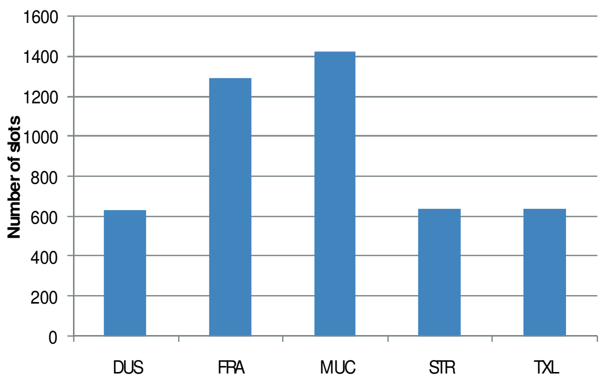

FIG. 3. Daily slot supply $\Phi_{\mathrm{TOT},d}$

Besides airport declared capacity values the number of slot requests (for ARR, DEP and TOT) is the second relevant input parameter for airport coordination:

(4) $D_{\mathrm{req},i,z,k}$ [Slots/ time interval]

with

D_{req}	Number of slot requests (demand requested)

Daily slot supply $\Phi_{\mathrm{TOT},d}$ and the number of slot requests per day $D_{req,\mathrm{TOT},d}$ allow determining the slot utilization factor $\rho_{\mathrm{req,TOT},d}$ at the initial slot request deadline (5). $\rho_{\mathrm{req,TOT},d}$ measures the system load and indicates demand excess on a daily basis. For $\rho_{\mathrm{req,TOT,d}} > 1$ some slots at least have to be rejected as the total number of slot requests exceeds the total number of available slots (slot supply).

(5) $$\rho_{\mathrm{req,TOT},d} = \frac{D_{\mathrm{req,TOT},d}}{\Phi_{\mathrm{TOT},d}} \ [-]$$

with

$\rho_{\mathrm{req,TOT},d}$ Utilization of available slots at initial request

As a result of the initial coordination slots will be allocated. The following formula symbol represents the total number of slots being allocated at the initial allocation:

(6) $D_{\mathrm{all},i,z,k}$ [Slots/ time interval]

with

D_{all} Number of allocated slots (demand allocated)

Analogous to (5) a slot utilization factor $\rho_{\mathrm{all,TOT},d}$ may be determined being based on the number of allocated slots (7). $\rho_{\mathrm{all,TOT},d}$ indicates the process output. If no rejections of slot requests are required during the initial coordination it will be $\rho_{\mathrm{all,TOT},d} = \rho_{\mathrm{req,TOT},d}$.

(7) $$\rho_{\mathrm{all,TOT},d} = \frac{D_{\mathrm{all,TOT},d}}{\Phi_{\mathrm{TOT},d}} \text{ [-]}$$

with

$\rho_{\mathrm{all,TOT},d}$ Utilization of available slots at initial allocation

After defining slot utilization factors $\rho_{\mathrm{all,TOT},d}$ and $\rho_{\mathrm{req,TOT},d}$ an adequate scheduling performance indicator is required to demonstrate the interdependency between those parameters. As conflict resolution focuses on full days of operations slot utilization factors $\rho_{\mathrm{all,TOT},d}$ and $\rho_{\mathrm{req,TOT},d}$ use a full day time basis accordingly. For a reasonable matching the performance indicator would need to feature this same attribute. Therefore average scheduled delays per allocated slot are calculated as follows:

(8) $$\bar{\delta}_{s,d} = \frac{\sum_{1\le i\le D_{\mathrm{all},d}} \delta_{s,i}}{D_{\mathrm{all},d}} \text{ [min / slot]}$$

with

$\bar{\delta}_{s,d}$ Average scheduled delay per allocated slot at day d

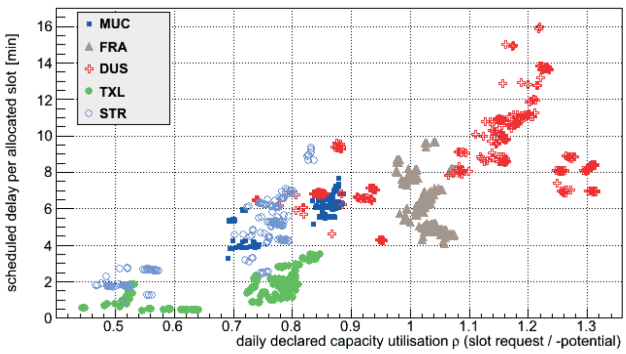

FIG. 4. Average scheduled delays vs. slot utilization at initial request

In figure 4 average scheduled delays (8) are related to slot utilization factors at the initial request (5) at German coordinated airports for every day in the scheduling seasons summer 2005 and winter 2005/2006. The dimension of required demand coordination in the form of rescheduled slot requests depends on the slot utilization and thus on the level of capacity scarcity and slot shortage. Average scheduled delays per allocated slot rise if slot utilization increases.

3. DEFINITION OF A MODEL TO PREDICT SCHEDULED DELAYS

In the following chapter, we introduce a deterministic approach to determine scheduled delays. This approach concentrates on modelling airport coordination with both coordination parameters and slot request as input parameters. An iterative solution of the initial coordination is adopted.

The main idea is coordinating all requested slots of every single day twice (from beginning to end and from end to beginning) of a given period. Considering a microscopic point of view, requested slots are moved one by one to the next coordination unit in chronological order as long as an airport's declared capacity is violated. A single slot's time displacement has to be measured as a scheduled delay, if the slot can be allocated. A non allocated slot has to be rejected and its scheduled delay discarded. The average scheduled delay per allocated slot is then calculated as mentioned in (8) where

$$\delta_{\mathrm{model},\,d} := \sum_{1\le i\le D_{\mathrm{all},d}} \delta_{s,i} \text{ [min].}$$

Slots are a priori indistinguishable in the model approach. The only priority respected is the amount of each slot shift. The more often a slot has been shifted, the higher its priority is to be shifted into the next coordination unit. This is caused by the fact that the number of slot requests exceeds the number of available slots in the present interval. The airport coordinator allocates slots in consideration of airport's declared capacity. In addition, he uses priorities such as grandfather rights, new entrant's privilege and the preference of slots requested in the whole season. Due to a lack of additional data on coordination decisions, we only focus on declared capacity values as input parameters.

It has to be pointed out, that the model approach is generic, but in this analysis, we only focus on slots requested in daytime (06:00 to 22:00 LT).

German airports use a ten minutes time span as the smallest coordination unit. If k = 06:00, 06:10, …, 21:50 denotes the coordination unit,

(9) $\mathbf{D}_{\mathrm{req},i,d} = (D_{\mathrm{req},i,k=06:00,d}, D_{\mathrm{req},i,06:10,d}, \ldots, D_{\mathrm{req},i,21:50,d})$ [Slots / time interval]

with i = ARR, DEP the number of requested slots at day d and the period z = 10, 30, 60 [min] of the considered coordination parameter, the k^{th} rolling block is defined as the sum of all slot requests within the next z minutes

$$f_{z,i}(k) = \sum_{j=00:10}^{(z/10-1)*00:10} D_{\mathrm{req},i,k+j} \quad \text{[Slots / time interval]}$$

with $f_{z,\mathrm{TOT}}(k) = f_{z,\mathrm{DEP}}(k) + f_{z,\mathrm{ARR}}(k)$.

Some airports differentiate declared capacity $\boldsymbol{C}$ [Slots/time interval] by arrivals and departures; furthermore, declared capacity values may change in the daytime. Coordinated flights have to be conform to coordination parameters (y = ARR, DEP, TOT) anytime; with

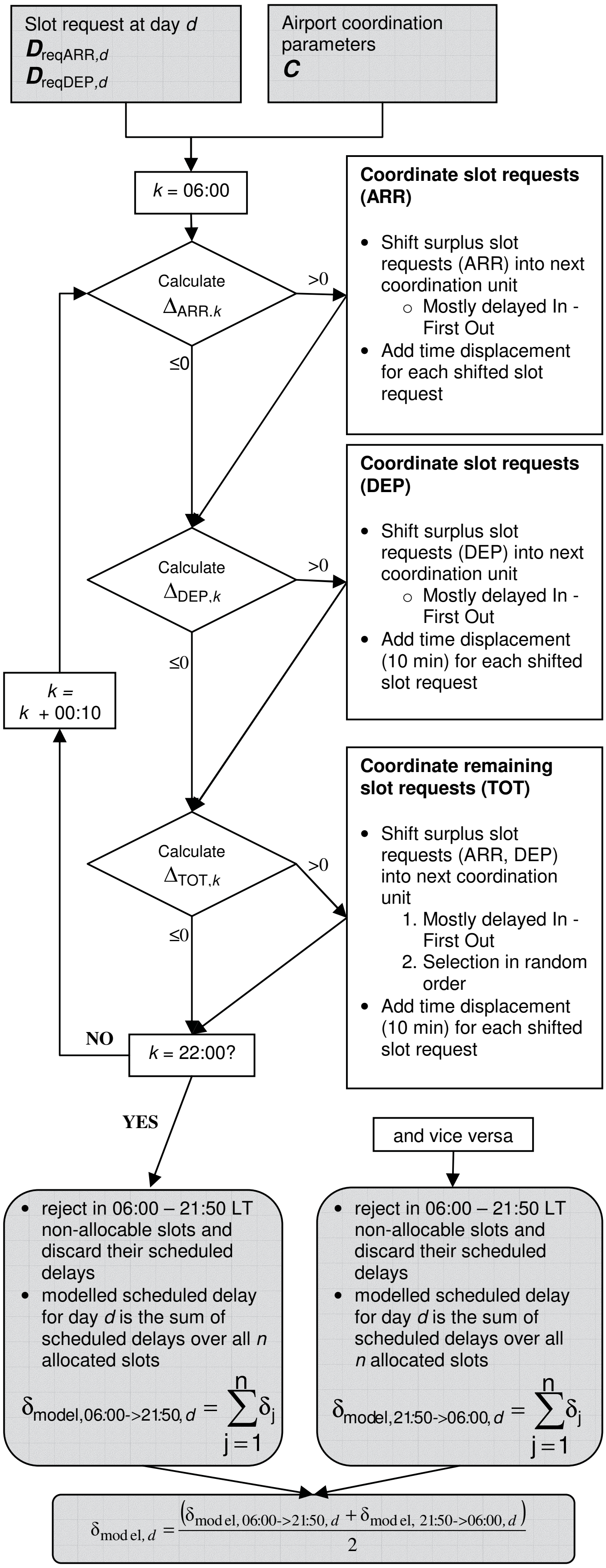

FIG. 5. Model approach: Initial allocation

$$(10)\quad \boldsymbol{C} = (C_{y,z,k}) = \begin{pmatrix} C_{ARR,10,k} & C_{ARR,30,k} & C_{ARR,60,k} \\ C_{DEP,10,k} & C_{DEP,30,k} & C_{DEP,60,k} \\ C_{TOT,10,k} & C_{TOT,30,k} & C_{TOT,60,k} \end{pmatrix}$$

[Slots / time interval]

the slot availability in the k^{th} coordination unit is then

$$(11)\quad \Delta = (\Delta_{y,z,k}) = \begin{pmatrix} \Delta_{ARR,10,k} & \Delta_{ARR,30,k} & \Delta_{ARR,60,k} \\ \Delta_{DEP,10,k} & \Delta_{DEP,30,k} & \Delta_{DEP,60,k} \\ \Delta_{TOT,10,k} & \Delta_{TOT,30,k} & \Delta_{TOT,60,k} \end{pmatrix}$$

[Slots / time interval]

where $\Delta_{y,z,k} = f_{z,i}(k) - C_{y,z,k}$.

In every single coordination unit k

$$\Delta_{ARR} := \begin{cases} \max(\Delta_{ARR,10}; \Delta_{ARR,30}; \Delta_{ARR,60}), & \max(...) > 0 \\ 0, & \text{else} \end{cases}$$

arrivals,

$$\Delta_{DEP} := \begin{cases} \max(\Delta_{DEP,10}; \Delta_{DEP,30}; \Delta_{DEP,60}), & \max(...) > 0 \\ 0, & \text{else} \end{cases}$$

departures and

$$\Delta_{TOT} := \begin{cases} \max(\Delta_{TOT,10}; \Delta_{TOT,30}; \Delta_{TOT,60}) - \Delta_{ARR} - \Delta_{DEP}, & \max(...) > 0 \\ 0, & \text{else} \end{cases}$$

arrivals or departures have to be shifted into the next interval;

(12) $\Delta_y > 0$ correspondes to excess slot demand,
(13) $\Delta_y < 0$ corresponds to excess slot supply

with y = ARR, DEP, TOT.

One should keep in mind that slots are requested by designating on block and off block times (gate times), but coordinator uses runway times. Arrival on block times are adjusted by a standard taxi times of -5 minutes, a departures off block times by +5 minutes at German airports (except FRA and MUC +10 minutes) [7].

Figure 5 represents the functional principle of modeling the initial coordination. The slot request ($\boldsymbol{D}_{req,ARR,d}$ and $\boldsymbol{D}_{req,DEP,d}$) is allocated on the available capacity (from 06:00 to 21:50 LT and vice versa). Therefore, a single slot's time displacement is be measured as δ_j (1), if the slot can be allocated. The modelled scheduled delay per day $\delta_{model,d}$ is the arithmetic mean of the following scheduled delays: $\delta_{model,06:00\text{->}21:50,d}$ and $\delta_{model,\ 21:50\text{->}06:00,d}$.

4. VALIDATION OF THE MODEL APPROACH

The model approach can be validated by available airport coordination data (summer 2005 and winter 2005/2006 scheduling seasons at TXL, DUS, FRA, MUC, STR).

Figure 6 describes the arithmetic mean of 100 iterations of the scheduled delay per allocated slot per day $\bar{\delta}_{model,\,d}$ (8). The standard deviation is taken into account as a statistical error due to this model approach's randomness (see figure 5: Selection in random order (TOT)). However, the statistical errors are quite small. The difference between modelled and actual average scheduled delays $\bar{\delta}_{model,\,d} - \bar{\delta}_{real,\,d}$ is illustrated in figure 7; $\bar{\delta}_{real,\,d}$ is defined as in (8) (see also figure 4).

We specify the following three areas of interest for the utilization of available slots at initial request ρ (5):

1) **$0.95<\rho\leq 1.32$**
It is obvious that there is a significant difference between modelled and actual scheduled delays at daily declared capacity utilization levels exceeding 0.95. In contrast to the expectation, modelled scheduled delays decrease due to the fact that our model approach follows a "Mostly delayed In - First Out" strategy. Especially when the amount of requested slots exceeds the amount of available slots considerably, requested slots are shifted from the beginning to the end. Thus, in our model, requested slots with highest scheduled delays are rejected at the end of the observation period. In contrast to our model, the national airport coordinator allocates slots bearing in mind several priorities and hence allocates fewer slots (here: with higher scheduled delays). Figure 8 points out the differences between the model approach and the real allocation in the quantity of allocated slots. The optimal ratio between an airport's available capacity per day (slot potential) and the number of allocated slots is represented by the bisecting line in figure 8. Differences between real allocation and model approach ($0.95<\rho\leq 1.32$) are evident and lead to a qualitative incorrect result. Therefore, we have to exclude this area from our analysis in regard to previous limitations.

2) **$0.84<\rho\leq 0.95$**
While the model approach allocates more slots with lower scheduled delays than the national airport coordinator in the area of $0.95<\rho\leq 1.32$, scheduled slots at DUS are mainly weekend-slots here. Slots being requested for a whole week can be coordinated consistently, even if there is no need to shift them on weekends. Therefore, our approach shows a small amount of quantitative discrepancies.

3) **$\rho\leq 0.84$**
The results of the model approach are consistent with actual data except for a systematic uncertainty of approximately

$$(14)\quad \sigma_{\bar{\delta}_{model,d}} = \text{-1:15}\pm\text{0:02 [min]};$$

estimated by using Least Squares Method for $\rho\leq 0.84$, sum of squares / ndf = 550.6 / 847.

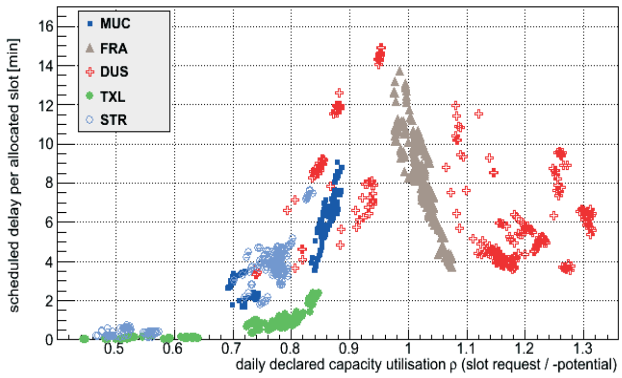

FIG. 6. Modelled scheduled delays $\bar{\delta}_{model,\,d}$ based on declared capacity utilization at the initial request

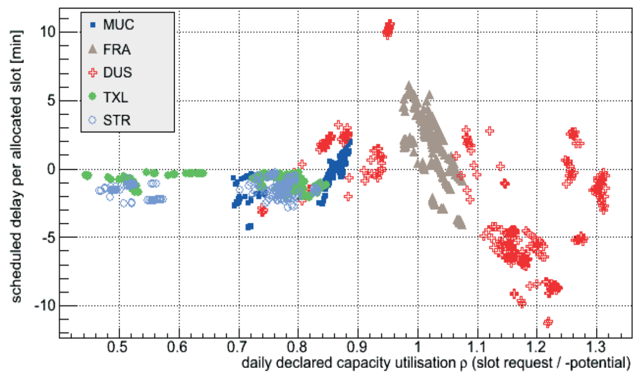

FIG. 7. Difference between modelled and actual average scheduled delays: $\bar{\delta}_{model,\,d} - \bar{\delta}_{real,\,d}$

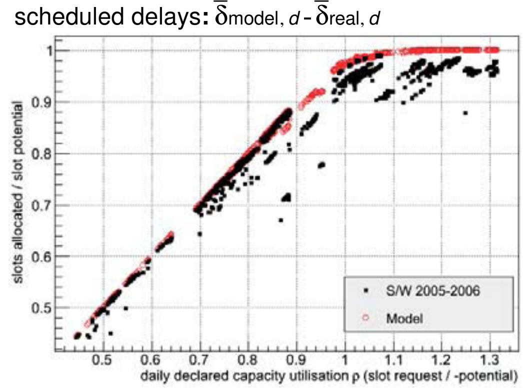

FIG. 8. Number of allocated slots: Model approach vs. initial allocation

In conclusion, it may be assumed that model accuracy is limited as a result of excluding relevant parameters which form the basis of initial conflict resolution decisions. Being the focal parameter of the initial coordination and conflict resolution decisions this is related to historical priorities of slot requests (grandfather rights) in particular. Thus available airport coordination data does not allow modelling the decision process completely.

Nevertheless, limited data restrains model approach's scope of application to a daily declared capacity utilization of $\rho<0.95$. It gives acceptable results for $\rho<0.95$. A utilization of $\rho<0.95$ is basically the field of interest if estimated scheduled delays should be used for airport planning and design issues.

5. APPLICATION OF THE MODEL APPROACH

Scheduled delays allow quantifying and measuring an airport's scheduling performance. Indicating its incapability and insufficiency to cope with the slot demand, this criterion can be used to deal with airport capacity and design issues.

Besides a retrospective scheduling performance analysis, existence of a model to predict scheduled delays extends the field of possible usage of the indicator. Future developments may be forecasted to determine maximum capacity utilization ratios still complying with predefined scheduling performance standards. This allows quantifying the required slot supply and thus minimum declared capacity values. Actual coordination results can be benchmarked towards an ideal model case to detect reasons for variations. Finally by using the model the impact of different initial coordination input parameters on the scheduling performance may be analyzed. The latter will be under consideration in the following.

So far the model approach is limited to the initial slot demand and declared capacity values as input parameters. Thus in this chapter we discuss the effects of different slot demand profiles (5.1.) and varying capacity restrictions (5.2.) on the scheduling performance. Characterizing the initial slot demand by a typical demand profile, we focus on the relation between scheduled delays and capacity utilization ρ for a given airport. Afterwards variation of declared capacity restrictions shows an overall influence on scheduled delays.

5.1. Analyzing the Impact of Different Demand Profiles on the Scheduling Performance

Here 'demand profile' is defined as the developing of demand volumes over the day. At different airports demand profiles may vary depending on airport function (e.g. hub vs. origin / destination airport), on capacity utilization resulting in constant demand volumes, on market segments (intercontinental, international, domestic flights) and on varying passenger needs (business, leisure, tourist). The alternation of peak and off-peak periods within the demand profile is characteristic at every airport. Although slight differences occur from day to day and between weekdays and weekends in particular, 'typical demand profiles' exist over one season at least.

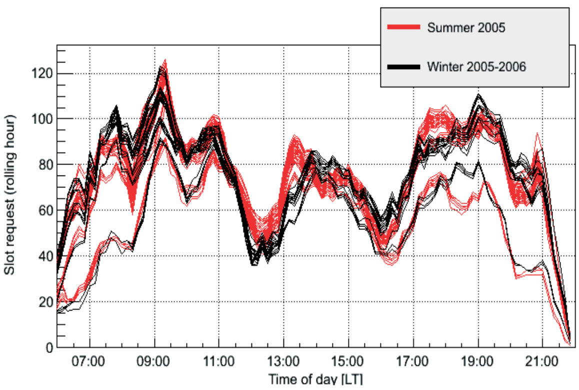

FIG. 9. Total slot request in rolling hours (MUC)

Exemplarily in Figure 9 is shown the bandwidth of total slot requests in rolling hours at MUC. Only slots requests from 06:00 – 22:00 LT are respected.

The following section (5.1.1.) describes how to deduce a "typical demand profile" with actual data for each German slot coordinated airport. This allows demonstrating the relation between scheduled delays and capacity utilization ρ for each typical demand profile (5.1.2.).

5.1.1. Typical Demand Profiles

Since slot requests differ significantly between summer and winter season, we only concentrate on one season (here: summer season). This is not a limitation, since the coordination of an actual summer season depends on the equivalent previous season. The demand profile is optimized for airport planning purposes and coordination activities by taking only weekdays in account.

Assuming that an airport's slot demand has a local structure, the magnitude of slot requests for a single day depends on individual factors such as the day of the week, peak seasons (e.g. holidays) and also inaccessible airline decisions. Scaling every single demand curve $\boldsymbol{D}_{\text{req,ARR},d}$ and $\boldsymbol{D}_{\text{req,DEP},d}$ with $\boldsymbol{D}_{\text{req},i,d}$ = $(D_{\text{req,i},06:00,d}, D_{\text{req,i},06:10,d}, \ldots, D_{\text{req,i},21:50,d})$] (9) for each considered day d by its total slot request $D_{\text{req,TOT},d}$ (4) and taking the arithmetic mean in every coordination unit (06:00, 06:10, … , 21:50) results in a standardized

$$(15)\ \text{“typical demand profile” } \mathbf{TDP} = \begin{pmatrix} \boldsymbol{TDP}_{\text{ARR}} \\ \boldsymbol{TDP}_{\text{DEP}} \end{pmatrix}.$$

[Slots / time interval]

As slot requests are summed up in ten minutes intervals according to a coordination unit of ten minutes (06:00 … 21:50), $\boldsymbol{TDP}_i$ (i= ARR, DEP) is a vector with dim($\boldsymbol{TDP}_i$) = dim($\boldsymbol{D}_{\text{req},i,d}$) = 96. Arrival and departure daily slot requests are evaluated separately regarding to divided arrival and departure coordination parameters.

If $\boldsymbol{TDP}_i$ describes the typical demand profile vector, the standardized typical slot request $(TDP_i)_k$ in the kth coordination unit (k = 06:00, 06:10, …, 21:50) is

$$(16)\ (TDP_i)_k = \frac{1}{n}\sum_{d=1}^{n}\frac{D_{\text{req},i,k,\text{d}}}{D_{\text{req,TOT,d}}} \quad ,\ i = \text{ARR, DEP}$$

with a total slot request at day d

$$(17)\ D_{\text{req,TOT},d} = \sum_k D_{\text{req,ARR,k},d} + D_{\text{req,DEP,k},d}\,.$$

The use of the arithmetic mean requires the estimation of errors on $\boldsymbol{TDP}_i$. The typical demand profiles $\boldsymbol{TDP}(Q_{0.15})$ and $\boldsymbol{TDP}(Q_{0.85})$ concerning 0.15- and 0.85-quantiles of given demand $\boldsymbol{D}_{\text{req},i,d}$ are considered as systematic errors.

A typical demand profile for Munich airport is shown in figure 10. For a better overview, the typical demand profile is represented with standardized total movements in rolling hours and therefore is not standardized itself.

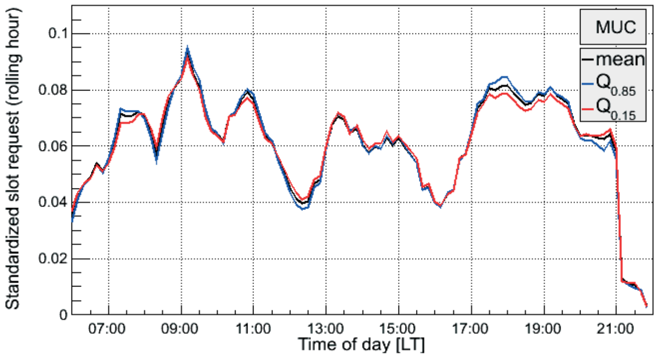

FIG. 10. Typical demand profile (rolling hours) at MUC

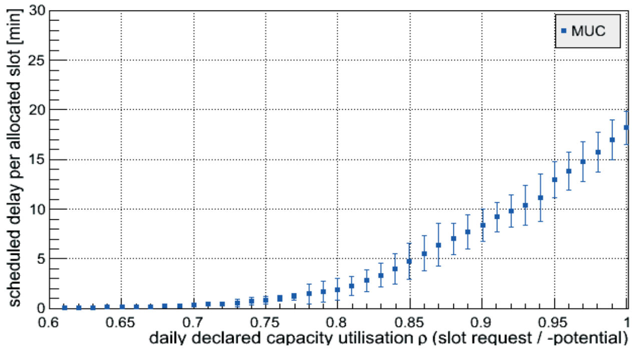

FIG. 11. Predicted scheduled delays at MUC

5.1.2. Prediction of Scheduled Delays

The expectation is that different demand profiles lead to specifiable estimated scheduled delays. The model approach is now applicable to typical demand profiles ***TDP*** which are multiplied by a slot request $D_{req,TOT}$. The daily declared capacity utilization ρ is defined as in (5)

$$(18)\ \rho_{req,TOT} = \frac{D_{req,TOT}}{\Phi_{TOT}}\ [\text{-}]$$

with number of available slots per day Φ_{TOT} as mentioned in (3).

Taking systematic errors on $\boldsymbol{TDP}_i$ into consideration, the propagated systematic uncertainty σ_{sys} on estimated scheduled delays δ_{model} is

$$\sigma_{sys} = \max(|\delta_{model}(\boldsymbol{TDP}(Q_{0.15})) - \delta_{model}(\boldsymbol{TDP})|,$$

$$|\delta_{model}(\boldsymbol{TDP}(Q_{0.85})) - \delta_{model}(\boldsymbol{TDP})|).$$

Therefore, the total error on δ_{model} is

$$\sigma_{\pm} = \sqrt{\sigma_{stat}^2 + \sigma_{sys}^2}$$

where σ_{stat} is the standard deviation of arithmetic mean δ_{model}. σ_{stat} respects modeling approach's randomness with 100 iterations (see figure 5: Selection in Random Order).

Estimated scheduled delays for a typical slot request are described exemplarily for MUC in figure 11. The estimation is valid for ρ≤0.95. The systematic error of $\sigma_{\bar{\delta}_{model,d}}$ = -01:15±0:02min in is not included in these plots.

Scheduled delays are already estimated for DUS, FRA, MUC, STR and TXL and a different run of estimated scheduled delay curves for different typical demand profiles was observed. In this case, the results hit our expectations. Since systematic uncertainties of the typical demand profiles are conservative assessed, propagated errors on estimated scheduled delays are quite large.

5.2. Analyzing the Impact of Declared Capacity Values on the Scheduling Performance

Chapter 5.1 describes the influence of varying demand (with given declared capacity restrictions) on scheduled delays; the following chapter evaluates the effect of different declared capacity values ***C*** (10) (with given slot demand patterns) on scheduled delays.

Various combinations of declared capacity values ***C*** are used at German coordinated airports (table 1). These absolute declared capacity values are based essentially on the number of available slots (total movements) per day $\Phi_{TOT,d} = n_d * C_{TOT,60}$ (3), as the number of daytime hours n_d is fixed to 16 hours (06:00 – 22:00 LT). As $C_{TOT,60}$ differs for investigated German airports, we consider the

$$(19)\ \text{“Restrictiveness”}\ R_{y,z} := \frac{60\text{min} \cdot C_{y,z}}{z[\text{min}] \cdot C_{TOT,60}}\ [\text{-}]$$

for each declared capacity value $C_{y,z}$ with y = ARR, DEP, TOT and z = 10, 30, 60 min (see 10).

Therefore, different declared capacity values $C_{y,z}$ for different airports are comparable and can be evaluated as “more restrictive” or “less restrictive”:

For example, as MUC has a ratio of 10 minutes declared capacity and 60 minutes declared capacity of

$$R_{TOT,10,MUC} = \frac{6 \cdot C_{TOT,10,\ MUC}}{C_{TOT,60,\ MUC}} = 1.01$$

and DUS $R_{TOT,10,DUS} = \frac{6 \cdot C_{TOT,10,\ DUS}}{C_{TOT,60,\ DUS}} = 1.5$,

MUC is quite more restrictive to its 10 minute's declared capacity value than DUS.

Assessing maximal effects of coordination parameters on scheduled delays, we concentrate only on restrictive values of coordination parameters. Practically, the lowest analysed ratio R (19) of a coordination parameter at German airports (table 1) is used in the following.

Using the rations R (19), we are free to define a fictive slot request of $D^*_{req,TOT}$ = 1600 (17) movements a day and a hourly total declared capacity (10) $C^*_{TOT,60}$ = 100. Since the estimated scheduled delay is measured as a relative quantity (estimated scheduled delay *per slot*) this does not have any effect on our results and is for rounding purposes only.

Concerning $C^*_{TOT,60}$ = 100, restrictive values are evaluated from German airports (table 1) to

	deduced from:
$C^*_{TOT,10}$ = 17, restrictive	MUC
$C^*_{TOT,10}$ = 25, non restrictive	DUS
$C^*_{ARR,10}$ = $C^*_{DEP,10}$ = 10	FRA
$C^*_{TOT,\,30}$ = 54	FRA
$C^*_{ARR,60}$ = $C_{DEP,60}$ = 53	FRA

where e.g.

$$C^*_{TOT,10} = R_{TOT,10,\,MUC} \cdot \frac{C^*_{TOT,60} \cdot 10\,\text{min}}{60\text{min}} = 17\ .$$

After having defined the declared capacity values $\boldsymbol{C^*}$ as one of the two input parameters for our model approach, we scale the (normalized) typical demand profiles (15) to the fictive slot request of $D^*_{req,TOT}$ = 1600 movements a day (17). Therefore, the diversified slot demand patterns for German coordinated airports are respected in our model. The effect of varying the declared capacity values on estimated scheduled delays for a given demand pattern can now be studied using our model approach.

With respect to the combinations of declared capacity values used at German coordinated airports, we define the following scenarios

1) $C^*_{TOT,60}$
2a) $C^*_{TOT,60}$, $C^{*\prime}_{TOT,10}$ (non restrictive)
2b) $C^*_{TOT,60}$, $C^*_{TOT,10}$ (restrictive)
3) $C^*_{TOT,60}$, $C^*_{TOT,10}$, $C^*_{ARR,10}$, $C^*_{DEP,10}$
4) $C^*_{TOT,60}$, $C^*_{TOT,10}$, $C^*_{ARR,10}$, $C^*_{DEP,10}$, $C^*_{TOT,30}$
5) $C^*_{TOT,60}$, $C^*_{TOT,10}$,, $C^*_{ARR,10}$, $C^*_{DEP,10}$, $C^*_{TOT,30}$, $C_{ARR,60}$, $C^*_{DEP,60}$
6) $C^*_{TOT,60}$, $C^*_{TOT,10}$, $C^*_{ARR,10}$, $C^*_{DEP,10}$, $C^*_{ARR,60}$, $C^*_{DEP,60}$

where all other as the mentioned capacity values are set to infinity.

Estimated scheduled delays per slot for a given scenario of declared capacities and derived demand patterns (chapter 5.1.1.) for declared capacity utilisations $0.6 \leq \rho \leq 0.95$ (5) can now be estimated using our model approach.

In order to make the different demand profiles comparable, those scheduled delays per slot are summed up for $0.6 \leq \rho \leq 0.95$. As those absolute cumulative values (of in $0.6 \leq \rho \leq 0.95$ integrated scheduled delays per slot) are not of interest, Scenario 1 is normalized to the sum of estimated scheduled delays per slot in $0.6 \leq \rho \leq 0.95$.

Figure 12 describes the (relative) change ($\frac{scenario\ x}{scenario\,(x-1)}$) of the sum ($0.6 \leq \rho \leq 0.95$) of the estimated scheduled delays per slot relative to the scenario numbered lower (scenario (x-1)) (where x is the number of the scenario). For example (scenario 2b), applying a quite restrictive ten minutes total declared capacity as MUC has (to an airport with a demand profile as FRA has) would lead to a four times higher scheduled delay as without this declared capacity value (cp. scenario 1). For example (scenario 4), applying an additional total 30 minutes declared capacity value to airports where already restrictive capacity restrictions as in scenario 3) exist, has no effect additional effect on scheduled delays at all.

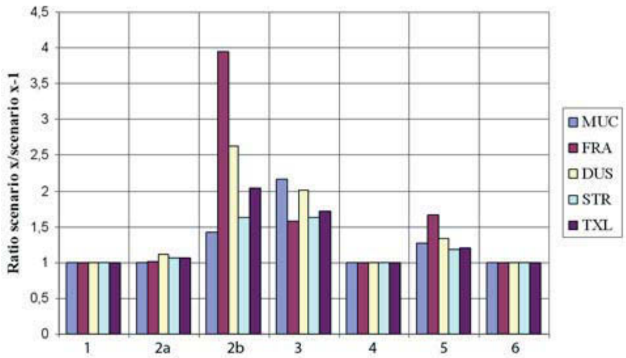

FIG. 12. Influences of additional capacity restrictions (from scenario x to x-1): Multiplicity of scheduled delay per slot in actual scenario x with respect to the scenario lower numbered (x-1)

It is obvious that a declared capacity value $C_{TOT,10}$ increases scheduled delays if it is too restrictive (scenario 2b). A non restrictive 10 minute coordination parameter as used in DUS has nearly no effect on scheduled delays (scenario 2a). Additional 10 and 60 minutes arrival and departure coordination parameters can double the scheduled delay (scenarios 4 and 6). 30 minutes declared capacity value $C_{TOT,30}$ has no effect on scheduled delays (scenario 5) while its importance is limited on keeping the quality of service during operations high.

6. RESUME

Scheduled delays allow indicating an airport's incapability and insufficiency to cope with the slot demand. By a retrospective scheduling performance analysis scheduled delays may contribute to addressing airport capacity and design issues therefore.

Within this paper a model was introduced to predict scheduled delays depending on the level of declared capacity utilization. This extends the field of possible usage of the indicator. Future developments may be forecasted to determine minimum declared capacity values still complying with desired scheduling performance standards. Also actual coordination results could be benchmarked towards an ideal model case. Here the impact of relevant initial coordination input parameters on the scheduling performance have been analyzed exemplarily: Demand profile and declared capacity restrictions.

Due to limited data availability the introduced model approach excludes some crucial parameters forming the base for the initial coordination: Priority categories of all slot requests in particular. Therefore model accuracy is sufficient for a limited capacity utilization range only ($\rho \leq 0.95$). Future research needs to aim at a full coverage of the decision process for conflict resolution during the initial coordination. Additional slot allocation data including priority categories would be required. To calibrate and finally validate a model approach being enhanced accordingly, data is needed to cover several scheduling seasons at different coordinated airports.

7. REFERENCES

[1] ICAO (Ed.): 'Global air traffic management operational concept', Doc. 9854, First edition, p. D1-D2, Montreal 2005.

[2] Dempsey, P. S.: 'Airport landing slots: Barriers to entry and impediments to competition', in: Air and Space Law, Volume 26, Number 1, February 2001, p. 20-48.

[3] Council Regulation (EEC) No 95/93 of 18 January 1993 on common rules for the allocation of slots at Community airports. Office Journal L 14, 22.1.1993, p. 1, Brussels 1993. As amended in 2002, 2003, 2004.

[4] Performance Review Commission (Eurocontrol) (Ed.): 'Report on punctuality drivers at major european airports', report commissioned by the Performance Review Commission, p. 5-17, Brussels 2005.

[5] Airport Council International – European Region (Ed.): 'Study on the use of airport capacity, an ACI Europe study, p. 1-2, Brussels 2004.

[6] Ulrich, C.: 'How the present IATA slot allocation works', in: Czerny, Gillen, Forsyth and Niemeier: 'Airport slots – international experiences and options for reform', p. 9-21, Hampshire 2008.

[7] Kösters, D: 'Airport scheduling performance – an approach to evaluate the airport scheduling process by using scheduled delays as quality criterion', proceedings of ATRS annual world conference, Berkeley 2007.

[8] IATA (Ed.): 'Worldwide scheduling guidelines', 14th edition, Montreal 2007.