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Priority rules as a concept for the usage of scarce airport capacity

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Abstract

The limited capacity available at airports regularly leads to an imbalance between supply and demand at busier airports. It is the runway systems at such airports which often set limitations on the number of possible flight clearances. In addition, existing systems of regulation sometimes use strategic resource allocation as a condition for access to specific infrastructure, as for instance the airport slot allocation in accordance with EU Regulation 95/93 and its amendments in Europe.

These regulation systems do indeed restrict the number of demanded slots to a level which the capacity can, on average, handle, but this alone cannot prevent unnecessary waiting times before customers are served. One reason for this can be temporary fluctuations in the capacity on offer (e.g. due to weather influences) and another is deviations from the forecast demand (e.g. due to delayed departures or short-notice changes to flight routes of an aircraft). Today's system applies a first-in-first-out system in allocating runway capacity to demand in the form of planned flights. In order to treat all flights equally, deficits in utilization of the available slots are accepted.

The concept presented in this Paper allows user-driven priorities to be set and true-to-schedule user behaviour to be promoted. It furthermore enables prioritization of high-profitability flights during clearance in cases where there are capacity deficits.
We show which runway system prioritization is suitable in aviation to increase efficiency in resource utilization. We present KPIs which would be required by an airport to make this effect appropriately measurable.

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Keywords: airport capacity; slot allocation; performance indicator; resource efficiency; transport performance; priority rules

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1. Introduction

Forecasts regarding the future development of air transport show that in Europe in the year 2035, the most probable scenario will be that 1.2 million flights per year will have to be cancelled, mainly due to a lack of runway capacity (Eurocontrol 2013). The flights which can be performed will have to operate at airports and on runways with significantly higher workloads than exist today. Through the higher degree of utilisation, the system will then become more sensitive to disturbances, e.g. the weather, which will lead to noticeably increased delays in the current operation. On the other hand, initiatives such as ACARE are striving towards being able to clear all flights within one minute of their planned arrival time, irrespective of the weather conditions (ACARE 2011). In order to fulfil future requirements, priority-based management procedures could help limited infrastructures. In the present study, concepts are being developed and evaluated which allow the prioritisation of incoming flights with regard to the criteria of transport performance, slot quality and slot adherence. Performance indicators are being developed for the assessment of the quality of the rescheduling results. Simulation scenarios are evaluated which process a real data-based pseudo demand for a runway with ICAO-based separation values under differing prioritisation strategies.

Nomenclature

AFD	airborne flight delay	FIFO	first in first out
AMAN	arrival manager	PPSA	Pre-selected Priorities and Slot Adherence
DMAN	departure manager	STA	scheduled time of arrival
ASD	airborne seat delay	TD	total delay
ATA	actual time of arrival	TSD	total seat delay
ASM	available seat miles	WVC	wake vortex category
ETA	estimated time of arrival		

2. Materials and methodology

2.1. Prioritisation strategies

Aircraft are usually handled according to the so-called FIFO principle. The order of arrival at a managed resource hereby directly decides the order of service; the first to arrive is also the first to be served. The application of the FIFO strategy is regarded as generally non-discriminatory, as the order of service requests is largely independent of the individual characteristics of the airlines. In the local management of heavily utilised infrastructures, the strict interpretation of the FIFO principle is waived in favour of improved resource utilisation possibilities. For example, the local sorting of the arrivals and departures at airports, taking into account the separation-relevant weight classes, enables an increase in the maximum number of movements to be processed compared to the FIFO arrivals, which are sorted independent of weight class. This management is achieved through arrival and departure management systems (AMAN/DMAN) (Zammit-Mangion, Rydell et al. 2012), whereby the renunciation of the strict FIFO regime is locally limited and is motivated by a mutual increase in the overall benefit.

The renunciation of the FIFO principle in, by and large, disregard of the industry-typical freedom from discrimination [see (Mensen 2013)] does, however, require an explanation at this point. Non-discrimination in the air transport sector is ultimately - and quite rightly - viewed as a precious asset. This study is able to demonstrate the potential for the differentiation of the air traffic users in the demand for service on the scarce resource runway and how a sufficient degree of non-discrimination could nevertheless be established.

For the investigations into the application possibility of priority-based operating systems at airports, two completely different methods have been used. On the one hand, the transport performance of the flights was used as a prioritisation criterion; on the other hand, a procedure was simulated which balances a user-driven prioritisation against its own plan compliance. As the slot allocation procedure in accordance with EU Regulation No. 95/93 or the IATA Worldwide Slot Guidelines (International Air Transport Association 2017) would have to be changed for the latter, the alternative slot allocation model with pre-selected priorities and slot adherence monitoring (PPSA) will be referred to from now on.

Table 1. Scenario selection

Scenario name	Queue policy
FIFO	first in first out
ASM	max. available seat miles
#3…#11	pre-selected priority and slot adherence

2.1.1. Transport performance as prioritisation criterion [see (Knabe and Schultz 2016)]

The performance capability of the runway systems of airports is usually stated in flights per unit of time. The standard prioritisation procedures also use flights as units. From the point of view of transport performance, however, flights differ considerably in their significance for the overall transport system. In (Knabe and Schultz, 2016), the indicators of transported seats per time unit and transported seat miles per time unit were introduced as the first approach to the extended evaluation of the transport capacity of runways. In compliance with this, for the prioritisation to be performed here, the sum of the transported seat miles for each flight is calculated as a prioritisation criterion. The calculation is performed linearly through multiplication of the seats of the aircraft type by the great circle distance between source airport and destination airport (OpenFlights 2015).

In the case of two or more flights awaiting service, the resultant prioritisation strategy always favours the flight with the highest seat miles.

2.1.2. PPSA categories as prioritisation criterion [see (Grunewald 2016)]

In (Grunewald 2016), the concept for the introduction of priority-substantiated airport slots was presented. Slots discretise the capacity of regulated airports planned for allocation in order to, in particular, limit a high demand to the operationally feasible level. From all interested parties, those will be selected at the strategic level who can then actually operate. Due to stochastic processes between the time of planning and the execution of the flight, waiting times can occur due to competing, simultaneous service requests. This is possible as the allocation of airport slots grants solely the general right of use; this right is, however, not stringently linked to a specific time at the point of execution. At best, a certain degree of consistency is desired, without, however, publishing comprehensible limits for the verification of compliance (European Union Airport Coordinators Association). This is aggravated by the fact that airport slots reference the on-block and off-block time, whilst the actually scarce resource is typically represented by the runway system. Operational deviations from the plan - even if the plan has been designed to be flyable with absolutely no conflicts - lead in reality to differing entry sequences, from which a conflict-free arrival sequence must be formed through separation. Despite limiting demand to an average accepted level, there is therefore a corresponding average delay, which must be regarded as a traffic-related level of service (Kösters 2010). PPSA replaces the previously universal slots with slots of differing priorities p. In the present example, two different priority classes are used, which represent the preselected prioritisation at the strategic level. Each flight which has been allocated a PPSA slot therefore reaches the airport vicinity with the priority $p_{slot}=1$ or $p_{slot}=2$, whereby priority class 1 has the highest rank. In the area of the arrival airport, it is then decided as to whether the originally selected priority can be retained. This is the case when the requesting aircraft arrives within a punctuality time window. Then $p_{slot} = p_{effective}$ applies. If the aircraft arrives significantly too early or too late at the regulated resource, it undergoes a devaluation of its priority as a penalty. An original priority of $p_{slot}=1$ becomes $p_{effective}=3$, priority $p_{slot}=2$ becomes $p_{effective}=4$. For reasons of clarity, the in (Grunewald 2016) opportunity for revaluation of the devaluated priorities of requesters arriving too early, who become punctual merely by waiting in a low-ranking position, is waived in the present evaluation. The total incoming traffic is here divided into four different classes $p_{effective}$. In line with the queueing theory, the operating system would receive a quadruple-parallel waiting space, which would be split according to priority classes. Within one priority class, the familiar FIFO procedure would be applied for sorting. That aircraft will now be served (selected for landing) which heads the queue due to having the highest priority. Queues for incoming traffic will, of course, be mapped through appropriate flight manoeuvres (holding patterns) and the air traffic controller has the task, as in the current system, of creating the correct order. The priorities thereby determine the average expected waiting time as a function of temporal demand and the operating capacity of the runway. The parameterisation of the PPSA procedure has, as expected, a considerable influence on the prioritisation process and therefore on the operating performance indicators of each prioritisation category. In the simulations, various parameters were selected exemplarily and combined with one another; the area of investigation could, of course, still be extended considerably. All simulations based on a variation of the PPSA procedure carry the identifiers #3 to #11 (nine variations) in the evaluations. As an example, the definition of punctuality was varied as its own contribution to system optimisation. Both the too-early and too-late arrival were sanctioned, as both cases are likely to interrupt carefully planned conditions and a balanced demand-capacity situation. Furthermore, the offer of slots was varied in terms of share per category and distribution amongst the requesters. In some cases, the slots were strategically allocated in such a way that they always switched (as regards STA) between the priority $p_{slot}=1$ or $p_{slot}=2$ (the process of this allocation procedure is not addressed; solely a fictitious result is assumed). In other scenarios, blanket prioritisation was carried out by means of the wake vortex category (WVC) of the aircraft. Aircraft of the highest WVC (SH for Super Heavy, H for Heavy) were thereby allotted the highest priority $p_{slot}=1$, whilst all other aircraft received the priority $p_{slot}=2$. As a causality exists between the WVC and the ASM (aircraft with higher WVC have, on average, more seats and are typically used on longer distances), these scenarios represent a practice-oriented variant of the strict ASM-prioritised scenario.

Table 2. PPSA scenario parameters

PPSA scenario ID	Punctuality *window begins*	Punctuality *window ends*	scheduled priorities
#3	STA - 1 h	STA + 5 min	alternating (1;2)
#4	STA - 1 h	STA + 10 min	alternating (1;2)
#5	STA - 1 h	STA + 15 min	alternating (1;2)
#6	STA - 10 min	STA + 5 min	alternating (1;2)
#7	STA - 10 min	STA + 10 min	alternating (1;2)
#8	STA - 10 min	STA + 15 min	alternating (1;2)
#9	STA - 10 min	STA + 5 min	WVC*
#10	STA - 10 min	STA + 10 min	WVC*
#11	STA - 10 min	STA + 15 min	WVC*

*Super Heavy, Heavy: $p_{slot} = 1$; Medium and less: $p_{slot} = 2$

2.2. Validation scenario

For the validation, a scenario with traffic demand in the form of successive landings on one runway is created within an airport-in-a-lab environment. For this, recorded traffic data from the London Heathrow airport with 19858 approaches from the month of March 2013 are extracted from DDR2 data sets from Eurocontrol (Eurocontrol 2014) and processed to create a pseudo demand. The last flight path points of a flight available there were introduced into the simulation as desired landing times ETA. With the ETA times, both the FIFO and the ASM strategies can be applied. The PPSA strategies additionally require STA values, which were generated as pseudo STA values from the ETA. For this purpose, a triangular distribution is applied (upper limit +30 min, lower limit -30 min, peak +5 min) in order to randomly generate generic STA. The output of the simulations, namely the landing occurrence of each aircraft following the prioritisation, is then (again) referred to as ATA. Compared to the source data, a completely alienated flight plan was therefore generated. Time Based Separations based on ICAO minimum values and a safety buffer of half a nautical mile were applied for the serving of the demand in the airport-in-a-lab scenario. Together with the high demand, this resulted in an artificial, very high demand-to-capacity ratio in the laboratory environment, in order for the prioritisation strategies to be employed as often as possible.

Table 3: Time-based separations by wake vortex categories

	leading aircraft			
trailing aircraft	SH	H	M	L
SH (super heavy)	77 s	77 s	77 s	77 s
H (heavy)	156 s	113 s	77 s	77 s
M (medium)	177 s	136 s	79 s	79 s
L (light)	197 s	157 s	136 s	79 s

2.3. Performance indicators

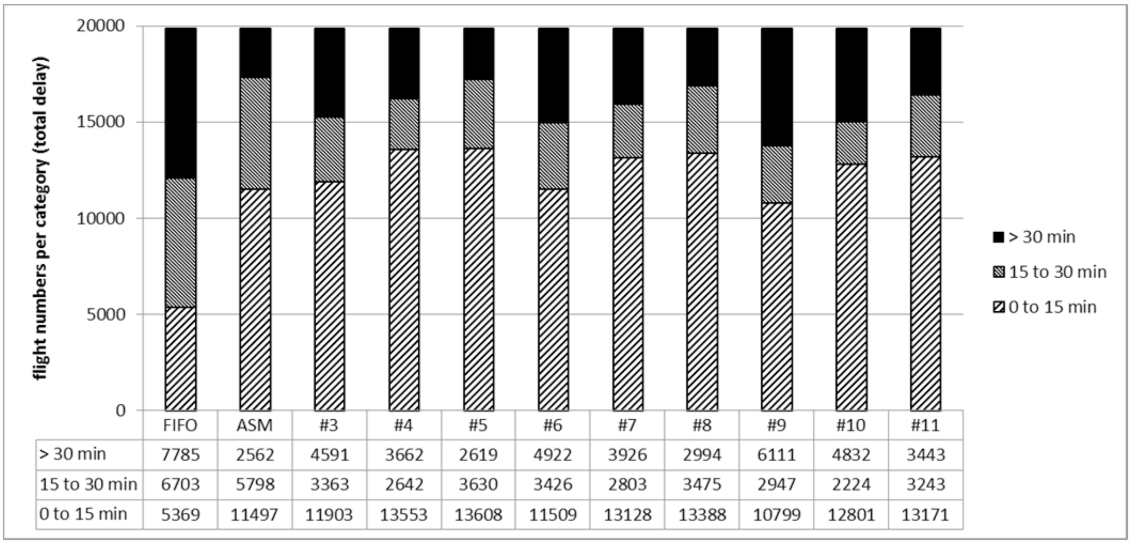
This paper examines the performance capability of prioritisation principles in the case of the operation of a runway. From a transport perspective, traffic throughput and effective delays are of particular relevance. The flight plan borrowed from the reality is also executed completely as a pseudo demand in all simulated scenarios. Through utilisation of the low-load night hours, all requesters are always served; sometimes, however, with impractical individual delays. The influence on the achievable traffic throughput can therefore not be assessed, as demand is capped. Instead, particular attention is paid to the quality of the operation. For each scenario, a comparison is made of the amount of additional delay which would be produced if the assumed demand were to occur in exactly the form in the reference flight plan. From the difference between ETA and ATA, the Airborne Flight Delay AFD is calculated for each planned flight. However, as the aircraft arrive at the destination airport with differing amounts of delay and, for example, connecting flights or ground transport modes, which need to be reached, are linked to one another on the basis of planned values, it is equally important to find out how the prioritisations affect the overall punctuality. This balance of STA and ATA, known as Total Delay TD, therefore supplements the approach. In the case of negative indicators, both AFD and TD are set to zero in order to rule out an effect-reducing influence of the too-early arrival on the mean value formation. These two delay values for TD and AFD are applied in the aircraft-related analysis of the effects. From the perspective of the passengers, this may seem unfair, as a different quantity of passengers could be affected per flight. The Total Seat Delay TSD and Airborne Seat Delay ASD indicators represent the respective corresponding products of available seats and aircraft delay. The evaluation of the delay values is accompanied by the comparison with aviation-standard benchmarks. The 15-minute criterion decides whether a flight is punctual or unpunctual. This punctuality is measured at the gate and not on the runway; a corresponding delay on the runway can, however, generally no longer be made up for by the time of reaching the gate position. Furthermore, a 30-minute benchmark exists. This value is derived from the requirement of the flight planning, which states that flights should carry enough reserve fuel for a 30-minute holding pattern. Airborne waiting times which go beyond this therefore potentially pose a risk of emergency caused by fuel shortages.

2.4. Simulation setup and execution

For the simulation of the prioritisation criteria, an event-based solution is applied from the Anylogic software. Geographical and spatial influences do not play a role in this process; instead, the elements of demand flow, holding patterns and service points (runway) are modelled in accordance with the queueing theory. As a result, the simulation provides the actual time of the landing (ATA) for each flight, taking into account the separation distances according to the corresponding wake vortex category (see Table 2) of the aircraft classes. The key performance indicators can be calculated from the documentation of STA, ETA and ATA.

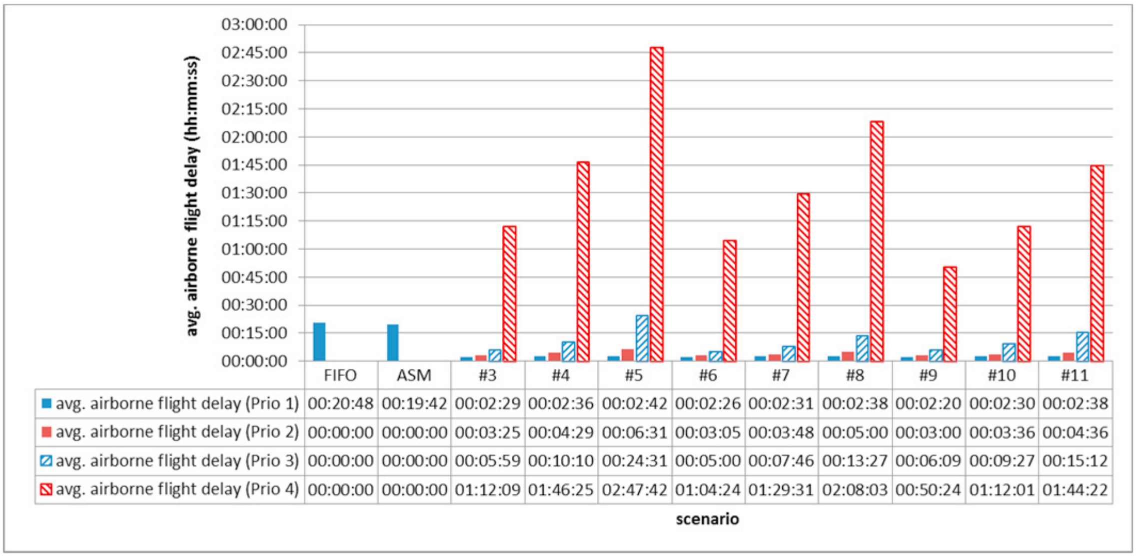
3. Simulation results

The differing strategies for the prioritisation of the incoming aircraft generate different amounts of airborne flight delays. Despite their very different philosophies, all tested prioritisation scenarios lead to increased volumes of more punctual aircraft. Whilst in the FIFO reference case only a good third experienced a maximum of 15 minutes' delay in the approach, this number doubled in more or less all other scenarios. The number of aircraft with 15 to 30 minutes' airborne delay was always also greatly reduced. The relatively low number of even more severely delayed arrivals also moved towards the desired direction of an improvement in punctuality. The downside of the success is the enormously increased individual waiting times for those who had to wait a long time. In some cases, waiting times of several hours occur. When the delays brought in from the generically generated flight plan are added in, it can also be shown that the prioritisation always at least doubled the proportion of the arrivals which were delayed by up to 15 minutes (see Fig. 1). Even though the traffic situation has been intensified, it may be assumed that this effect would also be achieved, albeit to a lesser extent, in more realistic traffic scenarios. The mean value of the additionally generated delay (airborne flight delay) is 20 minutes 48 seconds in the reference case. Prioritisation according to seat miles (ASM) leads to a reduction of one minute; the PPSA scenarios tend towards slightly higher values. The advantage of the ASM method is astonishing, as the delay was measured by plane (and not by seat). One explanation is tangent to the principle of an AMAN/DMAN-controlled airport. The prioritisation according to available seat miles ASM exhibits a statistical dependency on the aircraft size; high ASM are achieved by large aircraft. Large aircraft, in turn, have a large wake vortex category WVC and have to be further separated from following, smaller aircraft for safety reasons. With prioritisation according to ASM, throngs of the same WVC are more often formed than with FIFO; this has a capacity-increasing effect - recognizable in the shorter waiting times. The PPSA sorting does not optimize the wake vortex separation and therefore generates a similar amount of delay - on average. The special feature of the procedure is shown here in the differentiated distribution of the delays across the users. Even in particularly demanding traffic times, the majority of the aircraft accrue only very slight delays. The victims are the aircraft with the lowest priority. These are the ones which had already been afflicted with a low-priority slot which they had then missed. Their sanctioning with, in some cases, a very long delay leads to an alleviation of tension for all other requesters. Depending on the parameterisation of what is considered to be punctual and how the pre-selected slots have been assigned, the majority of the requesters benefit from extremely slight delays. Analogous to the delays of airborne flight delay AFD and total delay (TD), which reflect the delay situation by plane, the observation can also be focussed with a view to the affected passengers. In Fig. 3, the cumulative delay is represented for each possible passenger (available seat as the closest value; no generalised multiplication with load factors or similar elements). In the FIFO scenario, each flight accumulated an average of 2.97 days (!) of airborne seat delay ASD. The goal of reducing this value on a sustained basis is best achieved, unsurprisingly, by the ASM procedure, with an average of 2.08 days of ASD. The PPSA procedures #3 to #8, in which the arrival slots were alternately assigned according to STA, exhibit values of slightly more than three days. When the ASM and PPSA procedures are mixed by favouring larger aircraft during the slot allocation through higher priorities (#9 to #11), the result is correspondingly averaged ASD values of approx. 2.5 days. Ultimately, the sharply split image is once again shown in the distribution of the ASD according to priority. Values in the hour range on the side of high-priority requesters, compared to almost 13 days' ASD (in case #7) for the lowest priority. In the prioritising scenarios, there is a clear specification as to who should be awarded preference in the event of competing requests. All these variants therefore tend towards a differentiation of the waiting times. One group receives only a very slight delay, the other group all the more. This behaviour, which is also predicted in the queueing theory, must be taken into account in an application in air traffic. The extreme values for the delays are clearly not acceptable from the operational point of view. Incorporated into a sound prediction method for traffic demand, however, they offer a misinterpretation-proof indication as to which flight should not even request service at the destination airport due to a lack of prospect of success. These particularly affected flights could wait for a favourable take-off opportunity at the departure airport (cheaper than in the air) or approach an alternative airport without a detour from the original destination.



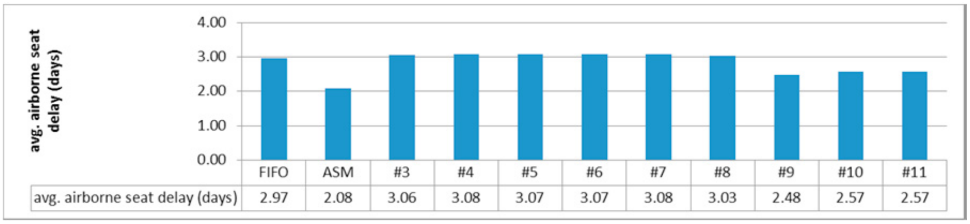
	FIFO	ASM	#3	#4	#5	#6	#7	#8	#9	#10	#11
> 30 min	7785	2562	4591	3662	2619	4922	3926	2994	6111	4832	3443
15 to 30 min	6703	5798	3363	2642	3630	3426	2803	3475	2947	2224	3243
0 to 15 min	5369	11497	11903	13553	13608	11509	13128	13388	10799	12801	13171

Fig. 1. General influence of queue policy on total delay distribution



	FIFO	ASM	#3	#4	#5	#6	#7	#8	#9	#10	#11
■ avg. airborne flight delay (Prio 1)	00:20:48	00:19:42	00:02:29	00:02:36	00:02:42	00:02:26	00:02:31	00:02:38	00:02:20	00:02:30	00:02:38
■ avg. airborne flight delay (Prio 2)	00:00:00	00:00:00	00:03:25	00:04:29	00:06:31	00:03:05	00:03:48	00:05:00	00:03:00	00:03:36	00:04:36
▨ avg. airborne flight delay (Prio 3)	00:00:00	00:00:00	00:05:59	00:10:10	00:24:31	00:05:00	00:07:46	00:13:27	00:06:09	00:09:27	00:15:12
▨ avg. airborne flight delay (Prio 4)	00:00:00	00:00:00	01:12:09	01:46:25	02:47:42	01:04:24	01:29:31	02:08:03	00:50:24	01:12:01	01:44:22

Fig. 2. Average airborne flight delay per scenario



	FIFO	ASM	#3	#4	#5	#6	#7	#8	#9	#10	#11
avg. airborne seat delay (days)	2.97	2.08	3.06	3.08	3.07	3.07	3.08	3.03	2.48	2.57	2.57

Fig. 3. Average airborne seat delay per scenario

4. Outlook

The path towards optimising the use of scarce airport infrastructures can, in accordance with the findings in this paper, also be followed via the prioritisation approach. Prioritisations result in a predictable selection in case of need. This expectation alone already holds economic advantages compared to the current procedure, in which occurring waiting times are distributed across all users. If a transparent prioritisation criterion is additionally created, this would certainly have an incentive effect. In the case of the PPSA method, this would affect the punctuality of the requesters, which would presumably improve in order to not be devaluated as regards priority. In the case of the ASM scenario, however, an incentive for larger aircraft would be created, which would - at least from the airport's point of view - be attractive, as revenue would increase. It is thereby clearly recognisable that the line between differentiation and discrimination is very narrow. It is therefore to be expected that a fundamental agreement on the elasticity of fairness would be necessary before such a system could come into effect.

A further research question for the future concerns the network-wide impact of such prioritisations on individual network nodes. A system-wide adaptation, including the airspace, would, after all, be conceivable in principle. As a driver for this approach, the trend towards intermodality and networked thinking could prove itself. The transfers between means of transport along a door-to-door travel chain make it necessary to provide reliable departure and arrival times, unless one acts as a purely stand-alone solution.

In particular the - in some cases - extreme delays for disadvantaged individuals in the prioritisation scenarios may perhaps appear discouraging at first glance. However, this is more an operational management tool for punctually rescheduling, cancelling or diverting such flights. The mitigation of this effect also appears conceivable. By means of a so-called constrained position shift procedure CPS (Balakrishnan and Chandran 2006), the maximum deferment within an operating system can be restricted. This allows the technical requirements to be complied with in order to further pursue the prioritisation idea with a reduced, but still inciting, effect.

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