BENEFITS OF PRIORITIZED USAGE OF SCARCE RUNWAY CAPACITIES

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1. SHORT ABSTRACT

Limited capacity at the busiest airports is a key driver for delays in commercial aviation. By introducing priority based resource allocation schemes, the provision of additional capacities at comparable levels of service becomes possible.

2. ABSTRACT

Limited capacity at the busiest airports is a key driver for delays in commercial aviation. Therefore, scarce infrastructure resources such as take-off and landing slots at international airports have long been the topic of many scientific investigations, for example by Gilbo (1993), Abeyratne (2000), Kösters (2007), and especially by n/e/r/a (2004), dealing with resource efficiency, equality, and welfare. According to IATA's Worldwide Slot Guidelines, strategic slot allocation already creates a limit on the total daily demand and at more granular intervals as required. However, the output of slot allocation and scheduling does not represent any ideal flight plan under real conditions. Instead, the traffic demand which arises during a day of operations, combined with the capacity actually available, thwarts any planning which is based on assumptions. In the existing air traffic system, this planning uncertainty is counteracted by way of a local resource allocation method, in order to find a satisfactory and primarily conflict-free solution. This local allocation takes into account the different possibilities which the arriving and departing aircraft have when creating control sequences. Essentially, arriving flights are regularly given preference over departing flights as a result of technical constraints, when these flights have to use the same or interdependent runways. Besides this, an adapted form of the first in, first out (FIFO) approach is applied. According to this, the operations at the runway are determined by the arrival at the regulated resource. Technical tools for influencing the take-off and landing sequences are available already at air navigation service providers. They can, however, only be used within very tight constraints in order to not breach the discrimination ban. That which would however be possible when utilizing the available capacities – when the air traffic system would allow a market-compatible differentiation – is demonstrated in this study.

Assuming that the slots allocated according to Regulation (EU) 95/93 have to be redeemed at the stated time - we show the effect on usable capacity. For effective improvements in capacity utilization, a differentiation of the commodity "slot" is proposed. The scientific discussion surrounding slot allocation has shown that slots have an economically measurable and differing value. Slots at attractive travelling times are more valuable than those at fringe times with falling demand. The value for each business might also be different and only airline managers can estimate this for their own fleet. However, none of this diversity is taken into consideration when resources are allocated at the airport. Based on the contribution from Grunewald et al. (2017), a close-to-reality simulation comes to bear which additionally allows both arriving and departing flights to be coordinated sensibly on the same runway and tolerates prioritization at the same time. We

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demonstrate by means of simulations the effects of different allocation modes at strategical level and at the day of operation on the available capacity, the quality of the traffic handling and discuss the incentivization effects of each approach. Best schemes maximize runway flow, punctuality or even connectivity. We use new indicators to highlight the outcome of different prioritization, for example to measure connectivity to and from ground based traffic.

The presented research is part of the Optimode project. Its aim is it to improve the intermodality of traffic hubs with a focus on passengers' door-to-door trajectory. The project proposes varieties of ways to establish true multi-stakeholder collaboration, between infrastructure and service providers, transportation service providers, and travelers. Runway slot allocation alteration as presented in this paper takes advantage of collaborative decision making and may help to improve customer's transfer to and from commuting traffic, including air travel, scheduled ground transportation, and individual mobility.

3. METHODOLOGY

The approach of this investigation lies in the variation of the slot allocation policy and/or in the variation of the allocation rules directly during the sequence processing. The variations are expressly non-compliant with the valid rules in aviation, which are based on the primary allocation in accordance with the respective law, but always in conformity with the IATA-WSG, as well as on FIFO-based sequence processing. At this point, we shall take the liberty of introducing a hitherto unconventional differentiation of the traffic clients and thereby investigate the possibilities for increasing the efficiency of scarce infrastructure services using the example of the scarce commodity "runway". Although the line between differentiation and discrimination is often narrow, examples from other industries exhibit similar differentiation mechanisms for mastering heavy capacity utilization of infrastructures, for example in toll-based traffic management on motorways.

3.1 Priority by first in, first out (FIFO)

The first in, first out method (Priority Policy FIFO) establishes the order of operations in dependence on the demanded service time. In the present case, this demand is generated when the flight appears within the area of the approach control or a start-up request is made. At this point in time, air traffic control will sort the flight into a planned take-off or landing sequence in dependence on its pre-calculated take-off or landing time. FIFO treats all participating flights equally. The advantage of FIFO is precisely this equal treatment on the basis of the individual flight. A major disadvantage is the lack of optimization possibility as regards capacity utilization over different temporal separation values between individual aircraft classes. At many airports, the FIFO principle is applied in modified form, i.e. position changes in the single-digit range do indeed take place both in landing approach and take-off in order to enable a higher throughput by virtue of lower separation rates. In this study, however, the pure FIFO method is applied in order to demonstrate the potential of the developed optimization strategies in comparison to a plausible reference case.

3.2 Priority by available seat miles (ASM)

With the FIFO strategy, each flight is treated like any other, regardless of whether it is an intercontinental flight with hundreds of passengers or a business flight with one or two passengers from a neighbouring airport. One possibility for taking into account such differences in sequence

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generation is the utilization of the transport performance of a flight as an optimization criterion (see Knabe and Schultz (2016)). The transport performance refers to the quantity of people or goods which are transported over a distance. The economic traffic importance of a slot usage by a flight can thereby be taken into account. In the case of a flight, the transport performance can be calculated approximately as the product of the great circle distance between source airport and destination airport and the number of passengers carried. The number of passengers carried is often a sensitive dataset for the airlines; the calculations performed here therefore use the number of available seats for the aircraft type, as this is generally accessible from the flight plan (available seat miles vs. revenue seat miles).

3.3 Pre-selected priority and slot adherence (PPSA)

In this scenario, in analogy to Grunewald (2016), slots are treated as differentiated goods during primary allocation. Instead of the universal commodity “slot”, product differentiations are now permitted. The entire available capacity of the airport (“declared capacity”) is thereby divided into an allocable quantity of slots, analogous to the proven IATA-WSG practice. In addition to the established procedure, these slots now also receive an attribute which makes decisions on prioritization in the event of scarcity. Which slots are thereby equipped with which attribute has a very significant effect on the attainable traffic events during the subsequent operations.

To clarify the principle, two product categories with the priorities p1=1 and p2=2 are sufficient. Slots are therefore assigned, for example, equally between the priorities p1 and p2, whereby p1 promises priority over p2. For reasons of simplification, we assume that slot categories are always assigned alternately in chronological order. The result of this primary allocation, which is not the subject of this investigation and whose result is only adopted as an example scenario, is implemented in such a way that the aircraft are alternately allocated the two primary allocation attributes in the order of demand. Were this method borrowed from reality it would, of course, have consequences for the airlines as regards the slots for which they would apply and for which flights. Instead, we take the randomly generated situation as given and assume that it is the result of a reasonably market-compliant regulatory mechanism concerning supply and demand.

Each flight in our example flight schedule reaches the regulated resource, the mutual take-off and landing runway, with a pre-selected priority in accordance with the primary allocation. In order to achieve an incentive-creating benefit from the product differentiation, in the case of demand for service, the punctuality of the customer is evaluated. The deviation from the planned slot produces the slot adherence. Depending on whether the actual demand time complies with the scheduled demand time, the effective prioritization of the individual customer is determined. With a prioritization of punctuality according to the flight plan, plan-loyal behaviour should be supported. The transfer of secondary delay to uninvolved airlines is hereby also avoided. This means that a delayed aircraft is not allowed to enter the queue in front of a punctual aircraft, thereby also delaying this aircraft. When assuming two slot categories in the primary allocation, four effective priorities arise with which customers are served. Customers who do not comply with slot adherence are devaluated in priority (from 1 to 3 or from 2 to 4). With the devaluation by two classes, it can be ensured that the pre-selected priorities remain in a relative relationship to one another, even in the case of devaluation.

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3.4 Pre-selected priority and slot adherence with timeout (PPSA-TO)

This procedure is an extension of the PPSA procedure described above. In addition to this, a timeout component is introduced which sets waiting-time limits for each class. Overly long waiting times for individual customers should thereby be prevented. When the waiting-time limit is reached, the customer moves into the new highest priority class “0”, which has precedence over all other classes. The timeout limits are 30 minutes for Priority 4, 20 minutes for Priority 3, 15 minutes for Priority 2, and 10 minutes for Priority 1. Through this separation in favour of higher prioritization, a moderate balance between the class-related waiting times and the prioritization effect should be created.

4. DATASET AND SCENARIO DESCRIPTION

For the investigation, a dataset from the London-Gatwick airport from March 2013 with a total of 18402 flight movements was used (Eurocontrol DDR2 dataset).

Table 1: Statistical values regarding aircraft seat size and available seat miles within flight plan

	seats	available seat miles
min	3	124
max	525	2143093
avg	160	185091
med	154	80838
stdev	61	321188

The majority of flights are scheduled to take place between around 6 and 24 o'clock; there are, however, a few flights during the night hours. We use the available data from recordings as a pseudo-demand; this means that we set the actually flown times as plan times and stochastically add a generic delay in order to achieve a stochastically distorted demand in the simulation. Whilst the flight plan used for the simulations is comparable to the real case Gatwick as regards quantity and structure, it does not compare with respect to its delay situation and the traffic management procedure, as these cannot be traced back from the result data. The stochastic individual delay for each individual aircraft is formed by randomly selected times of a triangular distribution (upper limit +30 min, lower limit -30 min, peak +5 min), as already utilized by Grunewald et al. (2017) In contrast to that analysis, however, this is a different airport with a one-way system and mixed operation, i.e. take-offs and landings on the same runway. This constellation requires the consideration of numerous separation intervals in order to safeguard radar and wake vortex separation between incoming and outgoing traffic.

In order to test the new procedures regarding their effects under differing workloads, two different separation matrices were applied. In the low-density scenario, separations in compliance with ICAO (2016) and v. Baren (2015) were used. In order to be able to use a scenario with significantly increased traffic load, we changed this separation matrix in such a way that larger separation spacings led to lower operating capacity. It was therefore possible to avoid the need to consolidate the real data-based flight plan through e.g. the cloning of individual flights.

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	Trail Arrival				Trail Departure			
Lead Arrival	SuperHeavy	Heavy	Medium	Light	SuperHeavy	Heavy	Medium	Light
SuperHeavy	110	152	172	192	60	60	60	60
Heavy	110	110	133	172	60	60	60	60
Medium	76	76	78	133	55	55	55	55
Light	76	76	78	78	50	50	50	50
Lead Departure								
SuperHeavy	65	65	65	65	120	120	180	180
Heavy	65	65	65	65	60	90	120	120
Medium	65	65	65	65	60	60	60	120
Light	65	65	65	65	60	60	60	60

Table 2: Time-based separations used in the scenario "low density" in [s] (separations in scenario "high density" are constantly 20% higher, e.g. 132 s instead of 110 s for Arrival Heavy / Arrival Heavy)

5. SIMULATION DESCRIPTION

For the evaluation of the different separation strategies, the model presented in the paper Grunewald et al. (2016) was further developed and extended through new functions. As it is once again a network model, the topology and geography of the airport are not considered.

The simulation determines the separation of the aircraft and ascertains the actual arrival and departure times based on the expected times. The consideration of both incoming and outgoing air traffic and the corresponding temporal spacings of their wake vortex classes has been added to the modelling. Simulatively, each of the 4 preceding separation strategies is respectively considered as a separate independent scenario.

The simulation period for the four scenarios runs from 1st March 2013 at 00:00 until 31st March 2013 at 23:59. During this period, 19129 flight movements take place at the simulated airport, which are divided into 9560 arrivals and 9571 departures. For each flight movement, a dedicated agent with corresponding parameters (callsign, time of arrival/departure, wake vortex class, seat miles, priority class...) is generated.

For the separation variants FIFO and ASM, the observed flights are injected into the network model during the simulation run on the basis of their time of arrival/departure, where they are placed in the waiting queue for runway usage, either in strict accordance with first in, first out or in compliance with the sorting using seat miles. As soon as an agent occupies the runway, the separation from the following agent, which is now the first element in the queue, is calculated on the basis of the separation matrix presented in chapter [x]. When clearance is granted for the runway, the agent leaves the network model and, when exiting, generates a dataset for postprocessing with the following values:

1. Flight_ID : consecutive unique number
2. Callsign : flight number
3. Seat_Miles : are determined by the simulation

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4. Date : simulation day on which the agent is created in the network model
5. Time : time of creation in the network model
6. incoming_seconds : point in time at which the agent leaves the waiting area
7. landing_time : point in time at which the agent leaves the waiting area to land
8. waiting_time : waiting time in the waiting area
9. real_separation : actual length of time which the agent must wait in order to maintain the separation.
10. schedule_separation : calculated temporal distance to predecessor
11. type : wake vortex class
12. seats : utilized seats
13. arr_dep : whether the flight is an arrival or a departure
14. prio_cluster : categorization of the flight in the corresponding priority class.

With the separation variants PPSA and PPSA-TO, sorting takes place according to the priority classes. For each of these classes, a dedicated waiting area is created; within these dedicated waiting areas, the agents are sorted in accordance with the first in, first out principle. For the separation, the following rules apply:

1. Firstly, the agents with the highest classification, Priority 1, receive access to the runway.
2. If no agent with Priority 1 is in the waiting area, the agents with Priority 2 are granted access.
3. If no agent with Priority 2 is in the waiting area, access is granted to the agents with Priority 3.
4. If no agent with Priority 3 is in the waiting area, the agents with Priority 4 are granted access.
5. The waiting areas are examined every second.

These rules apply to both PPSA and PPSA-TO. PPSA-TO is additionally extended through the following rules:

1. If an agent is in waiting area 4 for longer than 30 minutes, this agent is assigned the highest priority (0), which must be viewed as higher than Priority 1.
2. Agents in waiting area 3 are assigned Priority 0 after 20 minutes.
3. For agents in the waiting area, the assignment to Priority 0 applies after only 15 minutes.
4. Agents with Priority 1 are upgraded to Priority 0 after 10 minutes.
5. In this scenario, agents with Priority 0 are the first to be granted access to the runway.

The output in the variants PPSA and PPSA-TO is identical to that of the variants FIFO and ASM; the respective dataset is also generated when leaving the network model.

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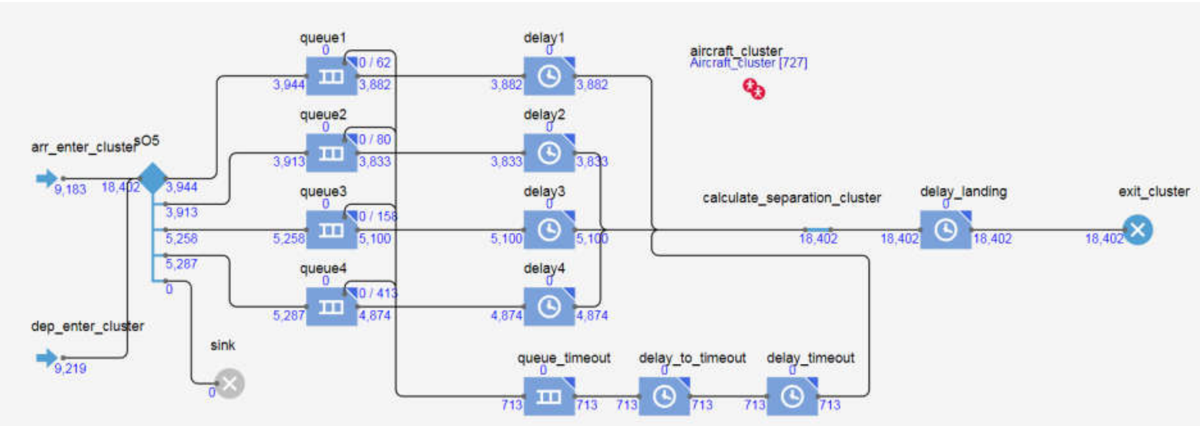

Figure 1: Network model PPSA-TO

The network model in Figure 1 shows the waiting areas queue1 to queue4 for the individual waiting areas to the corresponding priorities. To the left of these waiting areas is the quantity of agents who have entered this area. To the right, the quantity of agents that can leave the area again. The upper number in the right-hand area describes the quantity which, from the individual respective priorities, has been set to the highest priority 0. For Priority 1, this is 62 agents over the entire time period, for Priority 2, it is 80, for 3 it is 158, and for 4 it is 413. This results in a total of 713 agents who spent longer than the respective set maximum time in the waiting area for their priority.

In total, a dataset of 18402 entries was generated for each variant, which will be evaluated in the following chapter. Furthermore, 727 agents will be created whose generation time point lies outside the considered time horizon. This is due to the fact that for the relevant flights, the preceding or following station is served in the defined time period.

6. RESULTS

On the basis of the pseudo-demand situation, as we have generated based on real data from London-Gatwick airport with the aid of a randomly assigned individual delay for each aircraft (and which does not therefore represent real traffic events), the standard procedure in accordance with FIFO has, as expected, proved itself to be a balanced and moderate solution for the processing of the total demand. Whilst in the low-density scenario the new variants ASM, PPSA and PPSA-TO achieve comparable key performance indicators for average delay per flight and average seat delay per flight this is, however, accomplished at the expense of dispersion of the values, as can be seen from the (rarely occurring) maximum values of the delays. In addition, the results of PPSA and PPSA-TO are similar, as not one timeout for exceedance of the waiting time occurred. With a low workload, it is therefore not necessary to replace the FIFO procedure unless there are other cost advantages which have not been considered here, but which are also not expected.

For the high-density case, however, this changes significantly depending on the perspective. In this case, an average delay of 3 minutes 15 seconds per flight results when FIFO is applied. Heavily utilized airports regularly exploit their capacity in such a way that the average delay remains under 4 minutes; the flight plan used here, with larger separations, comes very close to such a situation. Giving preference to seat-quantitatively larger aircraft flying longer routes in the ASM scenario

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shows an effect here. The average accumulated seat delay exhibits the least increase here (0.276 days) despite a similar average delay per flight (≈ 0.63 to 0.38 days) for all variants FIFO, ASM, PPSA and PPSA-TO.

In contrast, when the priority classes in the variants PPSA and PPSA-TO are scrutinized, it can be seen that the punctuality assurance of the various priorities has been effectively implemented. In the variant PPSA, all customers with Priorities 1 and 2 are served within less than 15 minutes' waiting time following take-off or landing; for those with Priority 3, it is 99.8%, and for Priority 4 – the lowest priority – it is still 82.5%. The average waiting times for the Priorities 1, 2 and 3 lie significantly below the average waiting time for the reference case FIFO (3 minutes 15 seconds); solely Priority 4 results in a long wait for service. As a reminder: Priorities 3 and 4 were not primarily allocated, but instead represent downgrades for non-punctual use. Whilst the introduction of an additional waiting-time limit through the PPSA-TO procedure led to a slight improvement at the lower end of the priority scale, this was, however, at the expense of all other, better-placed priorities. The use of this method, which is related to the constrained position shift procedure in which a maximum position change may be granted in a shared queue (here, this has been replaced by class-differentiated timeout limits, due to a lack of a shared queue), can, on the basis of the simulation results, not be regarded as an improvement of the "pure" PPSA. However, such a procedure could function better if capacity gaps from those customers who renounce their demand prior to reaching the resource (cancellation or landing at alternate airport) could be exploited. In the simulation, this customer loss was not depicted. For a possible transfer into reality, however, this is precisely the point in which the added value of the procedure lies: the respective priority and the anticipated traffic load can be determined in advance and absurdly long expected waiting times could be used to revise the flight planning. Other users can make use of it and, depending on priority, prepare themselves for differentiated waiting times. If, in addition to the incentive to operate within an own slot time window, thereby reducing the variance of the demand diversification, a superordinate performance goal should be achieved, this could be organized within the primary allocation. Recurring slots with entitlement in accordance with "grandfather rights" could, depending on their own punctuality performance, be allocated with either the pre-selected Priority 1 (good performance) or 2 (bad performance).

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	Low density				High density			
	FIFO	ASM	PPSA	PPSA-TO	FIFO	ASM	PPSA	PPSA-TO
max. delay [hh:mm:ss]	00:11:00	00:40:20	00:21:37	00:21:37	00:50:55	09:50:21	02:26:37	10:11:29
avg. delay per flight [hh:mm:ss]	00:00:37	00:00:38	00:00:36	00:00:36	00:03:15	00:03:19	00:03:18	00:03:18
avg. seat*delay per flight [seat days]	0.068	0.065	0.066	0.066	0.361	0.276	0.365	0.375
movements with less than 15 minutes delay	**18402**	**18367**	**18375**	**18375**	**17573**	**17834**	**17468**	**17090**
movements total	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**
quote	**100.0%**	**99.8%**	**99.9%**	**99.9%**	**95.5%**	**96.9%**	**94.9%**	**92.9%**
movements with less than 15 minutes delay	**18402**	**18397**	**18402**	**18402**	**18149**	**18130**	**17911**	**17835**
movements total	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**	**18402**
quote	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**98.6%**	**98.5%**	**97.3%**	**96.9%**
movements PRIO 1 & <15 minutes delay			3944	3944			3944	3896
movements PRIO 1			3944	3944			3944	3944
quote			100.0%	100.0%			100.0%	98.8%
movements PRIO 2 & <15 minutes delay			3913	3913			3913	3822
movements PRIO 2			3913	3913			3913	3913
quote			100.0%	100.0%			100.0%	97.7%
movements PRIO 3 & <15 minutes delay			5258	5258			5249	5005
movements PRIO 3			5258	5258			5258	5258
quote			100.0%	100.0%			99.8%	95.2%
movements PRIO 4 & <15 minutes delay			5260	5260			4362	4367
movements PRIO 4			5287	5287			5287	5287
quote			99.5%	99.5%			82.5%	82.6%
movements PRIO 1 & <30 minutes delay			3944	3944			3944	3933
movements PRIO 1			3944	3944			3944	3944
quote			100.0%	100.0%			100.0%	99.7%
movements PRIO 2 & <30 minutes delay			3913	3913			3913	3894
movements PRIO 2			3913	3913			3913	3913
quote			100.0%	100.0%			100.0%	99.5%
movements PRIO 3 & <30 minutes delay			5258	5258			5258	5209
movements PRIO 3			5258	5258			5258	5258
quote			100.0%	100.0%			100.0%	99.1%
movements PRIO 4 & <30 minutes delay			5287	5287			4796	4799
movements PRIO 4			5287	5287			5287	5287
quote			100.0%	100.0%			90.7%	90.8%
avg. delay PRIO 1 [hh:mm:ss]	00:00:37	00:00:38	00:00:14	00:00:14	00:03:15	00:03:19	00:00:28	00:00:58
avg. delay PRIO 2 [hh:mm:ss]			00:00:19	00:00:19			00:00:43	00:01:28
avg. delay PRIO 3 [hh:mm:ss]			00:00:33	00:00:33			00:01:27	00:02:41
avg. delay PRIO 4 [hh:mm:ss]			00:01:08	00:01:08			00:09:09	00:07:02

Punctuality window for slot adherence was STA/STD -10 min to STA/STD +5 min.

Table 3: Simulation results

7. OUTLOOK

The examination of the efficiency of an operation on a scarce infrastructure such as a well-utilized airport is a prerequisite for deciding for or against expansion to secure sustainable competitiveness, as such measures generally take effect following an extremely long lead time. In order to exploit the available capacity, a priority-based resource allocation can, if necessary, be applied - provided that it is regulatorily legalized. With the tool of prioritization, economic aspects could be specifically

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managed which are not (yet) possible for the aviation market today. A consideration of the transport performance, as in the example based on the prioritization of available seat miles, would clearly have an incentive effect on the customer structure towards larger aircraft and towards longer distances. With a procedure such as the PPSA, which provides for differentiated priorities within the primary allocation, a more differentiated schedule planning, taking into account the necessary (and more predictable) buffer times, could be undertaken as early as the planning level. If the own punctuality in operations is then also included in the equation, a clear incentive to avoid delays is created. Due to the also omitted effect of "pushing in" a delayed customer into a queue, the transfer of secondary delays is effectively suppressed. The effect of this suppression of secondary delays on actually uninvolved customers constitutes a future investigation of the PPSA method, whereby the focus must then be directed upon entire cycles in order to be able to record all effects. An analysis of the necessary details for an associated primary allocation of slots would also be worthwhile. In this paper, a very simplified form has been adopted (alternate awarding of two priorities); primary allocation in particular thereby provides the key to management via the allocation mechanism which is to be determined.

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ISSN 2313-1853