Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Flight Prioritization and Turnaround Recovery

Integrating Tactical ATFCM Slot Swapping into Resource-Constrained Ground Operations

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Abstract*—The SESAR ATM Master Plan describes the goal to fully integrate airports into the ATM network, such that airspace user operations are facilitated and related user costs are reduced. The corresponding flight prioritization mechanisms of the user-driven prioritization process are in the process of being validated at several airports across Europe. This article studies the benefits of the underlying concept of tactical ATFCM slot swapping in relation to resource-constrained turnaround management of an airline. A case study at Frankfurt airport analyses different situations in which the airport is expected to operate with reduced capacity, such that a local hub carrier can prioritize its arrival (and departure) flights. Results indicate that arrival slot swapping in constraints is very efficient as long as fixed departure flights of the same aircraft obtain no critical delays for the downstream network. In our case study, such critical delays for the network occur at around 60 minutes of departure delay, such that flights which are assigned with higher delays require the additional flexibility of departure slot swapping in order to achieve significant cost reductions. We further find that optimal delay margins, which are calculated with our approach, suffice for the confidential communication of flight priorities, such that complex scoring and credit trading systems might be omitted. In exchange, we propose a secondary trading scheme, for which our model can define efficient slot prices while considering operational constraints of an airline.

***Keywords*—flight prioritization; slot swapping; user-driven prioritization process, turnaround management**

I. INTRODUCTION

The Ration-by-Schedule (RBS) principle is currently applied by Air Traffic Flow and Capacity Management (ATFCM) during periods of high airport or airspace sector capacity utilization (constraints) to allocate slot regulations to flights according to the First-Planned First-Served (FPFS) procedure. Despite continuous proposals to adapt or replace this principle, it is still operationally accepted for its qualities to minimize total delay in a constraint and preserve the equity of impacted airlines. However, RBS typically cannot minimize airline costs related to the allocation of ATFCM slots, such that alternative or complementary measures are still pursued by many research projects [1], [2].

For instance, the SESAR ATM Master Plan 2020 [3] describes the goal to facilitate airline operations and reduce their ATM related costs by achieving a full integration of airports into the ATM network. In this approach, airports are focused for their prominent position in airline network, being the nodes where aircraft, crew and passengers connect between subsequent flights. These interdependencies between flights imply a high risk of disrupting the airline network, which increases once some flights are subject to ATFCM regulations. This might be a reason why ground operations constituted the highest cause for primary departure delays in Europe in 2019. In combination with reactionary (i.e., secondary) delays, 77% of all delays in Europe have originated from or been passed on via airline ground operations [4]. Another 7.2% of delays are attributed to air navigation services at airports. Consequently, there is a high need to coordinate and improve tactical procedures in case of schedule deviations, such that ATFCM and airlines can equally benefit from the applied recovery principles.

A. Status Quo

A potential solution to grant airlines increased operational flexibility and reduce ATM related costs is the User-Driven Prioritization Process (UDPP) [5]. It has been developed in the SESAR framework and comprises several mechanisms which are intended for the prioritization of important flights by the airline during airport capacity constraints. Thus, airlines can define priority values for their flights in a constraint, such that the assigned slots can be swapped among them according to internal business interests (i.e., Fleet Delay Reordering (FDR) and Enhanced Slot Swapping (ESS)). Furthermore, an airline can decide to suspend one of its early flights in a constraint in order to protect the initially scheduled time of another flight (i.e., Selective Flight Protection (SFP)). The second mechanisms applies the Ration-by-Effort principle, such that the equity of other airlines (especially of non-participants) can be preserved even in case an airline wants to protect the initially scheduled time of a flight without any assigned slots during this period [6].

After initial validation, both mechanisms have been complemented with the option to assign time windows to flight, from which the assigned slot should not deviate. These so-called "margins" correspond to flight-specific delay cost profiles, which include step costs once downstream transfer

This project has received funding from the German Federal Ministry of Economic Affairs and Energy (BMWI) within the LUFO-V project OPsTIMAL under grant agreement No 20X1711M. Further funding was received from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 783287 (Engage KTN). The opinions expressed herein reflect the authors' views only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

connections or curfews are hit [6]–[8]. Recently, the second validation step was passed at SESAR level and has confirmed the potential of the UDPP mechanisms to reduce additional costs incurred by airlines during a constraint. At the same time, equity of non-users could be preserved, while airlines with many flights (e.g., the local hub carrier during a constraint at Paris CDG airport) gained additional flexibility [9]. Given the limited possibilities for airlines with few flights in a constraint to swap slots (which includes also large airlines at spoke airports in their network), the portfolio of mechanisms has been added by another option which allows equity transfer between several capacity constraints in the format of flexible credits [2], [10]. In contrast, for airlines with many flights in a constraint, it was concluded that they might need support in defining their individual flight priorities and margins.

The third validation step at SESAR level is already planned and will consider arrival capacity constraints at Zurich (ZRH), Paris (CDG) and Alicante (ALC) airports within a tactical setting, i.e., airlines need to define their priorities with a cut-off time of at least two hours prior to the estimated start of a constraint. The prioritization of departure flights is still out of scope of upcoming exercises.

B. Focus and Structure

Based on the conclusions of the recent UDPP validation exercises, this article will study the cost benefits airlines can obtain when tactical ATFCM slot swapping mechanisms are incorporated into their operational procedures for resource-constrained turnaround management. Thereby, we focus on a slot swapping mechanism which incorporates the features of the proposed UDPP concepts ESS and FDR with margins on a tactical time horizon (i.e., flight priorities need to be submitted at least two hours before the estimated arrival of the first flight). The objectives thereby are twofold: First, we aim at determining the recovery performance of our turnaround recovery model during an airport constraint if tactical slot swapping can be applied i) only to arrival flights and ii) to all flights of an airline in this period. Second, we explore how airlines may derive flight priorities and slot margins from these internal assessments. The used methodology is explained in Sec. II and applied in the context of a case study with different scenarios as detailed in Sec. III. Results of the case study analysis are presented in Sec. IV, whereby Sec. V discusses potential indications for proposed and to-be-developed slot trading mechanisms. Finally, Sec. VI draws conclusions and presents an outlook onto future research steps.

II. METHODOLOGY

The applied methodology introduces ATFCM capacity regulations related to an airport constraint into an airline-centric and resource-constrained turnaround scheduling model. There has been very little research on this agenda in the past, the article of Santos et al. [7] being the only one (to the authors knowledge) to incorporate airport capacity constraints in relation to the airline delay management problem. However, neither ATFCM slots nor links between arrival and departure flights via the related aircraft ground operations have been considered in there. Our article tackles these short-comings, such that a capacitated pool of standard turnaround resources (i.e., airport stands, personnel and ground handling equipment) needs to be assigned to each aircraft, while the related arrival and departure flights require ATFCM (runway) slots. The latter condition may create further bottleneck situations which may limit the flexibility of turnaround management, given that the following conditions need to be considered:

- aircraft should be allocated to slots such that the shared transfer connections between their arrival and departure flights can be maintained, whereby transfer times depend on the individual stand allocation;
- aircraft should be allocated to slots such that the limited amount of available stands is surpassed at no time;
- aircraft should be allocated to a pair of arrival and departure slots which guarantees a ground time larger than the estimated turnaround time (even if it is reduced by turnaround recovery options);

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Fig. 1 further shows the underlying cost and time dependencies for an airport constraint which affect three parallel aircraft turnarounds and their associated arrival and departure flights. Due to the reduced runway capacity during the constraint, the scheduled times of all flights have been assigned with increasing deviations according to the RBS principle. If the airline would maintain this initial sequence, two groups of transfer passengers might miss their connections at the airport, given that the arrival flights of aircraft m (highlighted in magenta) and aircraft b (highlighted in blue) have been assigned with arrival slots AS_2 and AS_3. This would incur local rebooking and compensation ("misconnex") costs once available transfer times fall below needed transfer times (i.e., when the transfer slack is consumed) as depicted by the dashed magenta and blue step cost curves. Note here that needed transfer times and the associated transfer slack may change in correspondence to the stand allocation of aircraft. Likewise, the scheduled off-block times of departure flights may be shifted due to a regulation, such that new transfer slack is induced. The same rationale applies to the turnaround of all aircraft, such that scheduled ground buffers are consumed by arrival slots while new buffer times are induced by departure slots. In case the airline could prioritize flights, an interesting case would arise if the airline decided to swap aircraft m to arrival slot AS_3. This would enable aircraft b to maintain its initially scheduled time of arrival in AS_2 but also make the turnaround of m critical, given that m is still assigned with the first departure slots DS_1. If allowed so, the airline may concurrently also swap departure slots among these two aircraft to ease this dependency. However, it should consider cost of departure delay in this process, which also contain cost steps in relation to transfer slack at downstream airports in the aircraft rotation.

A. Modelling Airline Slots in Airport Capacity Constraints

The capacity of an airport AQ is defined by the number of runway movements per period PE. According to the RBS principle commonly applied by central network management in periods when demand exceeds capacity, flights

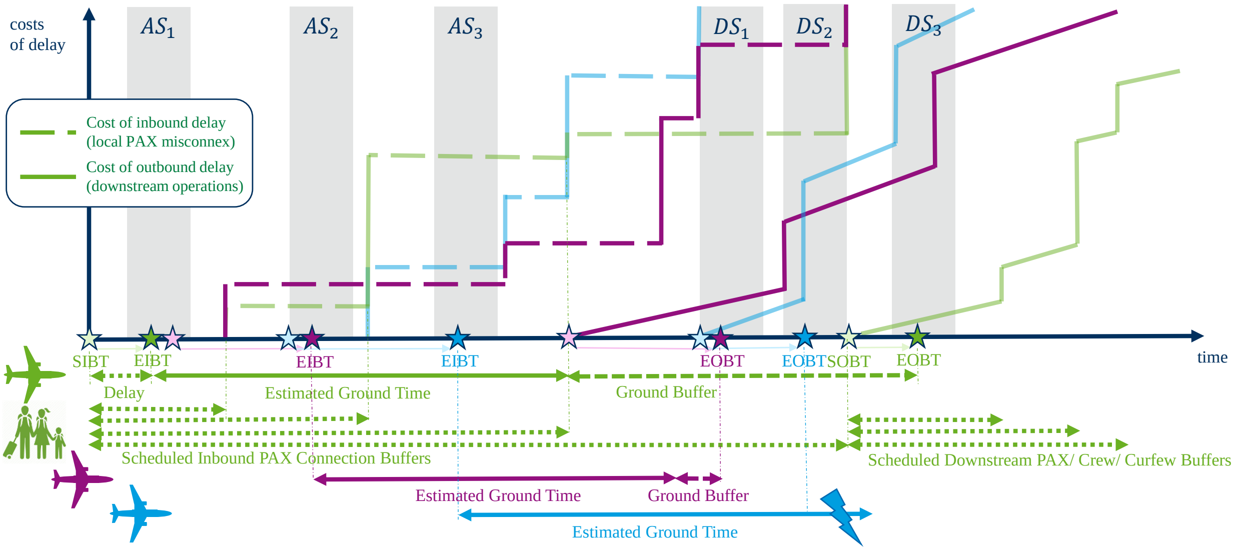
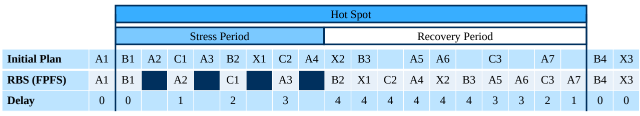


Figure 1: Time dependencies between arrival and departure flights of the same aircraft and corresponding cost functions (which relate to passenger transfer slack, crew and curfew buffers) if scheduled block times (SIBT/SOBT) are overrun. Starting from estimated block times relating to each slot (EIBT/EOBT), our model estimates the ground time of each aircraft based on constrained turnaround resources and generates a cost-minimal slot swapping solution such that all turnarounds are feasible between assigned slots (which is initially not the case for the blue aircraft above).

which are planned first are served with the first slots (FPFS). Thereby, Required Time of Arrival (RTA) and Calculated Take-Off Time (CTOT) are the reference values for the place of a flight in the queuing sequence.

For periods with reduced capacity at an airport (i.e., "stress periods"), this means that flights which are planned early on receive regulations with little deviation, while delay is increasing for later-planned flights. In the aftermath, delayed flights which remain from the stress period have priority over those which had been scheduled afterwards, such that a recovery period is needed until the airport returns to a "no-delay" situation. Thus, a constraint consists of stress and recovery periods [6], whereby the recovery period significantly depends on the length and severity of the stress period as well as the unassigned capacity afterwards (cf. Fig. 2).



		Hot Spot																			
		Stress Period								Recovery Period											
Initial Plan	A1	B1	A2	C1	A3	B2	X1	C2	A4	X2	B3		A5	A6		C3		A7		B4	X3
RBS (FPFS)	A1	B1	■	A2	■	C1	■	A3	■	B2	X1	C2	A4	X2	B3	A5	A6	C3	A7	B4	X3
Delay	0	0		1		2		3		4	4	4	4	4	4	3	3	2	1	0	0

Figure 2: Ration-by-Schedule principle in case of an airport/sector constraint.

B. Modelling Turnaround Management and Slot Swapping

All slots for arrival flights of an airline during an airport constraint are defined as set AS, while all slots for departure flights are defined as set DS. The assignment of an aircraft a from the set of all aircraft A to an arrival slot $s \in AS$, is done with $z^A_{as} \in (0,1)$, whereas a departure slot $s \in DS$ is assigned with $z^D_{as} \in (0,1)$. Each slot defines a calculated take-off time $CTOT_s$ and a required time of arrival RTA_s which are calculated according to the RBS principle for each flight of the airline within the respective constraint. In the baseline instance, each flight is fixed to its assigned slot from the FPFS-sequence. In case this is infeasible because there is not enough time for the turnaround between assigned arrival and departure slots, alternative slots are available after the last flight of the constraint. For the slot swapping exercises introduced in Sec. III, the fixed assignment can be lifted.

The slot assignment problem is incorporated into a turnaround recovery model which is formulated as an extension of the Resource-Constrained Project Scheduling Problem (RCPSP). The turnaround recovery model aims at assigning a limited set of turnaround standard and reserve resources to the above-mentioned set of aircraft A, such that the airline costs from a given disruption are minimised. Thereby, the turnaround of each aircraft $a \in A$ is defined by scheduled start and finishing times $SIBT_a$ and $SOBT_a$, which are adopted from the flight plan. It consists of a network of sub-processes P, where each sub-process $i \in P$ is characterized by the related aircraft ($RA_i = a$), has a variable starting time s_i and a duration D_i which corresponds to the 80%-quantile of a statistically-fitted time distribution [11]. Links between turnaround sub-processes are determined in the precedence matrix $PM_{ij} \subseteq P \times P$. Following the general RCPSP, each aircraft a needs to be assigned to an airport stand p from the set ST with $\chi_{ap} \in (0,1)$, whereby we differentiate between contact stands CS and remote stands RS, which are all equipped with the necessary personnel and resources for a standard turnaround. Thus, the in-block process $i \in IB \subset P$, as the first process of each turnaround, can only be scheduled if a stand is available which fulfills all operational requirements for aircraft and flights. It further depends on the estimated landing time $eldt_a$ in the assigned slot and the average taxi-in duration $\overline{EXIT}$. Downstream sub-processes can only start once all preceding processes are (scheduled to be) completed. Thereby, turnaround reserve resources enable schedule recovery options, such as a quick turnaround ($\omega_i \in (0,1)$), which reduces the duration of specific turnaround sub-processes, e.g., cabin cleaning $i \in CL \subset P$. These reserve resources are limited by QTR and incur recovery costs C_i^{qta} by each application. Another recovery options is stand reallocation which considers that aircraft which are positioned at a remote stands $p \in RS$ have reduced de-boarding and boarding duration, given that passengers can use front and rear doors. It further considers that the stand location of arrival and departure aircraft at an airport directly influences the needed transfer time NTT_{ij} for connecting passengers. By applying these options, airlines can influence the total duration along the critical path of a turnaround but also time dependencies between aircraft along transfer processes $i \in PA \subset P$. If a transfer process would require a departure flight to delay its off-block, the airline can either cancel the connection ($\kappa_i \in (0,1)$) or accept the delay. The prior decision would incur costs of care, rebooking and compensation C_i^{cnx}. In case the transfer involved a crew, it can only be cancelled if a standby is available. Delaying the departure of a flight results in marginal linear costs for crew wages, maintenance and passenger dissatisfaction C_{al}^{lin}. Furthermore, departure delay might disrupt transfer processes at downstream airports in the aircraft rotation, which incur step costs C_{al}^{stp} once the slack before this critical event is consumed (determined by $y_{as} \in (0,1)$). The estimated departure delay is captured within delay levels $l \in L$ after the scheduled off-block time $SOBT_a$. The resulting estimated off-block time $eobt_a$ is added with an average taxi-out duration $\overline{EXOT}$ to calculate the estimated take-off time $etot_a$, which needs to comply with the $CTOT_s$ of the slot s assigned to aircraft a.

C. Mathematical Formulation

$$\begin{aligned} \min \quad & \sum_{a \in A} \sum_{l \in L} \left(C_{al}^{lin}\ r_{al} + C_{al}^{stp}\ y_{al} \right) + \\ & + \sum_{i \in P} \left(C_i^{qta}\ \omega_i + C_i^{cnx}\ \kappa_i \right) \end{aligned} \tag{1}$$

$$\text{s.t.} \quad s_i \geq eldt_a + \overline{EXIT} \qquad \forall\, i \in IB \mid RA_i = a \tag{2}$$

$$eldt_a \geq RTA_s - 5 + M(1 - z_{as}^A) \qquad \forall\, a \in A; \forall\, s \in AS \tag{3}$$

$$eldt_a \leq RTA_s + 10 + M(1 - z_{as}^A) \qquad \forall\, a \in A; \forall\, s \in AS \tag{4}$$

$$\sum_{s \in AS} z_{as}^A = 1 \qquad \forall\, a \in A \tag{5}$$

$$\sum_{a \in A} z_{as}^A \leq 1 \qquad \forall\, s \in AS \tag{6}$$

$$s_i \leq SOBT_a + \sum_{l \in L} r_{al} = eobt_a \qquad \forall\, i \in OB \mid RA_i = a \tag{7}$$

$$eobt_a + \overline{EXOT} = etot_a \qquad \forall\, a \in A \tag{8}$$

$$r_{al} \geq (UB_{al} - LB_{al})\, y_{al} \qquad \forall\, a \in A; \forall\, l \in L \tag{9}$$

$$r_{al} \leq (UB_{al} - LB_{al})\, y_{a(l-1)} \qquad \forall\, a \in A; \forall\, l \in L \tag{10}$$

$$etot_a \geq CTOT_s - 5 + M(1 - z_{as}^D) \qquad \forall\, a \in A; \forall\, s \in DS \tag{11}$$

$$etot_a \leq CTOT_s + 10 + M(1 - z_{as}^D) \qquad \forall\, a \in A; \forall\, s \in DS \tag{12}$$

$$\sum_{s \in DS} z_{as}^D = 1 \qquad \forall\, a \in A \tag{13}$$

$$\sum_{a \in A} z_{as}^D \leq 1 \qquad \forall\, s \in DS \tag{14}$$

$$s_j \geq s_i + D_i \qquad \forall\, i \in IB, \forall\, j \in P \mid PM_{i,j} = 1 \tag{15}$$

$$s_j \geq s_i + D_i(1 - \chi_{ap}) + \alpha D_i \chi_{ap} \qquad \begin{aligned} & \forall\, i \in DE \cup BO, \forall\, j \in P \mid \\ & PM_{i,j} = 1; RA_i = a; \forall\, p \in RS \end{aligned} \tag{16}$$

$$s_j \geq s_i + NTT_{ij} \chi_{ap} \chi_{bq} - M \kappa_i \qquad \begin{aligned} & \forall\, i \in PA, \forall\, j \in P \mid PM_{i,j} = 1, \\ & RA_i = a, RA_j = b, \forall\, p, q \in ST \end{aligned} \tag{17}$$

$$\sum_{p \in ST} \chi_{ap} = 1 \qquad \forall\, a \in A \tag{18}$$

$$\sum_{a \in A \cup A0} xS_{abp} = \chi_{ap} \qquad \forall\, b \in A;\ \forall\, p \in ST \tag{19}$$

$$\sum_{b \in A \cup A0} xS_{abp} = \chi_{ap} \qquad \forall\, a \in A;\ \forall\, p \in ST \tag{20}$$

$$s_j \geq s_i + T - M(1 - xS_{abp}) \qquad \begin{aligned} & \forall\, a \in A;\ \forall\, b \in A \cup A0;\ \forall\, p \in ST; \\ & \forall\, i \in OB \mid RA_i = a; \\ & \forall\, j \in IB \mid RA_j = b \end{aligned} \tag{21}$$

$$s_j \geq s_i + D_i(1 - \omega_i) + \beta D_i \omega_i \qquad \forall\, i \in CL, \forall\, j \in P \mid PM_{i,j} = 1 \tag{22}$$

$$\sum_{b \in A \cup A0} xQ_{ab} \leq QTR \qquad \forall\, a \in A0 \tag{23}$$

$$\sum_{a \in A \cup A0} xQ_{ab} = \omega_b \qquad \forall\, b \in A \tag{24}$$

$$\sum_{b \in A \cup A0} xQ_{ab} = \omega_a \qquad \forall\, a \in A \tag{25}$$

$$s_i \geq eobt_a + T - M(1 - xQ_{ab}) \qquad \begin{aligned} & \forall\, a \in A;\ \forall\, b \in A \cup A0; \\ & \forall\, i \in IB \mid RA_i = b \end{aligned} \tag{26}$$

The objective function (1) minimizes total costs of delay and schedule recovery. This includes linear costs across all delay levels, step costs once a critical delay thresholds is overrun and costs related to turnaround recovery and cancellation of transfer connections. The start of each turnaround can only scheduled after landing and taxi-in of the arrival flight (2), whereby the estimated landing time must align with the assigned arrival slot (3)-(4). Arrival slots typically consists of an required time of arrival with a grace period of minus five and plus ten minutes. All arrival flights which are part of an airport constraint need to be assigned to exactly one arrival slot (5), while each slot can be used by maximum one flight (6). If the estimated turnaround off-block time exceeds the SOBT, departure delay is distributed across pre-defined delay levels (7) and is translated into an estimated take-off time (8). Each delay level is bounded such that delay can only occupy upper levels by taking into account the related step costs before them (9)-(10). Furthermore, constraints (11)-(14) consider that an aircraft can only be released "off-block", if a departure slot is available.

Standard scheduling constraints (15) ensure that all turnaround sub-processes following on the in-block process can only start once it has been finished. Similar scheduling constraints are defined for processes starting after deboarding and boarding (16), whereby the duration of both process can be reduced by factor α when an aircraft is positioned at a remote stand $p \in RS$. Constraints (17) consider needed transfer times for connecting passengers and crews between the stands of their arrival and departure flights, which directly influences their stand allocation. Hereby, note that the quadratic formulation needs to be linearized for the application of standard solvers (as described in [12]). Further note that this dependency is omitted for all transfer connections which are cancelled. Following the RCPSP, constraints (18) makes sure that each aircraft is allocated to exactly one stand, whereby the MTZ-formulation in constraints (19)-(21) defines the sequence of aircraft which use equal stands whereby dummy node $A0$ marks the start and end of each sequence.

The standard RCPSP formulation is extended by the possibility to assign turnaround recovery resources to some subprocesses (e.g., cabin cleaning) which then reduce the respective durations by factor β (22). Considering that turnaround recovery resources are limited (23), another MTZ-formulation in constraints (24)-(26) builds a sequence which ensures that only so many turnarounds can be prioritized in parallel as recovery resources are available.

III. SCENARIO AND APPLICATION

The integrated turnaround recovery and slot swapping model from Sec. II is applied in the context of an airline case study network with hub at Frankfurt airport. This sections presents the case study setting and introduces scenarios which include a airport capacity reduction during the morning hub bank. For each scenario, a new FPFS-sequence is calculated such that the applied turnaround recovery must adhere to the assigned arrival and departure slots. In further course, fixed assignments for arrival slots or respectively for all slots are lifted, such that we can assess the recovery performance of the model with tactical slot swapping.

A. Case Study Setting

A flight schedule was adopted from the summer schedule 2019 of a local hub carrier and comprises 15 parallel turnarounds during the morning hub bank (i.e., 7:30 a.m. to 11:00 a.m. local time). Between the related 30 flights (cf. Fig. 3), passenger connections are simulated to resemble potential itineraries which adhere to the average connection ratio (55% transfer passengers) and minimum connecting time in Frankfurt (45 minutes), a typical seat load factor of a hub carrier (85%) and avoid extreme detours (e.g., passengers from Madrid are unlikely to connect via Frankfurt to Barcelona). Crew connections and the initial stand allocation are generated with separate optimisation algorithms, such that they comply with official operational constraints and minimize crew assignment costs and the total needed transfer time respectively. Contact stands in Terminal 1A (cf. Stands A1, A2, A3 and A5 in Fig. 4) are reserved for flights to and from Schengen countries only. Contact stands with special security and customs areas (cf. Stands A3, A6, B1 and C1) can also operate flights to and from non-Schengen countries. Stands A3 and A6 are predominantly used for intercontinental flights with wide-body aircraft. Stands R1 and R2 are remote, which means that passengers need to be transferred with apron buses via the central bus stations (marked with a bus icon in Fig. 4).

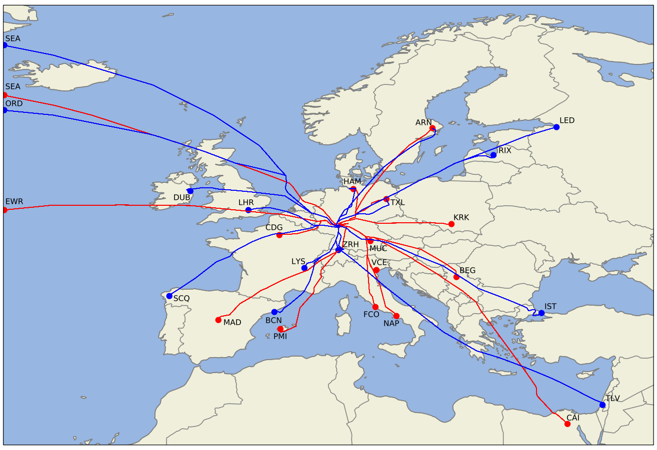


Figure 3: Initial Flight Plans (M1) as submitted by the case study airline for arrival (red) and departure flights (blue) to and from Frankfurt airport.

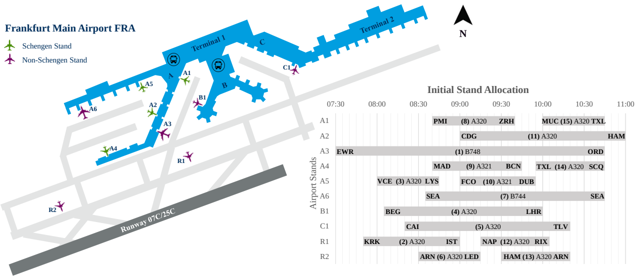


Figure 4: Case study setting at Frankfurt airport (FRA).

Three aircraft, including two wide-bodies, are fixed at their initial stands due to operational constraints, whereas the remaining twelve aircraft can be re-allocated to any other stand complying with the required security procedures of the respective arrival and departure flights. In total, one quick turnaround unit ($QTR = 1$, $C_i^{qta} = 500$ per turnaround) and one standby crew ($C_i^{cnx} = 1000$; two additional wage hours) enable the respective schedule recovery options. The cost of cancelling a passenger transfer C_i^{cnx} are adopted from reference values per passenger as determined in [13] and consider the additional trip time on the next alternative flight as well as that some passengers may not wish to be re-booked and need to be compensated and/ or reimbursed instead according to EU regulation 261. Note that we consider compensation by the airline as a worst case scenario, although the airline is not liable for ATFCM delays - but might be if it purposely changes the flight sequence and the assigned delays. Marginal costs of departure delay C_{al}^{lin} are constant per delay level and are also adopted from reference values as determined in [14]. They include additional crew wages, maintenance expenses and costs of passenger dissatisfaction in relation to the respective aircraft type. Step costs related to departure delay C_{al}^{stp} are calculated in the same way as local costs of rebooking and consider the downstream flight schedule of each aircraft and the related transfer processes at other airports with their respective slack time. Together they result in flight-specific delay cost functions (cf. Fig. 8).

B. Scenarios

The runway capacity at Frankfurt airport is defined with 108 movements per hour, which corresponds to an standard capacity of $AQ = 27$ per period $PE = 15\ minutes$. The planned capacity utilization is marked by the green line in Fig. 5 and was retrieved from the initial flight plan data (M1) on Friday, 16 August 2019 - a day which did not contain any capacity regulations at Frankfurt airport. Based on this initial flight sequence, three constraint scenarios are introduced, which each predict the runway capacity to reduce to $AQ = 15$ while the length of the stress period varies. All scenarios assume that all flights will be operated, such that potential cancellations are neglected. The stress period is estimated to start before the morning peak at 7:00 a.m. local time. In Scenario 1 (S1), it is estimated to last for two hours, while in Scenario 2 (S2) it includes three hours and in Scenario 3 (S3) four hours. As demand exceeds capacity during the entire stress period, slots are assigned according to the RBS principle. This results into a recovery period until 2:00 p.m. in S1 which also covers the entire midday bank. Given that more flights are affected by the stress period in S2, the recovery period covers almost the entire afternoon bank until 5:30 p.m.. In S3, it lasts for another 75 minutes (cf. Fig. 5). Based on this initial slot assignment, the calculated landing and take-off times per scenario are retrieved per flight of the case study airline and define sets of arrival slots AS and departure slots DS. Considering a cut-off time two hours prior to the start of the constraint, we assume a look-ahead time of three hours before the problem, such that there is one hour left for the airline to define the priorities of their flights within their assigned slots. Each scenario is run with two instances, whereby the first one (S1/2/3-A) allows the airline to swap only arrival flights within their slots, whereas in the second one (S1/2/3-A+D), arrival and departure flights can be swapped within their respective sets. Note that three hours before the constraint, three flights from Cairo (CAI), Newark (EWR) and Seattle (SEA) have already departed their airports of origin. Thus, they are fixed within their assigned arrival slots.

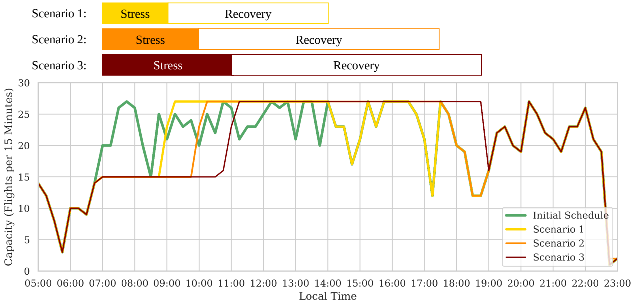


Figure 5: Airport constraint scenarios during the morning hub bank at Frankfurt airport.

Further note that from an airline perspective, runway slots in a capacity constraint need to be considered in pairs for arrival and departure flights of the same aircraft. This is due to the fact that both flights might be assigned with different delays, which is especially critical when the departure slot receives less delay and the scheduled turnaround time is very tight. In this case, it might be infeasible for the departure flight to use its assigned slot given that the higher arrival delay cannot be absorbed during the turnaround. Thus, a new departure slot needs to be requested, which might be far down in the sequence, especially when considering the long airport recovery period. The phenomenon of diverging delays is already visible in the exemplary sequence exhibited in Fig. 2, such that delays increase on flights early in the stress period, stagnate at the end of the stress period and begin to decrease once free capacity is available during the recovery period. A similar pattern can be found in all three scenario instances (cf. Fig. 6), where the effect is enforced by very heterogeneous ground times, such that the arrival sequence of aircraft significantly deviates from the departure one. In S1, almost all arrival flights receive higher delays than the departure flights of the respective aircraft. Thereby, the flights of aircraft 7 and 11 obtain the largest difference (i.e., 25 minutes), which is critical for aircraft 7, due to no scheduled ground buffer, but uncritical for aircraft 11, which has 75 minutes ground buffer. In S2, aircraft 11 to 15 have diverging arrival and departure delays, whereas in S3, only aircraft 14 and 15 are concerned. Thereby, aircraft 12 to 15 have very few to no absorption potential for arrival delays, given that their turnaround is scheduled for 45 and 50 minutes. Consequently, both departure flights require new departure slots, which are assumed to be available at 12:00 p.m. and 12:30 p.m..

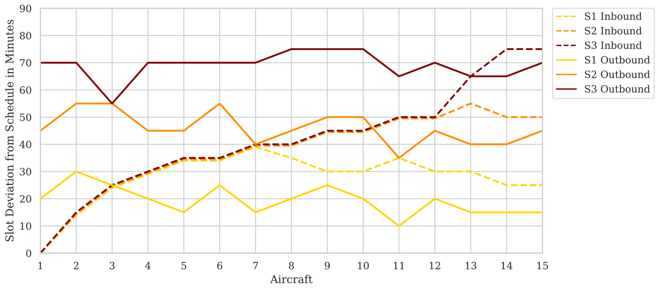


Figure 6: Slot deviation from schedule per aircraft and scenario according to the RBS principle.

IV. ANALYSIS

The turnaround recovery and slot swapping model was solved with IBM CPLEX Version 12.10.0-0 on a 4-core CPU with 8GB RAM. Aligning to the tactical decision horizon, the solution process was aborted after one hour if optimality of a solution could not be proven and there was still a gap between upper and lower bounds. A gap remained for some instances from the reference case (i.e., no turnaround recovery and no slot swapping) and the full slot swapping model (cf. Tab. I). This indicates that the turnaround recovery model with integrated slot allocation (arrival + departure) and stand allocation is np-hard, given that each of the three individual allocation problems can be related to the Generalized Assignment Problem (GAP), which itself is np-hard [15].

This may explain why even in the reference case, where the stand allocation is fixed, a gap remains within reasonable solution times. Due to the nature of the problem, there are too many partially symmetric options with similar objective values, which form a weak lower bound, such that standard solvers need to test all feasible options before converging to an optimal solution. In operational practice, this induces a managerial trade-off whether a solution should be optimal - may require very long solution time or development of a sophisticated solution method - or optimized - not proven to be optimal but close-to-optimal (relation to gap) - and anyway better than without the optimization process.

A. Total Airline Costs

Tab. I further exhibits total costs incurred by the airline per airport constraint scenario. Total costs rise exponentially in the reference cases from S1 to S2 and S3, which relates to higher assigned delays in the FPFS-sequence of S2/S3 that do not consider flight-specific cost drivers. The turnaround recovery model with integrated arrival slot swapping is very effective for shorter capacity constraints, such that total costs can be reduced by 85% in S1 and 57% in S2. In both scenarios, increased flexibility from departure slot swapping would result in only marginal additional costs savings of 1-2%. Given that in both cases the assigned delays range between 10 and 60 minutes, there is sufficient absorptive capacity to compensate delays during ground operations - especially when considering that less than 30% of all passenger connections have small slack of 30 minutes or less, while the average ground buffer is 25 minutes. In combination with the capacity of the recovery model to adapt the stand and arrival slot allocation, most of the critical connections can be saved. Furthermore, it needs to be taken into account that cost of departure delay are comparatively small on most flights during the first 60 minutes, such that a reallocation of the initially assigned departure slots in S1-A+D and S2-A+D does not result in high cost saving effects (cf. Fig. 8).

Conversely in S3, many of the assigned departure delays according to the RBS principle surpass cost-intensive thresholds which relate to disruptions in the downstream network of the case study (cf. Fig. 8). Consequently, swapping arrival slots while departure slots remain fixed, brings only limited cost benefits for the airline (i.e., 11% - cf. Tab. I). If this fixation would be lifted for departure flights, total costs in S3-A+D can be reduced by at least 41%.

TABLE I. Total airline cost per scenario including required solution time/ remaining gap after 3600s.

ID	Reference FPFS	Arrival SSW	Arrival+Dep. SSW
S1	54899 (1.17%)	8131 (260s)	7568 (2710s)
S2	115718 (0.61%)	49840 (0.40%)	47511 (2448s)
S3	205463 (15s)	183725 (326s)	121764 (16.03%)

B. Slot Allocation

As mentioned in Sec. III-B, it may be critical for airlines if a departure flight receives less delay during a capacity constraint than the arrival flight of the same aircraft. Once this is the case, airline have three options: 1) return the assigned (departure) slot and request a new one; 2) accelerate the turnaround; and/or 3) swap the slots such that there is sufficient ground time between both flights. Given that the latter two options are not available in the reference case, three departure slots cannot be used by the airline in S1, while in S2 and S3 the airline needs to request one new slot respectively. Conversely, in all instances that involve slot swapping, the airline can operate with all initially assigned slots and no additional slots need to be requested.

Fig. 7 highlights the optimized arrival slot allocation per scenario instance. When only arrival slot swapping is allowed, the optimal sequence remains stable across all three scenarios, although there being some alternative optimal solutions with different sequences. This indicates that there is a robust optimal arrival sequence for the airline in our case study, despite the fact that later slots obtain higher delays in S2 and S3. However, in case that arrival and departure slots can be swapped, the optimal arrival sequence changes significantly within each scenario and between scenarios. Based on that, we derive a strong correlation between the assigned arrival and departure flight slots of an aircraft, such that the robust arrival sequence in the first instances relates to the fixed FPFS-sequence for all departure flights. Conversely, the additional flexibility induced by departure slot swapping requires the calculation of an individual sequence per constraint, which can hardly be generalised if the delays within a constraint are changing (e.g., due to uncertainty about the length of the stress period). Note that none of the flights remains within its initially assigned FPFS-slot throughout all instances (except for all flights which already departed and are fixed within their slots). Some aircraft are prioritized in most instances (e.g., aircraft 3 [orange], aircraft 6 [maroon], aircraft 9 [cyan]), while others are typically suspended (e.g., aircraft 2 [ochre], aircraft 11 [light blue]).

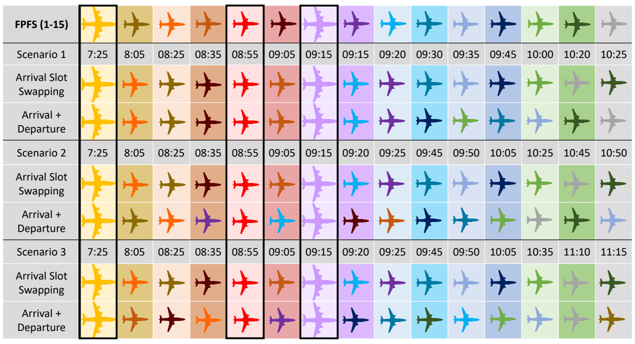


Figure 7: Optimized sequence of arrival flights within assigned airline slots per scenario.

For reasons already stressed in the previous section, there are only few departure slot swaps in S1-A+D and S2-A+D (i.e., 3 and 4). However in S3-A+D, almost all departure flights are swapped among each other such that critical cost steps are avoided. Thereby, three departure flights are suspended to later slots (e.g., aircraft 2 from the second position to the last in the sequence) while ten flights receive

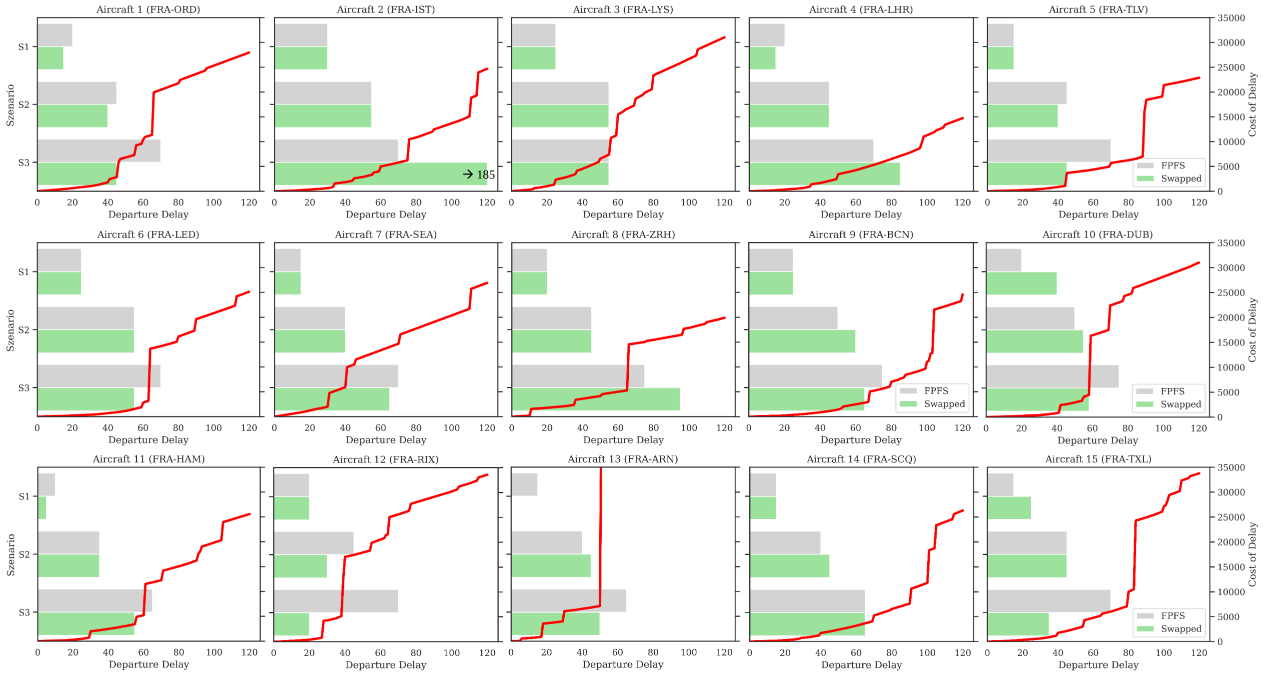


Figure 8: Assigned departure delay per flight in the FPFS-sequence and in the optimized recovery solution in comparison to departure delay cost functions.

earlier slots than assigned in the FPFS-sequence (cf. Fig. 8). This model output corresponds largely to the principle of the SFP mechanism - without using a credit system - such that the suspension of one early flight can mitigate delays on many others while the overall delay remains equal.

C. Applied Turnaround Recovery Options

Tab. II lists the optimal number of applied turnaround recovery options and derives the relative change in average passenger delay per scenario. Note that in S1, a quick-turnaround procedure is assigned to aircraft 7, given that the arrival slot obtains 25 minutes more delay than the departure slot and the scheduled ground time comprises no buffer (cf. Fig. 6). Likewise, in S2-A and S3-A, a quick-turnaround is required for aircraft 14 which obtains more arrival than departure delay in the FPFS-sequence. However, once departure slot swapping is allowed, the optimal solution in S2-A+D includes a quick-turnaround for aircraft 11 (which has a large ground buffer but is suspended in the arrival sequence), while in S3-A+D, the operation of the turnaround with additional personnel is not efficient for any aircraft. Stand changes are required throughout all instances and help to avoid missed passenger connections when only arrival slot swapping is allowed. Thereby, the optimal stand allocation relates to the optimal arrival sequence, such that no generally optimal scheme can be found for all scenarios. In case of combined arrival and departure slot swapping, up to 13 out of 151 passenger transfers need to be re-booked in order to allow a more comprehensive reordering of the initial flight sequences. Given that delay increases significantly for re-booked passengers (depending on the departure time of the next available flight towards the same destination), average delay increases by up to 2.6%. Though, average delay for passengers on their original flights decreases by up to 3.6%.

TABLE II. Optimal number of applied turnaround recovery options per scenario.

ID	Quick Turnaround	# Stand Changes	# Misconnex	Delay p.PAX
S1-A	Aircraft 7	8	0	-0.4%
S1-A+D	Aircraft 7	9	9	+1.7%
S2-A	Aircraft 14	7	0	+0.3%
S2-A+D	Aircraft 11	4	6	+2.6%
S3-A	Aircraft 14	8	0	+0.1%
S3-A+D	-	8	13	+0.6%

D. Definition of Flight Priority Values and Margins

From the perspective of an airline, we see three ways to determine priority values for flights in a constraint: 1) a qualitative approach which relates the ranks of flights in the optimal sequence to each other; 2) a quantitative approach which weights the assigned optimal delay of flights among each other; and 3) a heuristic approach which compares the flexibility of all applicable flights for a slot. For the first approach, we apply a version of the Analytic Hierarchy Process (AHP) to the optimal flight sequences [16]. Therefore, the optimal ranks of all flights from the arrival and departure slot swapping instances (S1/2/3A+D) are rated pair-wise against each other, such that, e.g., a flight which obtained the first rank in the arrival or departure sequence dominates another flight which was assigned with the fifth rank by factor 4, while the latter flight receives the inverted factor $1/4$. Despite of the different scoring system from 1 to 14 (the original AHP assigns priority values in the range between 1 and 9 between two attributes), the resulting matrix shows a low inconsistency value of less than 7%, which is acceptable [16]. The resulting rankings per scenarios are than multiplied with another by assuming equal probabilities for each of the three scenarios to derive a general sequence also for instances in which all slots can be swapped. The generalized sequence is then implemented with fixed slot assignments into the respective modelling instances and results in ”optimal” total costs which are 37% higher than in S1-A+D (27% in comparison to S1-A) and 7% higher than in S2-A+D (2% in comparison to S2-A) while in S3 it is infeasible due to conflicts with the limited stand capacity. Thus, as already concluded in Sec. IV-B, there is no generally optimal (robust) flight sequence if arrival *and* departure slots can be swapped among each other.

For the second approach, we assign priority values to flights based on the delay they obtain with their optimal slot. Thus, if a flight is assigned to a slot close to its initially schedule arrival or departure time, it has a high priority score, while priority values are decreasing with higher delays. Thereby, we consider equivalent delays between all priority scores which are determined by the difference of the highest and the lowest assigned delay within a set, divided by $N-1$ (N being the number different priority values).

Fig. 9 displays the resulting priority values for arrival flights in scenario S1-A. Similar to the UDPP, 1 marks the highest flight priority, 9 the lowest, three flights are fixed (f), while each flight cannot be assigned to any slot before its scheduled time of arrival. Note that only few mid-range values appear in this instance, which was also found in UDPP validation exercises [17]. Further note that assigning slots to flights according to these priority scores - by respecting FPFS for flights with equal scores - does not yield the optimal flight sequence if the delay is unbounded for all flights (cf. Fig. 7).

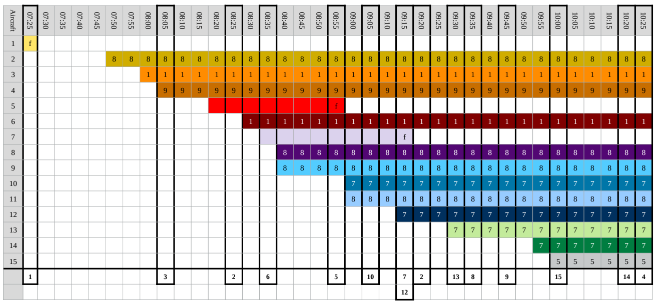


Figure 9: Flight priorities without margins in S1-A.

However, once the corresponding delay from the assigned optimal slots is incorporated as upper bound of the respective flight margin, the optimal sequence can be derived using the following algorithm:

1) Assign flights with fixed slots;
2) Assign flights with from hightest to lowest priority scores (* if several with same score, first those with least margin after slot, then FPFS);
    a) if no slot is available, break assignment in latest possible slot for this flight and assign there;
    b) assign detached flight to next possible slot;

For the third approach, we consider that priority scores and margins are both based upon the optimal amount of delay, such that priority scores may also be omitted if optimal delay margins are used. Each slot is then assigned with a simple heuristic to the applicable flight with the least available margin (cf. Fig. 10). The heuristic without priority scores but margins only was tested for all arrival and departure sequences and always yielded the optimal sequence.

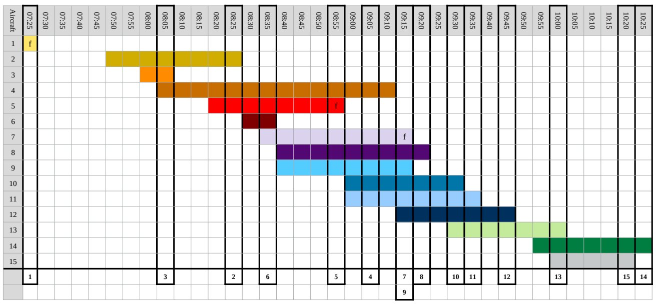


Figure 10: Flight priorities with margins in S1-A.

V. DISCUSSION ON CREDITS AND SLOT TRADING

The currently incorporated slot swapping mechanism grants flexibility to airlines without compromising the equity of other users, given that the overall delay remains equal. However, its efficiency may depend on a certain market share within an airport capacity constraint, as otherwise the available swapping options are very limited. The UDPP framework enhanced the SFP mechanism for this issue, such that low-volume users were envisioned to trade slots into credits and transfer them into other constraints. Such complex regulations tend to contradict initial intentions and may create new problems as a result of the developed solutions, e.g., credit systems are prone to human behavioural biases [18]. Furthermore, simplified approaches tend to be more stable during operations (i.e., controller can follow decisions). Thus, similar to omitting flight priority values, we aim at creating a simple trading mechanism, which is based on the secondary trading scheme instead of credit values. Thereby, we consider that sometimes airlines may prefer to maintain a transfer connection instead of using their assigned slots. Consequently, we conducted an small experiment in which we neglect an assigned departure slot at 9:00 a.m. in the optimization process, such that we analyse the additional costs the airline would incur by using an alternative slot at the end of the sequence instead. These additional costs may then represent the minimum price another user needs to pay for trading the released slot. Conversely, we consider also an additional departure slot at 8:10 a.m. (released by another airline) in our model in order to determine the associated extra cost savings, i.e., the maximum price our airline should pay for using this slot. Tab. III lists the related changes in total costs, which are volatile per scenario instance and depend on the position of the slot in relation to all other slots, operational restrictions of turnaround resources and the amount of delay that can be saved by a bought slot/ is added by an alternative slot at the end of the sequence.

TABLE III. Change of total costs in case of secondary trading.

ID	**Sold Dep Slot**	**Δ Total Costs**	**Bought Dep Slot**	**Δ Total Costs**
S1-A	9:00	+12448	8:10	0
S1-A+D	9:00	+13046	8:10	-250
S2-A	9:00	+58031	8:10	-4842
S2-A+D	9:00	+15268	8:10	-4829
S3-A	9:00	+17715	8:10	-53855
S3-A+D	9:00	+12343	8:10	-22676

VI. CONCLUSION

In this paper we incorporated a tactical ATFCM slot swapping mechanism into a resource-constrained turnaround scheduling model, such that airlines can calculate an optimized flight prioritization and resource allocation strategy during airport capacity constraints. Within a case study of a hub airline at Frankfurt airport, we find that swapping only arrival flights within their assigned slots is very efficient as long as the assigned delays do not exceed critical cost thresholds which correspond to downstream network disruptions. In the analysed airline case study network these thresholds appeared at around 60 minutes, but might differ in other airline networks. Leaving departure slots fixed as defined in the FPFS-sequence, yields a stable optimal arrival flight sequence, which seems to be unaffected by the length of a constraint and the related volatile delay in some slots.

Departure slot swapping and the corresponding additional flexibility for airlines brings only marginal cost benefits for constraints with small and medium delay below the critical threshold. These benefits are likely to be compensated by administrative efforts, given that due to an increased solution space no robust optimal sequence can be calculated across different constraints. Thus, the parallel prioritization of arrival and departure flights would require an airline to make case specific calculations, which may only be efficient in high delay scenarios, when delays exceed the critical threshold and cause many cost-intensive downstream disruptions. Note that in these instances also the complexity of the problem increases, which is np-hard, such that an optimal solution may not always be found within reasonable time. Future research should increase the number of studied constraint scenarios to test if these findings can be generalized, e.g., by determining the efficiency of slot swapping for airlines as a function of the magnitude of assigned delays.

In any case, our simple slot swapping mechanism has demonstrated the capacity to grant airlines additional flexibility and significant cost savings during airport constraints. This comes without any complexities such as credit systems or priority scores as initially envisioned by the UDPP. Priorities in-between flights can be defined by assigning maximum delay margins to each flight, which ensures a confidential way of communication between ATM stakeholders. Unused slots can be traded directly with other airlines, whereby our models can calculate a minimum price for selling a slot and a maximum price for buying a slot. The opportunity to define such efficiency bounds for secondary slot trading or auction systems may provide incentives for an early release of unused slots. Future research should study how this may benefit airlines with a low volume of flights in a constraint.

As a necessary pre-condition to our approach, airlines need to integrate ground operations into their schedule recovery procedures [12] and define flight-specific delay cost functions in correspondence to the scheduled downstream operations of each aircraft [8]. Further note that not all schedule recovery options are considered in our current model, given that aircraft swaps and flight cancellations are neglected. Future research may include these options and study our approach also outside of airport constraints such that tactical slot swapping may contribute to daily airline recovery procedures.

ACKNOWLEDGMENT

The authors would like to thank Eurocontrol for the provision of initial flight plan data which have been used as baseline for the flight sequence at Frankfurt airport on the scenario day in August 2019.

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