SESAR Engage KTN – PhD final report

PhD title:	Resource-Constrained Airline Ground Operations: Optimizing Schedule Recovery under Uncertainty
Candidate's name:	M.A. Jan Evler
Lead supervisor's name:	Prof. Dr.-Ing. Habil. Hartmut Fricke
Co-supervisor's name (if applicable):	Prof. Andrew Cook
Proponent institute:	Technische Universität Dresden
Consortium institutes (if applicable):	-
Thematic challenge:	TC4 Novel and more effective allocation markets in ATM
Edition date:	30 April 2022
Edition:	1.0
Dissemination level:	Public

This project has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 783287.

1. Abstract

Air Traffic Flow Management (ATFM) and airlines use different paradigms for the prioritisation of flights. While ATFM regards each flight as individual entity when it controls sector capacity utilization, airlines evaluate each flight as part of an aircraft rotation, crew pairing and passenger itinerary. As a result, ATFM slot regulations during capacity constraints are poorly coordinated with the resource interdependencies within an airline network, such that the aircraft turnaround – as the connecting element or breaking point between individual flights in an airline schedule – is the major contributor to primary and reactionary delays in Europe.

This dissertation bridges the gap between both paradigms by developing an integrated schedule recovery model that enables airlines to define their optimal flight priorities for schedule disturbances arising from ATFM capacity constraints. These priorities consider constrained airport resources, such as ATFM slots, airport stands or ground handling personnel and different methods are studied how to communicate airline-internal priorities confidentially to external stakeholders for collaborative solutions, such as the assignment of reserve resources or ATFM slot swapping.

The integrated schedule recovery model is an extension of the Resource-Constrained Project Scheduling Problem and integrates aircraft turnaround operations with existing approaches for aircraft, crew and passenger recovery. The model is supposed to provide tactical decision support for airline operations controllers at look-ahead times of more than two hours prior to a scheduled hub bank. System-inherent uncertainties about process deviations and potential future disruptions are incorporated into the optimization via stochastic turnaround process times and the novel concept of stochastic delay cost functions. These functions estimate the costs of delay propagation and derive flight-specific downstream recovery capacities from historical operations data, such that scarce resources at the hub airport can be allocated to the most critical turnarounds.

The model is applied to the case study of a network carrier that aims at minimizing its tactical costs from several disturbance scenarios. The case study analysis reveals that optimal recovery solutions are very sensitive to the type, scope and intensity of a disturbance, such that there is neither a general optimal solution for different types of disturbance nor for disturbances of the same kind. Thus, airlines require a flexible and efficient optimization method, which considers the complex interdependencies among their constrained resources and generates context-specific solutions. To determine the efficiency of such an optimization method, its achieved network resilience should be studied in comparison to current procedures over longer periods of operation.

For the sample of analysed scenarios in this dissertation, it can be concluded that stand reallocation, ramp direct services, quick-turnaround procedures and flight retiming are very efficient recovery options when only a few flights obtain low and medium delays, i.e., 95% of the season. For disturbances which induce high delay into the entire airline network, a full integration of all considered recovery options is required to achieve a substantial reduction of tactical costs. Thereby, especially arrival and departure slot swapping are valuable options for the airline to redistribute its assigned ATFM delays onto those aircraft that have the least critical constraints in their downstream rotations.

The consideration of uncertainties in the downstream airline network reveals that an optimization based on deterministic delay costs may overestimate the tactical costs for the airline. Optimal recovery solutions based on stochastic delay costs differ significantly from the deterministic approach and are observed to result in less passenger rebooking at the hub airport.

Furthermore, the proposed schedule recovery model can define flight priorities and internal slot values for the airline. Results show that the priorities can be communicated confidentially to ATFM by using flight delay margins, while slot values may support future inter-airline slot trading mechanisms.

2. Objective of the study

This dissertation aims at developing an integrated decision support model for an Airline Operations Control Centre (AOCC) that helps the airline to align its tactical schedule recovery actions with ATFM capacity constraints (see Engage thematic challenge 4) and the constrained resources of other operational stakeholders, such as airports or ground handling service providers. The research objectives that support this overarching goal are threefold:

The first objective is to integrate the most relevant schedule recovery options of an airline and to analyse their recovery performance at the tactical planning level, i.e., when short-term ATFM capacity constraints become known on the day of operations. In particular, the model shall incorporate the complexity and recovery capacity of stochastic ground operations at an airline's hub-airport rather than compressing the turnaround into a single static process between two flight legs.

The second objective is to incorporate flight-specific delay propagation under uncertainty and the related cost impact of downstream operations into the local solution of an integrated schedule recovery model that optimizes ground operations at the airline's hub airport.

The third objective is to analyse how the integrated schedule recovery model can help airlines to define their flight priorities and coordinate them confidentially with ATFM. In alignment with Engage thematic challenge 4 and the User-Driven Prioritisation Process (UDPP), it is studied which prioritisation mechanisms are simple and can provide incentives for airline recovery decisions that benefit the entire ATM system.

3. Motivation

The motivation for this research project is derived from seven observations about operational practices and the status quo of the literature on airline operations management:

1st Observation: Sub-Division of Airline Schedule Planning and Schedule Recovery

Operations research has not yet advanced so far as to solve the holistic airline schedule planning problem to optimality. Thus, no flight plan is entirely robust to the influence of stochastic forces (Wu, 2016). This can be as much attributed to the diverse characteristics of the strategic and tactical schedule as to the nature of the General Assignment Problem, which is NP-hard (Fisher et al., 1986). Consequently, the scheduling of flights and the assignment of resources to flights creates a problem which is also NP-hard. Thus, robust schedule planning and schedule recovery will remain separate research problems for the near future, to be optimized independently, whereby this work will focus particularly on the latter planning problem.

2nd Observation: Fragmentation in Airline Schedule Recovery

Innovative schedule recovery approaches have rarely been adopted by the industry, given that they lack essential operational requirements (Heger, 2018). Consequently, the process remains a largely manual and fragmented task. Most studies that aim at diminishing fragmentation, do not consider all sub-problems, while some approaches simplify the constraints of some AOCC-units to include at least all airline network layers. The latter approach is extended within this dissertation.

3rd Observation: Lack of Consideration for Ground Operations Recovery

Especially at large nodes in an airline network, the turnaround is a critical connecting element between flights and, therefore, a major producer of primary and reactionary delay. Current schedule recovery models do not incorporate all interdependencies between turnaround sub-processes of different aircraft, such that undesirable chain effects cannot be detected and proactively addressed at their source. This may require the application of excessive recovery solutions elsewhere in the network. Most integrated schedule recovery models neglect recovery capacities comprised within the turnaround and omit the airport control unit in the AOCC that is dedicated to the coordination of turnaround recovery options (Hassan et al., 2021). Thus, the generated solutions may not comply with operational constraints at the airport. This work therefore sets out to incorporate the operational constraints of the airport control unit as an additional network layer of an airline that needs to be integrated into the schedule recovery problem.

4th Observation: Lack of Consideration for Uncertainty

Uncertainty about system parameters adds another dimension to schedule recovery models - time continuity. Almost all processes in aviation have underlying stochastic influences, such that the validity of a schedule recovery solutions may change within minutes (Fricke and Schultz, 2009; Wu and Law, 2019). Future decision support models/systems can only add value when they consider such complexities and reveal data patterns in the system comprehensively for AOCC operators, which is why this dissertation will consider them explicitly.

5th Observation: No Tactical Prediction of Delay Propagation

Despite reactionary delay being the biggest contributor to departure delay in Europe, i.e., 44% (Eurocontrol, 2020), there still remains a lot of work in this area to obtain better predictions on tactical delay propagation issues. Having no clear picture about which amount of reactionary delay and costs a particular primary delay may cause, limits the scope for tactical schedule recovery. In fact, the prioritisation between individual flights is currently based on general 'rules of thumb' – despite variable network effects arising from daily changing aircraft rotations, crew and passenger itineraries. As a solution, this work aims at predicting delay propagation based on case-specific operational constraints.

6th Observation: Interaction between Stakeholders in a System of Systems

Airlines not knowing about their flight-specific delay costs is a major issue for the entire ATM system. Sensitive cost data and recovery policies are kept internally, such that the limited situational awareness heavily jeopardizes the interaction with external stakeholders and fails to unleash the full potential of currently implemented monitoring concepts, such as Airport-Collaborative Decision Making (A-CDM). On top of that, all stakeholders seem to follow divergent flight prioritisation paradigms. Thus, there is a fundamental need to synchronise recovery procedures among all ATM system stakeholders. Thereby, it is especially the reduction of minor delays which is estimated to provide major benefits to the ATM system as a whole and to airlines in particular (Eurocontrol, 2016). Consequently, the analysis of the proposed model focuses on minor and medium schedule deviations and disturbances and neglects major operational disruptions, such as airport closures, aircraft breakdowns or flight cancellations.

7th Observation: Need for Confidential ATFM and Airline Coordination

A potential solution to grant airlines increased operational flexibility and reduce ATM-related costs is the UDPP (Pilon et al., 2019). Though, with the introduction of novel flight prioritisation mechanisms, airlines need to consider yet another dimension during their schedule recovery procedures. Given the complexity and biases within the recently proposed UDPP mechanisms, this research takes the perspective of an airline and studies how internal cost profiles and recovery decisions can be coordinated with ATFM without compromising data confidentiality.

4. Advances this work has provided with regard to the state of the art

The scientific contributions of this dissertation lie in a more profound understanding of process interdependencies between aircraft at large nodes in an airline network. This includes the inherent recovery capacity available to airlines during aircraft ground times. Thus, this dissertation can bridge the gap between two recently pursued research approaches for schedule recovery: 1) AOCC decision support models which focus primarily on large-scale network disruptions and see limited recovery capacity during the turnaround aside from schedule buffers, and 2) models on airport (ground) operations which analyse isolated problems for a particular turnaround sub-process or airport resource.

The methodological contribution lies in the integrated formulation of all relevant interdependencies related to airline ground operations as linear constraints, such that standard Mixed-Integer Linear Programming (MILP) solution techniques can be applied in a centralised decision support model. This holistic approach outperforms fragmented solutions as it considers options and constraints of several sub-problems at once which otherwise need many iterations to synchronise towards a feasible solution. The considered sub-problems include:

- prediction and control of turnaround target times;
- prediction of reactionary delay costs;
- tactical flight prioritisation;
- tactical passenger transfer management;
- tactical crew management;
- tactical stand allocation, and
- routing and assignment of ground handling equipment and staff.

In particular, the novel features developed by this dissertation include:

A standardisation and categorisation of airline schedule recovery options

Many different schedule recovery options have been modelled in the literature for the same operational procedures. This dissertation clusters those options which pursue similar objectives, such that standardised recovery options can be derived and implemented into an integrated schedule recovery model.

A stochastic control concept for multiple parallel turnarounds

Prediction models have been developed for a single turnaround that rely on stochastic input data. This dissertation extends this concept to multiple turnarounds, such that passenger and/or crew transfer dependencies, as well as constrained airport resources, are considered. This enables the identification of critical process dependencies across parallel turnarounds, such that standardised recovery options can be allocated more effectively, while the recovery capacity of different options can be determined.

A methodology for defining flight-specific delay cost functions

In case recovery resources are limited, priority should be given to those aircraft/flights whose delay would result in the highest downstream network costs. While most downstream dependencies appear on a linear timescale, there is not always a linear relationship between a delay and its costs. This dissertation provides a flight-specific mathematical formulation for the cost of delay. To the best of the author's knowledge, this is the first time that a cost formulation is provided which considers all downstream constraints and recovery capacities within an entire aircraft rotation. The methodology is extended to describe stochastic delay cost functions, which allow a pro-active assessment of delay costs under uncertainty to be used by airlines for flight prioritisation at the hub airport.

A flight prioritisation concept for ATFM slot swapping and slot trading

The network performance and recovery capacity of an airline are significantly affected by ATFM regulations, such that some recovery options may not be effective while airport/sector capacity constraints are imposed. This dissertation incorporates ATFM slot regulations and proposes a tactical swapping mechanism as a complementary schedule recovery option. Thus, slot swaps can be evaluated in comparison to other recovery options. Based on this, airlines can determine the minimum price for selling a slot and the maximum price for buying another one. The proposed mechanism further ensures a confidential way of communication between affected ATM stakeholders by using flight delay margins as a way to express priorities among the flights of an airline. This renders any complex credit systems unnecessary.

5. Methodology

The first step of the research project was comprised of an extensive literature review to document the status quo on airline operations management. Thereby, the concepts of robustness and resilience in airline schedules were defined and methods were summarised how to study them appropriately. The review resulted in an overview of the modelling approaches to achieve robustness or resilience, including a summary of the applied robustness/resilience options in previous research projects.

In the second stage, a new modelling approach was proposed that aims at filling the research gap between high-level models for aircraft, crew and passenger recovery and very detailed models for the optimal scheduling and assignment of ground operations. The goal was to develop a tactical decision support model which facilitates better coordination between the AOCC – that controls the entire airline network – and the airport control unit of the AOCC – that has often been neglected in recovery models but in real operations considers local constraints at a central node in the airline network.

Given that disturbances typically occur on a local level (e.g., during the turnaround), the newly proposed model is based on a modelling class that has already been applied to ground operations scheduling problems, i.e., the Resource-Constrained Project Scheduling Problem (RCPSP). The purpose of the local modelling focus is to mitigate schedule deviations directly at the root of the problem before they induce critical interdependencies onto subsequent flights. Thus, local intervention may spare complex recovery options, such as flight cancellations, aircraft or crew swaps, which require network-wide adjustments of the initial schedule. Therefore, an optimized nominal schedule (which may include options for achieving network-wide robustness) is adopted from long-term schedule planning, including all relevant hard constraints corresponding to aircraft rotations, maintenance and crew duty time regulations. At the tactical planning level, the RCPSP model integrates a maximum level of resilience by jointly considering the recovery capacity of all applicable options at the airline's hub airport. These options are derived from a summary of recovery options that was retrieved from the research literature, such that the classical RCPSP is extended with recovery options to accelerate turnaround processes, to eliminate interdependencies between processes and to reassign resources to different process sets.

For the consideration of downstream operations after the departure of a flight from the airline hub airport, a new method was developed within this PhD project that calculates flight-specific delay cost functions on the basis of individual constraints and cost parameters that typically occur during the subsequent flight legs of an aircraft rotation. The resulting cost functions per flight are further integrated with historical operations data of the airline to consider probabilistic block times of all downstream flights. The incorporation of these stochastic block time distributions allows to estimate the stochastic propagation of delay and its related costs within the downstream airline network, such that the resulting stochastic delay cost functions are implemented into the RCPSP model.

Across the literature, airline and airport operations are predominately analysed in case studies of a specific environment, i.e., within one airline's network or at one airport. Thus, the extended RCPSP model was applied to a self-developed airline case study network (see details in the next section).

Given the wide range of independent variables within the socio-technical system of air transportation, a factorial design with scenario techniques was considered to analyse the impact of the newly proposed model on an existing operational environment. Thereby, according to the study of Cook et al. (2016), three predominate elements need to be incorporated in a factorial setup for measuring resilience: "1) systemic impact; 2) total recovery effort, and; 3) resilience-enhancing investments".

ATFM capacity constraints are considered as systemic impact and are differentiated according to their type, spatial and temporal scope. Thus, three scenarios (S1-S3) include airport capacity constraints at the airline's hub airport that affect all flights of the airline with increasing magnitude of delay, while three other scenarios (S4-S6) consider airspace capacity constraints somewhere else in the network, such that only a fraction of flights obtains ATFM delays. In all six scenarios, aircraft rotations, crew pairings and passenger itineraries remain constant to compare the impact of the ATFM disturbances among scenarios.

In terms of recovery effort, each scenario was split into various instances with increasing availability of recovery options – starting from a reassignment of aircraft stands only and ending at a full integration of all options, including quick-turnaround, stand reassignment, passenger rebooking as well as airline-internal ATFM arrival and departure slot swapping. For the fully integrated model, further instances were calculated with different types of delay cost functions to study the impact of downstream constraints onto the local schedule recovery solutions.

Finally, to consider resilience-enhancing investments, a sensitivity analysis was conducted to study the impact of reduced or increased schedule buffers as well as a higher availability of reserve resources for the turnaround.

In the final stage of the project, all scenarios were analysed with respect to the three research objectives and according to three common key performance indicators: tactical airline costs (which was also the objective function of the extended RCPSP model), average flight delay and average passenger delay. Furthermore, also the number of required recovery options as part of an optimal solution was studied to gain further insights about the total recovery effort.

6. Description of the data the study relies on

In order to analyse the recovery performance of the integrated schedule recovery model, the study required airline data for at least one day of operations for all network layers, i.e., flight plan, aircraft rotations, crew pairings, passenger itineraries, airport stand allocation, ground handling schedules, initial flight plans and ATFM capacity regulations per flight.

Given that most of these data are confidential, the development of an airline case study network was required to perform the analysis. Therefore, 17 aircraft rotations (84 flights that form a representative sample of domestic, continental and intercontinental flights from the total flight schedule on that day of operations) were extracted from a pre-pandemic and publicly available Lufthansa flight plan during the summer season 2019. The schedule data were enriched with data from a self-developed crew assignment model and a passenger transfer simulation. Airport data at the Lufthansa hub in Frankfurt airport were retrieved from public websites on the day of the case study, while ground handling schedules were built arbitrarily as part of the research design. Initial flight plans (M1) were provided by EUROCONTROL for all flights on the day of the case study, whereas ATFM capacity constraints were generated as part of the scenario design.

Further long-term airline operations data were required to fit probability density functions as a basis for the stochastic turnaround target time prediction model and the flight-specific stochastic delay cost functions. Those data were obtained by the department in previous research projects and re-configurated for the application in the scope of the case study.

7. Computational experiments

A stochastic turnaround process estimation model has been adapted from previous research projects (Fricke and Schultz, 2009; Oreschko et al., 2012) at the department of Air Transport Technology and Logistics at Technische Universität Dresden as described in Evler et al. (2021, 2018). Furthermore, the methodology to generate flight-specific stochastic delay cost functions is documented in Evler et al., (2022b). Both methods were used to generate input parameters for the RCPSP turnaround scheduling model based on the operational circumstances of the case study.

The model was then split into various instances to reflect upon the various levels of integration. Table 1 documents all the instances with their respective recovery options that have been applied to all disturbance scenarios. Note that the considered flight-specific stochastic and deterministic delay costs have been defined as part of this project, while reference delay costs have been adapted from statistically averaged values per aircraft type as determined in Cook & Tanner (2015).

Table 1 – Overview of all calculated recovery model instances per disturbance scenario.

Scenario ID	***Available Recovery Options***	***Considered Delay Costs***
Baseline	PAX Rebooking (to ensure feasibility)	Stochastic Delay Costs Deterministic Delay Costs Reference Delay Costs
Inbound Recovery	Stand Reallocation, Quick PAX Transfer, Quick De-/Boarding	Stochastic Delay Costs
Outbound Recovery	PAX Rebooking, Standby Crew, Flight Retiming (Wait for PAX)	Stochastic Delay Costs
Turnaround (TA) Recovery	Inbound + Outbound Options	Stochastic Delay Costs
TA + Arrival Slot Swaps	Inbound + Outbound Options + Internal Swap of Arrival Slots	Stochastic Delay Costs
TA + Arrival + Dep. Slot Swaps	Inbound + Outbound Options + Internal Swap of Arrival Slots + Internal Swap of Dep. Slots	Stochastic Delay Costs Deterministic Delay Costs Reference Delay Costs

Each instance of the extended RCPSP turnaround scheduling model was solved with IBM CPLEX Version 12.10.0-0 on a 24-core CPU with 32GB RAM. In order to reflect the tactical setting, the solution process for each scenario instance was aborted after one hour if the optimality of a solution could not be proven, e.g., there was still a gap between the upper and lower bounds, and the respective solution was considered within the analysis.

8. Results

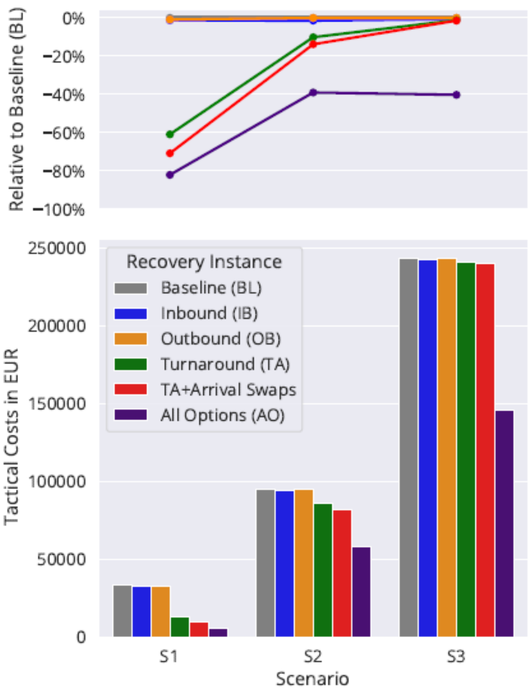
Results were documented with respect to the three research objectives, while a sensitivity analysis has tested their general validity.

Efficiency of Schedule Recovery with Constrained Resources

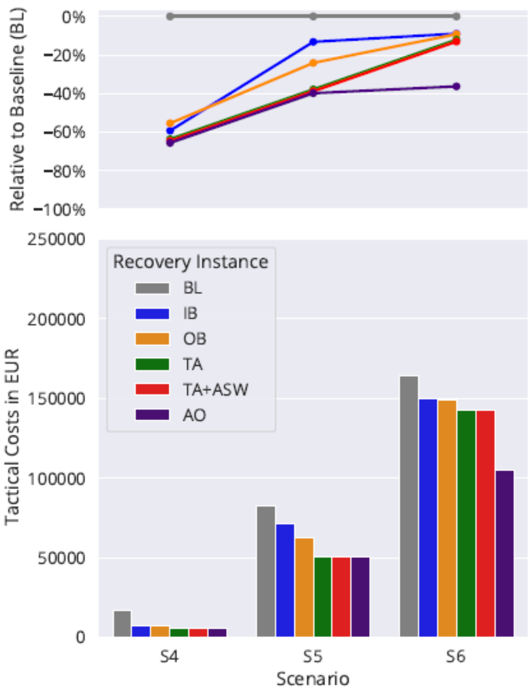
Fig. 1 compares the tactical cost for the airline (objective function) across all scenarios and recovery instances. Looking only at airport constraint scenarios *S1-3* (see Fig. 1a), it is obvious that inbound and outbound recovery options have almost no impact on costs when applied individually. Conversely, in the airspace constraint scenarios (see Fig. 1b), both recovery categories are able to reduce tactical airline costs by more than 50% in the low delay scenario *S4* and 9% in the high delay scenario *S6*.

The tactical cost reduction achieved by all turnaround recovery options without or with arrival slot swapping (i.e., instances *TA* or *TA+ASW*) lies above 60% in the low delay scenarios but reduces sharply at higher magnitudes of delay. Thus, with high delays for all flights in *S3*, both recovery instances have no considerable impact on costs, whereas in *S6* they can reduce tactical costs by less than 20%. The reasons for this are further discussed in the next section when the emphasis is put on downstream costs. Generally note that the additional savings gained by arrival slot swapping on top of all turnaround recovery options are only marginal in *S1-3*, while no benefit is achieved in *S4-6*. In both cases, the limited efficiency may be caused by the fixed departure slots, which cause high reactionary delay costs that cannot mitigated during the turnaround.

The consideration of all recovery options in instances *S1-6 AO* naturally scores the highest cost reductions. During airport constraints (see Fig. 1a), the inclusion of *departure slot swapping* and *flight retiming* helps to reduce tactical airline costs by another 12% in comparison to *S1 TA+ASW* and 39% in comparison to *S3 TA+ASW*. In contrast, under the influence of airspace disturbances (see Fig. 1b), the *AO* instances outperform the *TA* and *TA+ASW* instances only under high delay circumstances. Thus, independent of their scope, airport constraints require a relatively high level of flexibility for airlines, while scenarios with low to medium delays in a part of the network may also be recovered without tactical slot swapping.



(a) Recovery performance in Scenarios 1-3.



(b) Recovery performance in Scenarios 4-6.

Figure 1 – Objective values of the turnaround scheduling model compared per scenario instance.

Influence of Downstream Operations on Schedule Recovery

Fig. 2 shows the optimal departure delay per flight in comparison to the applied delay cost functions (green = reference delay costs, red = deterministic delay costs, blue = stochastic delay costs). It is obvious that the optima slot assignment (delay bars) mirrors the shape of the incorporated cost functions. Given that all cost functions are still closely aligned with each other at low delay levels, many of the assigned slots are similar or even equal between instances in *S1* and *S2*. Thereby, the difference in the mean absolute deviation of optimal delays from the baseline is 1.3 minutes in *S1* and 3.1 minutes in *S2*.

Starting at delays above 45 minutes, the offset between all types of cost function becomes more apparent, such that it causes a larger heterogeneity among optimal delay values per flight in *S3*. The mean absolute deviation of optimal delays from the baseline ranges from 4.6 minutes in *S3* when reference delay cost functions are applied to 30.3 minutes and 36.9 minutes with stochastic and deterministic delay cost functions respectively. The low deviation in the reference cost instance is also expressed by a low cost efficiency of a schedule recovery with such cost functions. Thereby, the homogeneity of cost functions among all flights results in the outcome that a certain slot is associated with similar delay costs on many flights, such that swapping flights among slots cannot reduce these costs. Furthermore, reference cost functions overestimate downstream costs of the baseline delays for eight of the 15 aircraft rotations, which induces higher baseline costs in *S3*.

Vice versa, the heterogeneity of deterministic and stochastic cost functions among all flights creates more efficient slot swapping opportunities as part of the schedule recovery process. Note how in the deterministic instances many delays are assigned directly before larger step costs (see 85 and 95 minute thresholds on flight F92, the 35 minute threshold on F132 and the 40 minute threshold on F152 in Fig. 2). In comparison, stochastic cost functions consider downstream recovery potential and block time uncertainties, which smooths the blue cost functions and allows some flights to obtain departure delays slightly higher than a critical delay threshold -- best visible on blue delay bars of flights F102 and F132 in comparison to their respective red delays with deterministic costs. This frees up time and resources which can be allocated to more critical aircraft rotations.

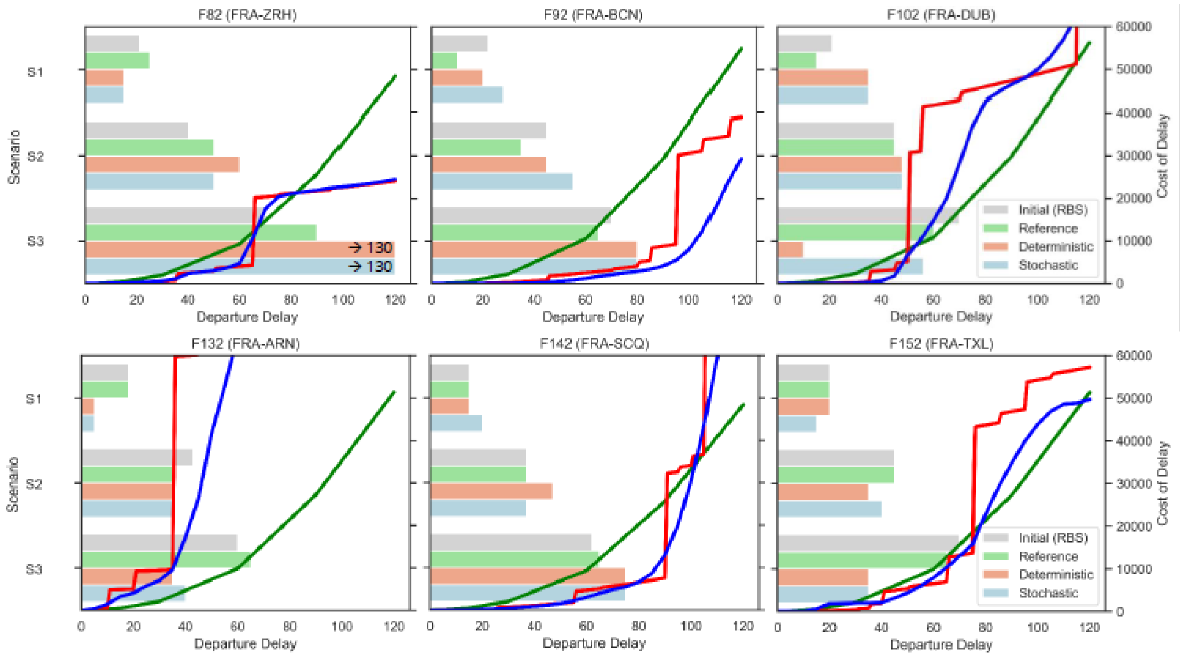


Figure 2 – Assigned departure delay per flight and scenario in comparison to the respective delay cost function.

Definition of Flight Priorities and Slot Values

When arrival and departure slots can be swapped in instances with full integration of all options (AO), the complexity of arrival and departure slot swaps increases along with the magnitude of delays. Complexity in this case means the average number of flights involved across all swap cycles. Thus, for arrival swaps it ranges from 2.5 in *S1* to 5.5 in *S3*, while for departure slots it goes from 3.0 in *S1* to 5.0 in *S3*, whereby in the last case, all departure flights are swapped to another slot (see Fig. 3 left).

For the coordination with ATFM, the concept of flight delay margins allows to omit priority values introduced by the UDPP (Pilon et al., 2016) entirely and reproduces the optimal flight priority for the airline by assigning each slot to the valid flight with the least available delay margin. A delay margin starts with the scheduled in-block time for the respective arrival flight (scheduled off block time for departure flights) and ends with the arrival/departure delay associated to its optimal ATFM slot that was calculated by the turnaround scheduling model (see Fig. 3 right).

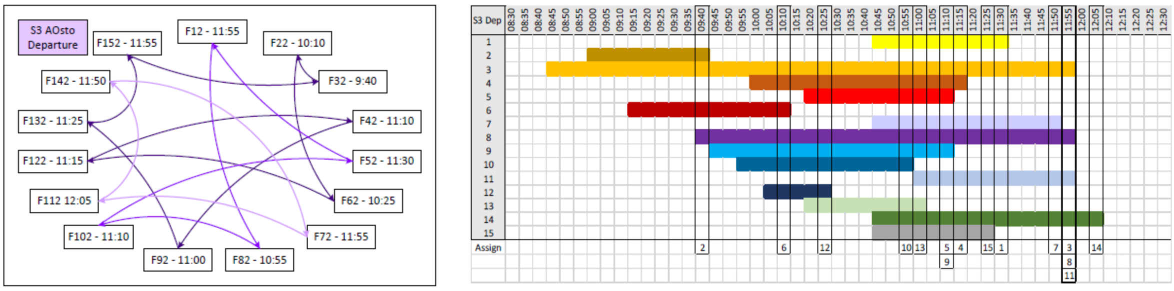


Figure 3 – Optimal departure slot swaps for departure flights in S3 (left) can be expressed by flight delay margins (right).

Slot values are analysed for inter-airline trades and also for cases in which the airline could buy additional slots from a central institution (e.g., the network manager). Fig. 4 (left) exhibits the change in tactical costs for the airline when it would vacate five different arrival slots and would gain another slot instead by trading with another airline in scenario *S1*. It is obvious that tactical costs are rising progressively when gained slots are later and especially when a gained slot is only available at the end of a hub bank after the last initially assigned arrival slot, i.e., at 11:00 a.m.

If the airline would gain an additional slot without trading one of its initial slots, one might expect that tactical costs are decreasing. In turn, this would imply the value of the additional slot and a maximum price the airline should pay for it. Fig. 4 (right) shows that an additional departure slot early during the departure hub wave can reduce tactical costs by up to 56,000 EUR (38%) in the high delay scenario *S3*. Later departure slots may still have a value of up to 25,000 EUR (17%) in *S3* but no benefit in *S1*.

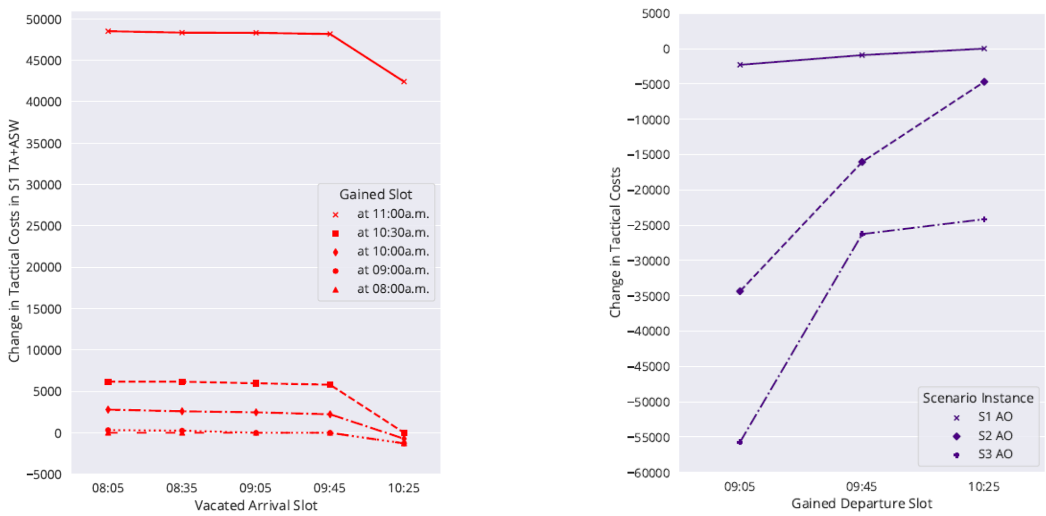


Figure 4 – Impact of trading an initially assigned slot with a newly gained slot on tactical costs for the airline (left) in S1 and impact of an additionally gained slot (without vacating an own slot) on costs in different delay scenarios (right).

Sensitivity of Optimized Schedule Recovery Solution

The previous three sections have already highlighted that optimized schedule recovery solutions are sensitive towards the scope and intensity of a disturbance, the incorporated costs of delay and the possibility to swap arrival or arrival *and* departure slots. This section of the analysis has studied three further aspects that have a more strategic planning focus: 1) it assesses whether the system resilience and related tactical costs can be generalised for similar disturbance intensities (low, medium, high delays) or are also sensitive to the temporal occurrence of a capacity constraint; 2) it attempts to determine the tactical value of strategic schedule buffers by increasing and decreasing ground buffers, such that the change in tactical costs and system performance can be compared to the strategic costs of buffers; and 3) it does the same with regard to the strategic costs of reserve resources, such that the tactical cost savings of extra resources are analysed.

The analysis of a capacity constraint *S3** that starts one hour earlier than the one studied in *S3* shows that the efficiency of inbound and turnaround recovery is much higher in such a constellation, given that arrival flights obtain higher delays in such a constraint than the planned departure flights of the same aircraft (see Fig. 5 left). This increases the time pressure on turnaround processes in *S3** in comparison to the standard scenario S3, in which most departure flights obtained higher delays than their associated arrival flights. Consequently, the efficiency of the fully integrated model (AO) increases in *S3** (see Fig. 5 right) and all results emphasize the high sensitivity of airline recovery results with respect to the circumstantial parameters.

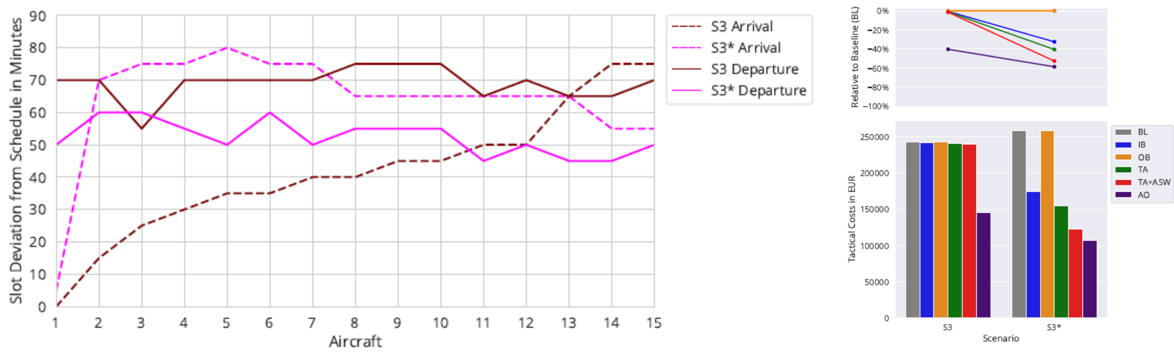


Figure 5 – Deviation of ATFM slot from schedule per aircraft (left) when airport capacity constraint starts at 7 a.m. (beginning of airline arrival hub wave) and at 6 a.m. (one hour before first arrival) and the impact of tactical costs in both cases (right).

The sensitivity analysis of the second point has shown that additional buffers seem to improve the efficiency of schedule recovery significantly, though have only limited value for the absorptive capacity of the nominal schedule (baseline costs and performance). In turn, reduced schedule buffers by on average 5 minutes on some turnarounds would increase the baseline tactical costs in *S3* by 38,000 EUR (+15.6%). In comparison, 60 minutes of higher aircraft utilisation (it might be less depending on newly planned aircraft rotations) save the airline about 950 EUR in opportunity costs.

Finally, the tactical cost savings achieved by additional recovery resources are only marginal (< 0.5%).

9. Analysis of the results

First Research Objective – System Resilience in an Airline Network

System resilience has been analysed for two types of disturbance in six scenarios with five different levels of schedule recovery integration each. The findings suggest that the highest level of integration naturally results in the lowest tactical costs for the airline. The highest level of integration includes recovery options to accelerate turnaround and transfer processes, to reallocate aircraft among stands and to reassign aircraft among arrival and departure slots. However, in terms of operational efficiency metrics, full integration does not always guarantee the highest resilience.

As a matter of fact, in scenarios in which all flights are impacted by airport capacity constraints, average flight delay within the assigned ATFM slots remains unchanged as stipulated by the concept of fairness among airspace users. Flight delays can only be recovered in situations in which some aircraft would not reach their initial departure slots, given that their arrival flights obtain higher delays than their departure flights. Swapping arrival and departure flights among their slots (AO instances) can render alternative slots unnecessary but may require more transfers to be rebooked to make the swaps feasible.

In scenarios in which only some flights are impacted by a disturbance, e.g., during airspace constraints somewhere in the airline network, flight delays tend to increase when all recovery options are integrated (AO). This is due to some initially not affected flights being purposely delayed to wait for important transfer passengers. It implies that the airline would incur higher tactical costs from passenger rebooking (and the resulting higher delay for these passengers) in comparison to flight delays when both metrics are optimized under a common objective function. Indeed, according to EU Regulation 261, the rebooking of passengers onto alternative flights may involve substantial costs for care, compensation and lodging. These may even apply in cases of external influences, given that the airline may be liable for the delay if it actively engages in schedule recovery, i.e., the redistribution of delays among flights.

Neglecting some recovery options in such situations can have a wide range of consequences. For instance, maintaining all passenger transfers and not engaging in slot swapping (inbound instances IB) results in the lowest flight and significantly reduced passenger delays -- mainly due to the limited possibilities to wait for high liability transfer passengers or to rebook less costly passenger groups onto later flights. At the same time, these limitations provide the least reduction in terms of tactical costs. Conversely, integrating just the turnaround recovery options (TA) may lead to increased flight and passenger delays. Passenger connectivity may be equal and fewer rebooking is required, but the impact on tactical costs is only limited. This is because departure flights obtain delays within their firmly assigned slots that may infringe cost-intensive downstream constraints in the aircraft rotations. In the analysed case study, such cost-intensive constraints mainly appear for delays above 45 minutes, such that the inclusion of arrival and especially departure slot swapping (AO) is very important in all high delay scenarios to redistribute delays onto rotations with less costly constraints and larger downstream recovery capacities. Table 2 presents a summary of the findings.

Table 2 – Summary of results on system resilience

Disturbance Type	Tactical Costs	Avg. Flight Delay	Avg. Passenger Delay
Airport Constraint	if avg. flight delay > 45min, main reduction only with ***AO***, as it redistributes dep. delays onto less cost-critical rotations*	equal → fairness guaranteed; ***TA*** and slot swapping render alternative slots unnecessary	slightly increase with ***AO***, as more rebookings are required to make departure slot swaps feasible
Airspace Constraint	higher impact of ***TA***, but ***AO*** needed for high delays as it redistributes dep. delays onto less cost-critical rotations	delays tend to increase as initially not affected flights wait for transfer passengers from delayed flights	best with ***IB***, increase with ***TA*** and can be maintained at ***BL*** level with ***AO***

*all solutions are very sensitive to exogenous parameters

Second Research Objective - Influence of Downstream Delay Costs

The findings emphasize that schedule recovery based on statistically fitted reference delay costs per aircraft type demonstrates a poor system resilience and has only little impact on tactical costs at higher delays. Thereby, it is the homogeneity of reference delay cost functions for a fleet of similar aircraft that makes them unsuitable for flight-by-flight prioritisation. For instance, when swapping flights among ATFM slots, aircraft of the same type are represented with similar delay costs, such that most swaps make no difference in terms of tactical costs for the airline. This highlights the further dangers of using average delay costs in decision-making.

By studying the raw data of the statistical fitting procedure, this dissertation presents a mathematical formulation for flight-specific delay cost functions. These functions can incorporate all major constraints, buffers, and recovery capacities in the downstream aircraft rotation without having to model the entire downstream network explicitly. They further allow the consideration of uncertainty in the delay propagation by describing stochastic delay costs. Optimal schedule recovery solutions are calculated with and without respecting downstream uncertainty and the results suggest that an optimization based on deterministic delay cost functions, i.e., excluding uncertainty, consistently overestimates the potential (baseline) tactical costs arising from a disturbance. Compared to this, an optimization based on stochastic delay cost functions, i.e., including uncertainty, provides a more realistic estimation of the costs caused by delay propagation, given that they reveal 'hidden' downstream recovery potential and routes that foster delay propagation.

Stochastic cost functions further benefit the local schedule recovery, such that in the case study, optimal recovery decisions based on stochastic delay costs result in different slot allocations and can maintain more passenger transfers at the hub airport. In consequence, tactical costs in the analysed scenarios are up to 22,000 EUR (15%) lower in comparison to an optimization based on deterministic delay costs.

Third Research Objective - Flight Prioritisation and Slot Values

The analysis has revealed that no general optimal slot swapping scheme can be identified for the analysed scenarios. This is due to the optimal swaps being highly sensitive to the magnitude of delay and the available recovery options. In fact, optimal swaps differ between instances in which departure slots are fixed and when they can be swapped. Thereby, the number of flights involved per swap (the complexity) increases with the magnitude of assigned delays, such that almost all flights are swapped with each other in the high delay scenario.

Unaffected by the swap complexity, flight priorities are best communicated by defining optimal delay margins for all flights, i.e., 'best' in terms of preserving confidentiality and providing a priori flexibility. Delay margins contain the scheduled in-/off-block time and the optimal delay per flight as calculated by the schedule recovery model. Any further assigned recovery options can be kept internal and the definition of priority values is not required. Deriving priority values from an optimal ranking or from optimal flight delays are found to create issues about the appropriate time-distancing of flights within the available slots and should best be avoided.

Optimal delay margins have the additional advantage of revealing only one delay margin per flight for a particular disturbance (UDPP describes several margins per flight). Only one margin provides a very high level of confidentiality, especially when considering that solutions are very sensitive to several circumstantial parameters. In fact, with different disturbances or delay constellations, the optimal delay margin per flight is frequently changing and is unlikely to reveal sensitive details about the underlying cost function.

Finally, the integrated schedule recovery model can define the value of ATFM slots for the airline. These values may either be used within future slot trading mechanisms or slot auctions, although practical issues of transferability between different airports and days may persist. Thereby, they may be considered as part of the objective function by using a dummy price for a traded slot, while initial slots are free of charge.

The results emphasize the necessity that airlines evaluate potential slot trades with a sophisticated decision support tool and within the context of other available recovery options. In fact, the value of a slot and the efficiency of a slot trade for an airline is highly sensitive to operational constraints and depends on:

1) the ratio between flights and slots;
2) the temporal relationship between vacated and gained slots;
3) the affiliation of the slot to the set of arrival or departure flights;
4) the possibility to swap slots for arrival or arrival AND departure flights; and
5) the disturbance intensity and the related delays obtained by all flights.

Considering that vacating an arrival slot seems to increase tactical costs much more than any additional arrival slot might bring added value, it will be interesting to explore which slot trades would be beneficial for both participating airlines. At least in cases in which an airline needs to cancel a flight, receiving some compensation for the vacated slot might incentivise an earlier slot release.

10. Conclusions and look ahead

Generally, it must be noted that the system resilience of an airline hub network is highly sensitive to the scope and intensity of a disturbance, its temporal occurrence in relation to a hub bank, the incorporated method for downstream delay costs, as well as the available recovery options and strategically assigned buffer capacities. Further system volatility may result from the airline business model, e.g., daily changing aircraft rotations, crew pairings and passenger itineraries that have been fixed for this study to obtain comparable results for one day of operations. It might be concluded that airline network resilience should not be defined based on a small sample of scenarios but rather for longer periods, e.g., an entire season containing all types of disturbance.

Given that the analysis is limited to a few scenarios, the reviewed case study finds no optimal schedule recovery solutions which might be generalised for certain types of disturbance, or which could validate 'rule-of-thumb' procedures as currently applied in AOCC decision-making. An airline network around a major hub airport is a stochastic system that typically puts a strain on the available capacity of the airport (especially during peak times). In such a system, the complex interdependencies among constrained resources may constantly create new schedule deviations which require a flexible and efficient optimization method as part of an AOCC decision support system. *Flexible* means that the method needs to cope with the volatility of exogenous circumstances and the changing availability of recovery resources. This may include flexible recovery objectives ranging from 1) cost-minimisation in times of economic crisis; 2) high connectivity before important holidays (e.g., rebook no passengers before Christmas); or 3) high punctuality for different airline business models. *Efficient* means that all available recovery options are integrated, such that their combined performance can be assessed without iterations within a given time frame – typically in a close to real-time setting.

The schedule recovery model developed in this dissertation provides a high level of flexibility and is among the first to integrate all recovery options that are available to airlines at major airports in their network. The chosen integration based on costs enables the optimization of various performance metrics at once, all of which may obtain different weighting factors or additional constraints to support the individual recovery objectives mentioned above. Costs may also be used as a common denominator in strategic schedule planning and tactical schedule recovery to assess the resilience of a seasonal schedule for typical disturbances well in advance. In fact, results of a sensitivity analysis show that additional schedule buffer can further reduce tactical costs and increase system resilience, despite having no added value in terms of delay absorption (i.e. schedule robustness).

Finally, the proposed model supports the case-specific and automated evaluation of inter-airline slot trading procedures which may be required for the implementation of future ATM performance enhancements.

Future research may proceed in five directions:

1. **Model Validation in Real Operations**

A next step could be the further validation of the integrated schedule recovery model in real operations – namely in shadow-mode operation of the daily procedures in an AOCC. This may enable a comparison between the recovery performance of current AOCC procedures and the optimal solutions of the proposed model. Over longer periods (e.g. one winter and one summer month), it may further help to determine the resilience of the given airline schedule by considering daily changing aircraft, crew and passenger flows and the influence of various disturbances.

2. **Stochastic and Robust Optimization of Turnaround Processes**

While this dissertation has analysed whether optimal schedule recovery solutions are sensitive to different disturbance intensities, future research may study the impact of smaller, system-inherent deviations and aim for robust solutions based on stochastic input data.

A conceptual study has already transferred the proposed model into a chance-constraint model for the schedule recovery of a single turnaround (Asadi et al., 2020), such that future research might aim at increasing the scope to multiple parallel turnarounds which are connected via passenger transfers.

3. **Integration of Local Schedule Recovery with Trajectory Management**

Due to the application of the proposed model on ATFM capacity constraints, arrival delays per slot are considered as given and cannot be reduced by recovery options which may manage the trajectory of the arrival flight. Though, other disturbances might allow more flexibility for arrival flights, such that the local schedule recovery model at the hub airport may be extended by in-flight recovery options, e.g., dynamic cost indexing and flight re-routing. Including trajectory management into schedule recovery may also enable the consideration of environmental parameters and an even wider policy context with trade-offs between airline costs, delay and ecological footprint resulting from a disturbance.

4. **Integration of Local Schedule Recovery with Aircraft Recovery**

Given that the integration of schedule recovery options focuses on local capacities at the airline's hub airport, tactical recovery options within downstream aircraft rotations, such as aircraft swaps, equipment changes, using reserve aircraft or flight cancellations are currently neglected. Thus, future research may integrate the local schedule recovery model with common approaches to the aircraft recovery problem or proceed with the proposed approach of flight-specific delay cost functions, or a combination of both. A conceptual study has already tested the integration of the proposed local schedule recovery model for ground operations with an aircraft recovery model based on the Heterogeneous Vehicle Routing Problem with Time Windows (HVRPTW) – see Evler et al. (2022a).

5. **Model Application within Slot Trading Mechanisms**

Finally, the integrated schedule recovery model may be used in the context of the Airport Operations Centre (APOC) by several airlines negotiating for the best usage of the available airport resources during capacity constraints. If all airlines were to apply the model, this would allow the evaluation of the efficiency of inter-airline slot trades, such that new ATFM slot trading mechanisms, such as secondary slot trading or slot auctioning, could be studied and validated.

11. References

11.1 Link to PhD thesis / repository

The dissertation will be published as an open-access document at the TU Dresden platform https://tud.qucosa.de/ after the defence and once all requirements named by the evaluators are incorporated into a final public version.

11.2 Associated outputs and publications

1. Evler, Asadi, Preis, Fricke (2018), Stochastic Control of Turnarounds at HUB-Airports – 8th SESAR Innovation Days
2. Evler, Asadi, Preis, Fricke (2020), Integrated Operations Control at Hub-Airports with Uncertain Arrival Times , 9th ICRAT (Best Paper Award – later published in 4.)
3. Evler, Schultz, Fricke, Cook (2020), Development of Stochastic Delay Cost Functions – 10th SESAR Innovation Days
4. Evler, Asadi, Preis, Fricke (2021), Airline ground operations: Optimal schedule recovery with uncertain arrival times – Journal of Air Transport Management 92
5. Evler, Asadi, Preis, Fricke (2021), Airline ground operations: Schedule recovery optimization approach with constrained resources – Transportation Research Part C: Emerging Technologies 128
6. Evler, Schultz, Fricke (2021), Flight Prioritization and Turnaround Recovery – 14th ATM R&D Seminar
7. Evler, Lindner, Fricke, Schultz (2022), Integration of Turnaround and Aircraft Recovery to Mitigate Delay Propagation in Airline Networks - Computers & Operations Research 138
8. Evler, Schultz, Fricke, Cook (2022), Stochastic Delay Cost Functions to Estimate Delay Propagation under Uncertainty, IEEE Access 10
9. Evler, Rosenow, Fricke (2022), Airline Schedule Recovery at Hub Airports with Flight Re-Routing and Dynamic Cost Indexing, 10th ICRAT

11.3 References cited in this report

Asadi, E., Evler, J., Preis, H., Fricke, H., 2020. Coping with Uncertainties in Predicting the Aircraft Turnaround Time at Airports, in: Operations Research Proceedings 2019, Operations Research Proceedings. Springer International Publishing, Dresden. https://doi.org/10.1007/978-3-030-48439-2_94

Cook, A., Delgado, L., Tanner, G., Cristóbal, S., 2016. Measuring the cost of resilience. Journal of Air Transport Management 56, 38–47. https://doi.org/10.1016/j.jairtraman.2016.02.007

Eurocontrol, 2020. PRR 2019 - Performance Review Report. https://doi.org/10.1163/1570-6664_iyb_SIM_org_39214

Eurocontrol, 2016. Resilience 2050. Final Report Summary - RESILIENCE2050.EU (New design principles fostering safety, agility and resilience for ATM). URL https://cordis.europa.eu/project/id/314087/reporting/fr

Evler, J., Asadi, E., Preis, H., Fricke, H., 2021. Airline ground operations: Schedule recovery optimization approach with constrained resources. Transportation Research Part C: Emerging Technologies 128, 103129. https://doi.org/10.1016/j.trc.2021.103129

Evler, J., Asadi, E., Preis, H., Fricke, H., 2018. Stochastic Control of Turnarounds at HUB-Airports, in: 8th SESAR Innovation Days 2018. Salzburg, p. 9.

Evler, J., Lindner, M., Fricke, H., Schultz, M., 2022a. Integration of turnaround and aircraft recovery to mitigate delay propagation in airline networks. Computers & Operations Research 138, 105602. https://doi.org/10.1016/j.cor.2021.105602

Evler, J., Schultz, M., Fricke, H., Cook, A., 2022b. Stochastic Delay Cost Functions to Estimate Delay Propagation Under Uncertainty. IEEE Access 10, 21424–21442. https://doi.org/10.1109/ACCESS.2022.3152570

Fisher, M.L., Jaikumar, R., Van Wassenhove, L.N., 1986. A Multiplier Adjustment Method for the Generalized Assignment Problem. Management Science 32, 1095–1103. https://doi.org/10.1287/mnsc.32.9.1095

Fricke, H., Schultz, M., 2009. Delay Impacts onto Turnaround Performance, in: 8th USA/Europe Air Traffic Management Research and Development Seminar (ATM2009). p. 10.

Hassan, L.K., Santos, B.F., Vink, J., 2021. Airline disruption management: A literature review and practical challenges. Computers & Operations Research 127, 105137. https://doi.org/10.1016/j.cor.2020.105137

Heger, S., 2018. Entwicklung und Einsatz eines Entscheidungsunterstützungssystems in der Verkehrszentrale einer Fluggesellschaft. Technische Universität Darmstadt, Darmstadt.

Oreschko, B., Kunze, T., Schultz, M., Fricke, H., Kumar, V., Sherry, L., 2012. Turnaround Prediction with Stochastic Process Times and Airport Specific Delay Pattern, in: 5th International Conference for Research in Air Transportation (ICRAT2012), ICRAT. p. 9.

Pilon, N., Cook, A., Ruiz, S., Bujor, A., Castelli, L., 2016. Improved Flexibility and Equity for Airspace Users During Demand-capacity Imbalance, in: 6th SESAR Innovation Days. Delft, p. 8.

Pilon, N., Hermann, K.-D., Ds, A., Hlousek, P., Hripane, M., Parla, E.P., Rousseau, F., Chiesa, D., Albert, G.Q., Muller, D., 2019. PJ07 Final Project Report. Eurocontrol.

Wu, C.-L., 2016. Airline Operations and Delay Management: Insights from Airline Economics, Networks and Strategic Schedule Planning. Routledge.

Wu, C.-L., Law, K., 2019. Modelling the delay propagation effects of multiple resource connections in an airline network using a Bayesian network model. Transportation Research Part E: Logistics and Transportation Review 122, 62–77. https://doi.org/10.1016/j.tre.2018.11.004

Annex I: Acronyms

Term	**Definition**
APOC	Airport Operations Centre
AOCC	Airline Operations Control Centre
ASW	Arrival Slot Swapping (Schedule Recovery Option)
ATFM	Air Traffic Flow Management
HVRPTW	Heterogeneous Vehicle Routing Problem with Time Windows
MILP	Mixed Integer Linear Programming
RCPSP	Resource-Constrained Project Scheduling Problem
TA	Turnaround Recovery (Set of Schedule Recovery Options)
UDPP	User Driven Prioritisation Process