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Stochastic Control of Turnarounds at HUB-Airports

A microscopic optimization model supporting recovery decisions in day-to-day airline ground operations

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Abstract— **A new approach is proposed to stochastically model parallel turnaround operations. Based on a microscopic process model, this paper introduces analytical and simulative methods to determine a presumable target off-block time and presents a scheduling approach to find optimal process alterations. An exemplary implementation at a HUB-airport provides extensive insights on the potential working procedure of the system, which will ultimately yield network costs for various disruption scenarios and give decision support for robust schedule recovery actions.**

Keywords - Aircraft Turnaround, Recovery Management, Scheduling, Simulation, Stochastic Control, Decision Support

I. Motivation

The aircraft turnaround is commonly described as a network of individual sub-processes which are carried out partly in parallel and partly in succession. Whilst not all scholars agree on the same number and sequence of sub-processes, the turnaround is uniformly defined to start with the arrival of an aircraft on position, commonly referred to as "In-Block" (IB), and ends with removal of wheel chocks, "Off-Block" (OB), after all servicing activities for the next flight have been completed [1]–[5]. The timespan in-between IB and OB, also known as available ground time (AVGT), is the only part of an aircraft's operational schedule that can be autonomously controlled by an airline and has been spotlighted in various research projects. Most of these rely on the assumption that airline schedules and their subsequent ground servicing contracts and recovery policies are created in a deterministic way. Thus, the sum of the individual sub-process durations, which are taken from aircraft constructors' handling manuals, determines the minimum ground time (MGT) needed in order to service an aircraft in-between two flight assignments, excluding taxi-in and out times. If possible, schedule buffers are added strategically to avoid delay propagation and relax the AVGT. In combination with the stochastic nature of aviation processes and the ever-increasing traffic density in the international air space, these scheduling procedures are observed to cause frequent and large-scale disruptions to the entire Air Traffic Management (ATM) system, which consequently turn into a loss of welfare for all related stakeholders, especially for airlines and passengers [6].

In order to deal with the occurring schedule deviations in day-to-day operations, a series of automated decision support tools was implemented by EUROCONTROL over the course of the last two decades in the context of Airport Collaborative Decision Making (A-CDM). At the moment, the most advanced procedures cover the arguably tightest bottleneck in aviation operations – the runway capacity. Arrival Manager (AMAN) and Departure Manager (DMAN) calculate optimal pre-sequences for Air Traffic Control (ATC) according to the specific characteristics of the queued aircraft. The Surface Manager (SMAN) extends this concept to the parking positions. Once an aircraft has reached its assigned position, ground operations proceed individually for each aircraft at the airport until ATC issues an engine start-up time and the new flight is scheduled for Departure Sequencing. In-between, the complex interaction among the involved stakeholders of one turnaround (see Fig. 1) is currently supervised by a Ramp Agent and monitored by an Airline Operations Controller (AOC) of the respective airline. Prior work of the Research Chair in Aviation and Logistics at TU Dresden has expanded the tool chain of AMAN, SMAN and DMAN for ground operations (Ground Manager GMAN – dashed box in Fig. 1) and introduced the stochastic prediction of target off-block times (TOBT), resp. target start-up approval times (TSAT), for single aircraft [7].

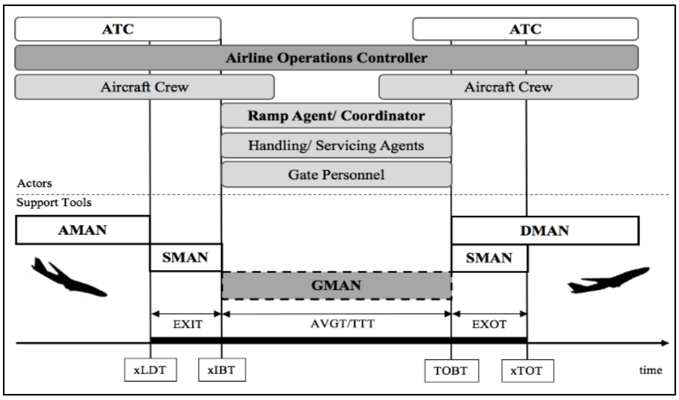

Figure 1. GMAN concept with involved actors and support tools in EUROCONTROL perspective. Modified from [7].

However, given the complexity of involved resources and their individual schedules, the concept of the GMAN should –

similar to A/D/SMAN – possess a station-wide perspective in order to be of better assistance to the AOC. In this way, negatively interacting schedule recovery interventions of parallel turnarounds could be avoided and AOCs get a better overview on the consequences of their clearances.

With the aim of presenting a modelling approach under simplified stochastic circumstances, this paper will start in Chapter 2 with an overview on the most recent research undertaken on the topic of turnaround operations. Chapter 3 and 4 will present the two fundamental functions of the new stochastic turnaround model – stochastic target time prediction and deterministic process scheduling. An implementation approach of the working procedure at a HUB-airport is outlined and analyzed in Chapter 5, while Chapter 6 provides conclusions and describes the scope of further research.

II. Research on Turnaround Operations

The precise prediction of the total turnaround time (TTT) and the modelling of the involved processes and disruption causes, also described as aircraft turnaround problem (ATP), has been approached from different methodological viewpoints [8]. Schlegel [9] used linear regression in order to describe the finishing times of individual turnaround processes for different aircraft types operated by the Lufthansa Group based on ALLEGRO-data. Building on the underlying principle of the Critical Path Method (CPM), some authors tried to implement the stochastic nature of ground handling processes by using the Project Evaluation and Review Technique (PERT) [2], [10]. As introduced above, Oreschko et al. [7] developed a stochastic simulation tool, called GMAN, for the prediction of the TOBT based on variable process parameters (starting time as a function of delay patterns) previously defined by Fricke & Schultz [11]. In a different piece of research, Rosenberger et al. [12] proposed a stochastic model for airline operations using Semi-Markov chains in combinations with Monte-Carlo Simulation, which was later extended by Wu & Caves [5] for the detailed simulation of turnaround activities. The peculiarity of the model by Wu & Caves is the inclusion of process disruptions as separate states, in which the network progress sojourns until the matter is resolved, which is usually depending on parameters drawn from delay code analyses.

There are some approaches addressing the problem of resource availability. Kuster et al. [4] extended the Resource Constraint Project Scheduling Problem (RCPSP) to include turnaround control options in a variable network graph. From a set of pre-defined task variations, a supervisor can choose which turnaround procedures are likely to produce the best outcome, given a certain schedule deviation. Conversely, a number of articles describes solving heuristics for the optimal allocation of ground servicing equipment (GSE), staff and deicing vehicles [3], [13], [14], or the tactical gate assignment [15].

A third group of scholars [16], [17], [18] acknowledged the ATP as a result of the multi-stage, deterministic airline scheduling procedure and built optimization models for the ideal implementation of buffer times as a pre-tactical control option to design schedules more robust.

The general aim of all concepts might be summarised as to provide a more accurate prediction of the flight-specific TOBT to an AOC in the airline´s operations control center (OCC). The TOBT is influenced by stochastic trigger parameters and acts as a foundation for the selection of potential schedule recovery decisions. However, the final decision on aircraft recovery actions might significantly affect turnaround events running in parallel at other aircraft and their respective downstream networks. This is especially the case at large-scale HUB-airports where process interdependencies can hardly be handled manually based on operational experience. Furthermore, it needs to be taken into account that recovery actions may fail to cut time from the projected duration and underlie the same probabilistic distributions as ground handling processes do. Concluding from this overview, a decision support system at this stage should use (1st) the probability prediction for a milestone in order to detect schedule deviations and (2nd) suggest tactical as well as proactive turnaround interventions so that overall network delay costs can be kept as low as possible. These two fundamental steps will be outlined in the next two chapters.

III. Prediction of the Target Off-Block Time

In order to predict the TOBT of a flight, one needs to predict the total processing time of the respective network chain. In a deterministic graph there is usually only one critical path, which is characterized by zero slack (highlighted in red in Fig. 2). However, in a stochastic model, more than a unique critical path might be expected due to variable individual process times. A standard turnaround comprises several core processes (highlighted in solid boxes in Fig. 2) and some optional processes, which are executed only occasionally, depending on e.g. weather (De-Icing) or crew schedules (Crew Exchange). Others have a relatively short duration and appear almost never on the critical path (Water and Toilet Servicing) or cause exceptional big disruptions, such as maintenance and repair, which are so far still out of the scope of this research. Sometimes and depending on the airline´s business model, even some of the traditional core processes are left out to guarantee short turnaround times, e.g. Catering or Cleaning for Low-Cost Carriers or Fuelling at out-stations (Tankering). For the remainder of this paper, only the processes highlighted in solid boxes in Fig. 2 will be considered for stochastic modelling. Dashed gray processes might be taken up in future research.

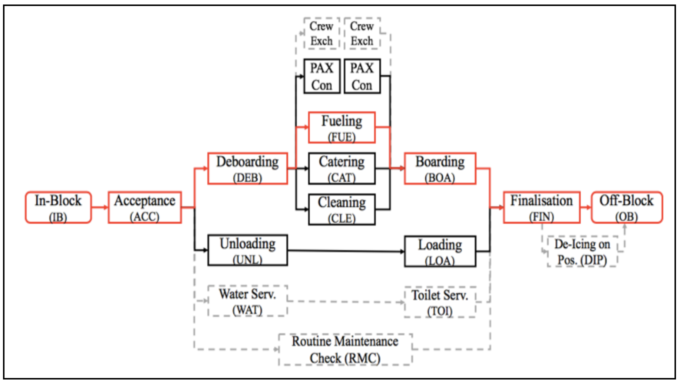

Figure 2. MPM Network Graph of a Standard Turnaround (dashed gray processes will not be further considered in this paper).

For the introduction of stochastic process times, normally distributed process durations were assumed with a mean which corresponds to deterministic values taken from an Airbus 320 ground operations manual (GOM) and an assumed standard deviation of one fifth of the mean (see Table I). This was done with the primary purpose of simplifying the mathematical expression of stochastic parameters in the analytical validation process, rather than respecting results of previous operational analyses, which found a good fit for Weibull-, Beta- and Gamma-distributed process durations [5], [11], [19].

TABLE I. STOCHASTIC TURNAROUND PROCESS DURATIONS

Process		**Mean Duration in min**	**St.Dev. in min = (0.2·Mean)**
Abbrev.	***Name***		
IB*	In-Block	-	-
ACC	Aircraft Acceptance	2	0.4
DEB	Deboarding	7	1.4
FUE	Fuelling	12	2.4
CAT	Catering	10	2.0
CLE	Cleaning	10	2.0
BOA	Boarding	21	4.2
UNL	Unloading	14	2.8
LOA	Loading	19	3.8
PAX	Passenger Transfer	30	6.0
FIN	Aircraft Finalization	4	0.8
OB*	Off-Block	-	-

All processes are normally distributed. *IB and OB as start and end events have no duration.

Starting from the defined distributions of the individual process durations, there are basically two ways to predict the joint network distribution for OB times – analytical convolution and Monte Carlo (MC) Simulation.

A) Analytical Convolution

To the best of our knowledge, no analytical solution deriving the joint network distribution of the TOBT was found so far. However, using step-wise analytical convolution and assuming the independence of the single processes, it is possible to determine the integral of a cumulative density function (CDF). This is done from inside out as shown in (1) to (9) based on the parameters of the individual distributions where $f_{X_i}(a)$ is the probability density function (PDF) for the duration $a \in R_0^+$ of process i and $F_{X_i}(a)$ is the corresponding CDF. In the first step, the distribution of the maximum of three parallel processes – fuelling, catering, cleaning – is determined by (1) to (3). Since these processes are assumed to be independent, it is worth mentioning that the CDF of the maximum can be written as multiples of the single CDFs (2), which, however, is no longer normally distributed [20], [21]. In the next step (4), the joint distribution of de-boarding and boarding X_1 is convoluted with the extreme-value distribution Y_1 from (3). Let X_1 and Y_1 be independent random variables having the respective probability density functions $f_{X_i}(a)$ and $f_{Y_i}(a)$. Then, the cumulative distribution function $F_Z(a)$ of a random variable $Z = X_1 + Y_1$ can be given as in (5). Further steps follow the same principle.

$$Y_1 = \max(X_{FUE}, X_{CAT}, X_{CLE}) \tag{1}$$

$$F_{Y_1}(a) = F_{X_{FUE}}(a) \cdot F_{X_{CAT}}(a) \cdot F_{X_{CLE}}(a) \tag{2}$$

$$f_{Y_1}(a) = F'_{Y_1}(a) = f_{FUE}F_{CAT}F_{CLE} + F_{FUE}f_{CAT}F_{CLE} + F_{FUE}F_{CAT}f_{CLE} \tag{3}$$

$$Z = X_{DEB} + Y_1 + X_{BOA} = X_{DEB+BOA} + Y_1 = X_1 + Y_1 \tag{4}$$

$$\begin{aligned} F_Z(a) &= \int_0^a \int_0^{a-y_1} f_{X_1,Y_1}(x_1, y_1) dx_1 dy_1 \\ &= \int_0^a f_{Y_1}(y_1) \int_0^{a-y_1} f_{X_1}(x_1) dx_1 dy_1 \\ &= \int_0^a f_{Y_1}(y_1) F_{X_1}(a - y_1)\, dy_1 \end{aligned} \tag{5}$$

$$\begin{aligned} Y_2 &= \max(X_{UNL} + X_{LOA}, Z) = \max(X_{UNL+LOA}, Z) \\ &= \max(X_2, Z) \end{aligned} \tag{6}$$

$$F_{Y_2}(a) = F_{X_2}(a) \cdot F_Z(a) \tag{7}$$

$$M = X_{ACC} + Y_2 + X_{FIN} = X_{ACC+FIN} + Y_2 = X_3 + Y_2 \tag{8}$$

$$\begin{aligned} F_M(a) &= \int_0^a \int_0^{a-x_3} f_{X_3,Y_2}(x_3, y_2) dy_2 dx_3 \\ &= \int_0^a f_{X_3}(x_3) \int_0^{a-x_3} f_{Y_2}(y_2) dy_2 dx_3 \\ &= \int_0^a f_{X_3}(x_3) F_{Y_2}(a - x_3)\, dx_3 \end{aligned} \tag{9}$$

Having a convoluted CDF for the TOBT has the great advantage that the probability of turnaround completion within duration a can be directly calculated, e.g. $P(a \leq 46) = 0.407$.

B) Monte Carlo Simulation

A MC simulation is usually run with several thousand iterations, which means that for each of the ten listed processes in Table I, 10,000 random durations are generated with the according mean and standard deviation. The simulation process was done in MATHEMATICA and led to the slightly right-skewed distribution depicted in Fig. 3 with a mean μ = 47.19 min and standard deviation σ = 4.52 min. Among the simulation results in Table II and Fig. 3, it needs to be highlighted that the joint distribution of all possible network paths shows a higher mean duration and a lower standard deviation than each of the four individual paths. This effect can be explained by two network mergers before BOA and FIN (see Fig. 2) which result in extreme-value distributions as previously described in the convolution procedure.

TABLE II. NUMERICAL RESULTS OF THE MC SIMULATION

Network Path		**Mean in min**	**St.Dev. in min**
1	*ACC-DEB-FUE-BOA-FIN-OB*	46.00	5.12
2	*ACC-DEB-CAT-BOA-FIN-OB*	44.00	4.94
3	*ACC-DEB-CLE-BOA-FIN-OB*	44.00	4.94
4	*ACC-UNL-LOA-FIN-OB*	39.00	4.80
JP	**Joint Path Distribution**	**47.19**	**4.52**

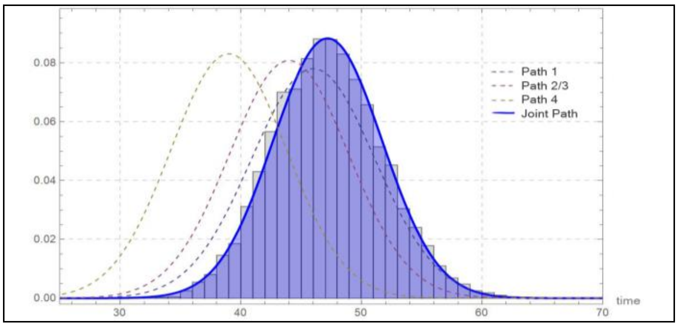

Figure 3. Graphical Result of MC Simulation in MATHEMATICA

For the validation of the new analytical convolution function, a chi-square goodness-of-fit test was performed with the results of the MC simulation. The 10,000 simulated network processing times were clustered into 20 homogeneous classes and the expected values per class were calculated in MATHEMATICA using the convoluted network equation (9). The resulting chi-square value $\chi^2 = 14.29$ is smaller than the corresponding test value χ^2 (95%, 17) = 27.59, which indicates a good fit between the results of both methods and that the simulation results can be obtained directly by applying (9).

Once the distribution of the TOBT is estimated and the prediction exceeds airline internal delay criteria, e.g. OB is 20 minutes behind schedule with 90% probability, certain recovery actions need to be considered in order to minimize the resulting overall network costs. The approach to model this optimization problem is the core of the next chapter.

IV. Modelling Turnaround Control With RCPSP

An optimization model based on RCPSP was chosen to include multi-dimensional time dependencies as well as resource-availability constraints. In order to meet the requirements of practical implementation, the scope of the model is expanded from single turnarounds, see Kuster et al. [4], to multiple parallel turnaround operations. Therefore, this paper introduces free-scalable process durations, variable network dependencies and airport-wide resource constraints. The final concept of a stochastic turnaround model aims at providing a cost-benefit-comparison of various schedule recovery actions under the influence of uncertainty.

In the model, set A comprises all activities over all parallel aircraft turnarounds. Set A is divided into subsets for the individual activities presented in Table I, defined with the respective abbreviation, e.g. all "Acceptance" processes are set $ACC \subset A$, etc. The predecessor-successor-relationships are defined within the precedence matrix $PM \subseteq A \times A$. Overall objective function OF (10) is the minimization of delay costs DC and costs RC_k incurred by all applied recovery actions RA. The elements that constitute each of the two blocks are outlined in detail below. Standard operating costs are not considered.

$$OF = DC + \sum_{k \in RA} RC_k \rightarrow min \tag{10}$$

A) Delay Costs

With $S_i \in R_0^+$ being the variable starting time of an activity i, (11) assures that operations cannot start before the arrival of the aircraft ES_i. The duration of activity i is $d_i \in R_0^+$, so that (12) ensures that succeeding processes j in the network can only begin after process i has been finished. Since OB is fixed as a milestone and has no duration, a delayed network processing time is induced into variable $v_j \in R_0^+$ as shown in (13) once the scheduled off-block time LS_j is surpassed. For the time being, delay costs per minute C_{v_j} are assumed to be constant and are included in the OF by (14).

$$S_i \geq ES_i \qquad \forall\, i \in IB \tag{11}$$

$$S_j \geq S_i + d_i \qquad \forall\, i,j \in A \mid (i,j) \in PM \tag{12}$$

$$S_j \geq LS_j + v_j \qquad \forall\, j \in OB \tag{13}$$

$$DC = C_{v_j} \cdot v_j \qquad \forall\, j \in OB \tag{14}$$

B) Schedule Recovery Costs

In the following, a not exhaustive sample of potential turnaround control methods is presented to outline the basic principle of the stochastic model. For each core process, one methodological control example is given although it might be possible to apply various methods on the given process.

1) Parallelization of Activities

For the Parallelization of two serial processes, their network dependency in the PM needs to be modified. This alteration usually underlies a certain costs C_{Para} and is only applied once the saved delay costs are higher than the control costs (see (10) and (17)). In practice, FUE and BOA are normally completed sequentially. In order to perform a quicker turnaround, this sequential dependency can be changed into a parallel design after explicit confirmation of the aircraft captain and the local fire brigade. Thus, the link that connects FUE to BOA is relocated to go directly from FUE into FIN (see Fig. 4) and the boarding process can start even without the finishing of FUE, once CLE and CAT have been completed. In mathematical terms, the link dependency of FUE and BOA needs to be excluded from (12) and redefined as given in (12a). Additionally, (15) and (16) introduce a new dependency by forcing a binary variable $y_i \in \{0,1\}$ to become "zero" in case FUE and BOA should run as scheduled in sequence and "one" in case the parallel procedure would be more efficient. The trade-off is made within the objective function through (17).

$$S_j \geq S_i + d_i \qquad \forall\, i,j \in A \mid (i,j) \in PM \cup (i,j) \notin (FUE \times BOA) \tag{12a}$$

$$S_j \geq S_i + d_i - BigM \cdot y_i \qquad \forall\, i \in FUE, j \in BOA \tag{15}$$

$$S_j \geq S_i + d_i - BigM \cdot (1 - y_i) \qquad \forall\, i \in FUE, j \in FIN \tag{16}$$

$$RC_{Para} = y_i \cdot C_{Para} \qquad \forall\, i \in FUE \tag{17}$$

2) Process Acceleration through Additional Resources

Since the duration of all manually supported aircraft servicing activities is directly depended on the number of allocated staff or equipment units, in some cases it might be possible to accelerate the process through the assignment of additional resources. In fact, during the catering process, front and rear galleys of a narrow-body aircraft are restocked sequentially by only one catering vehicle. In case enough catering vehicles would be available, see (23), this procedure could be speeded up by assigning two entities to perform the changing process in parallel. In the model, the initial process duration would be reduced by 50% as the number of available units $cat_i \in Z$ doubles and cuts the duration in half (18). Similarly, more loading agents can be assigned to hasten the cargo activities. Here the standard procedure foresees three agents $gh_i \in Z$ and each additional agent would diminish the original duration but with decreasing marginal effect (20). For simplification purposes, the optimal assignment is determined only once for UNL and LOA (21) and is limited to the total number of available loading agents (24). Note that in case of available slack, the number of loading agents might also be reduced for one turnaround in order to free agents for parallel processes at other aircraft, which would induce a process deceleration (20) and result in negative recovery costs (22).

$$S_j \geq S_i + d_i \qquad \forall i,j \in A \mid (i,j) \in PM \cup (i,j) \notin (UNL \times LOA),(LOA \times FIN) \qquad (12b)$$

$$S_j \geq S_i + \frac{1}{cat_i} \cdot d_i \qquad \forall i \in CAT, j \in BOA \qquad (18)$$

$$RC_{CAT} = C_{CAT} \cdot (cat_i - 1) \qquad \forall i \in CAT \qquad (19)$$

$$S_j \geq S_i + \frac{3}{gh_i} \cdot d_i \qquad \forall i \in UNL, LOA, j \in A \qquad (20)$$

$$gh_i = gh_j \qquad \forall i \in UNL, j \in LOA \qquad (21)$$

$$RC_{GH} = C_{GH} \cdot (gh_i - 3) \qquad \forall i \in UNL \qquad (22)$$

$$\sum_{i \in CAT} cat_i \leq Num_{CAT} \qquad (23)$$

$$\sum_{i \in UNL} gh_i \leq Num_{GH} \qquad (24)$$

3) *Process Acceleration through Reduced Execution*

Some activities might be quickened by eliminating certain steps in their standard operating procedure. The proportional time saved through reduced execution can be defined by a free-scalable parameter $m, n \in (0,1)$ which is multiplied with the original duration. Potential applications of this method are *Reduced Cleaning*, where the airline might determine an internal penalty or opportunity costs C_{CLE} for superficial cabin cleaning, and the so-called *Rapid Passenger Transfer (RPT)*, where delayed connecting passengers might be assigned a special transfer bus for the costs C_{RPT} in order to shorten their way through the terminal transfer area. In both cases, the standard time sequence needs to be eliminated for the links from CLE/ PAX to BOA (12c) in favor for variable process durations, which are selected according to binary variables $q_i^{CLE}, q_i^{PAX} \in \{0,1\}$ as in (25) to (28).

$$S_j \geq S_i + d_i \qquad \forall i,j \in A \mid (i,j) \in PM \cup (i,j) \notin (CLE \times BOA),(PAX \times BOA) \qquad (12c)$$

$$S_j \geq S_i + q_i^{CLE} \cdot d_i \cdot m + (1 - q_i^{CLE}) \cdot d_i \qquad \forall i \in CLE, j \in BOA \qquad (25)$$

$$RC_{CLE} = q_i^{CLE} \cdot C_{CLE} \qquad \forall i \in CLE \qquad (26)$$

$$S_j \geq S_i + q_i^{PAX} \cdot d_i \cdot n + (1 - q_i^{PAX}) \cdot d_i \qquad \forall i \in PAX, j \in BOA \qquad (27)$$

$$RC_{RPT} = q_i^{PAX} \cdot C_{RPT} \qquad \forall i \in PAX \qquad (28)$$

4) *Acceleration through Link Elimination*

If one network dependency causes a large overall delay, sometimes it might be effective to just eliminate this specific link from the network in order to save the rest of the schedule. While some processes are mandatory and cannot be neglected without prior scheduling, e.g. fuelling, most of the routing dependencies (connecting passengers, crews or aircraft between flights) have more room to maneuver. Once the link elimination is done, all prior control options need to be reconsidered, especially when they focus on the same process. In case of passenger transfer, *RPT* and *Cancelled Connection* are mutually exclusive actions, which is why (27) needs to be reformulated into (27a). In fact, for connecting passengers, the "pushback" of OB of the receiving flight to guarantee connection [12] would result in delay costs which are only acceptable as long as they remain less than the accumulating expenditures arising from the re-scheduling and caretaking of the affected passengers C_{CAN}. Once this threshold is exceeded, it would make sense to cancel the connection of these passengers and release the aircraft as originally scheduled. In reality, airlines usually define such trade-offs in their recovery policies, however, in the present case, the model will mathematically decide $cpc_{ij} \in \{0,1\}$ when it is favorable to cut off the network link between two flights based on costs for all affected passengers $Num_{CP_{ij}}$ (30).

$$S_j \geq S_i + d_i \qquad \forall i,j \in A \mid (i,j) \in PM \cup (PAX \times BOA) \qquad (12d)$$

$$S_j \geq S_i + q_i^{PAX} \cdot d_i \cdot n + (1 - q_i^{PAX}) \cdot d_i - BigM \cdot cpc_{ij} \qquad \forall i \in PAX, j \in BOA \qquad (27a)$$

$$S_j \geq -BigM(1 - cpc_{ij}) \qquad \forall i \in PAX, j \in BOA \qquad (29)$$

$$RC_{CAN} = cpc_{ij} \cdot C_{CAN} \cdot Num_{CP_{ij}} \qquad \forall i \in PAX, j \in BOA \qquad (30)$$

5) *Consideration of Resource Sequencing*

While the first four measures enable an acceleration of the delayed network processing time, there is also a number of side constraints, such as resource dependencies and equipment schedules, that need to be respected [3], [15]. Especially, resources which are renewable but cannot be used in parallel need to be brought into the right sequence, e.g. one position can only be occupied by one aircraft at a time or one fire truck can only supervise one parallel FUE/BOA procedure at a time. Following the latter example of parallelization, it doesn't matter in which sequence the FUE/BOA procedures are supervised as long as they are all supplied once $x_{ij} \in \{0,1\}$ if needed, see (31), (32). The number of available fire trucks Num_{FB} is determined in (33), while (34) creates the corresponding routings from a fire brigade depot *FB* with transition times *t* between the single stations (highlighted in magenta in Fig. 4).

$$y_i = \sum_{j \in FUE+FB} x_{ij} \qquad \forall i \in FUE \qquad (31)$$

$$y_j = \sum_{i \in FUE+FB} x_{ij} \qquad \forall j \in FUE \qquad (32)$$

$$\sum_{j \in FUE+FB} x_{Depot \to j} = Num_{FB} \qquad (33)$$

$$S_j \geq S_i + d_i + t - BigM \cdot (2 - y_i - x_{ij}) \qquad \forall i \in FUE, j \in FUE + FB \qquad (34)$$

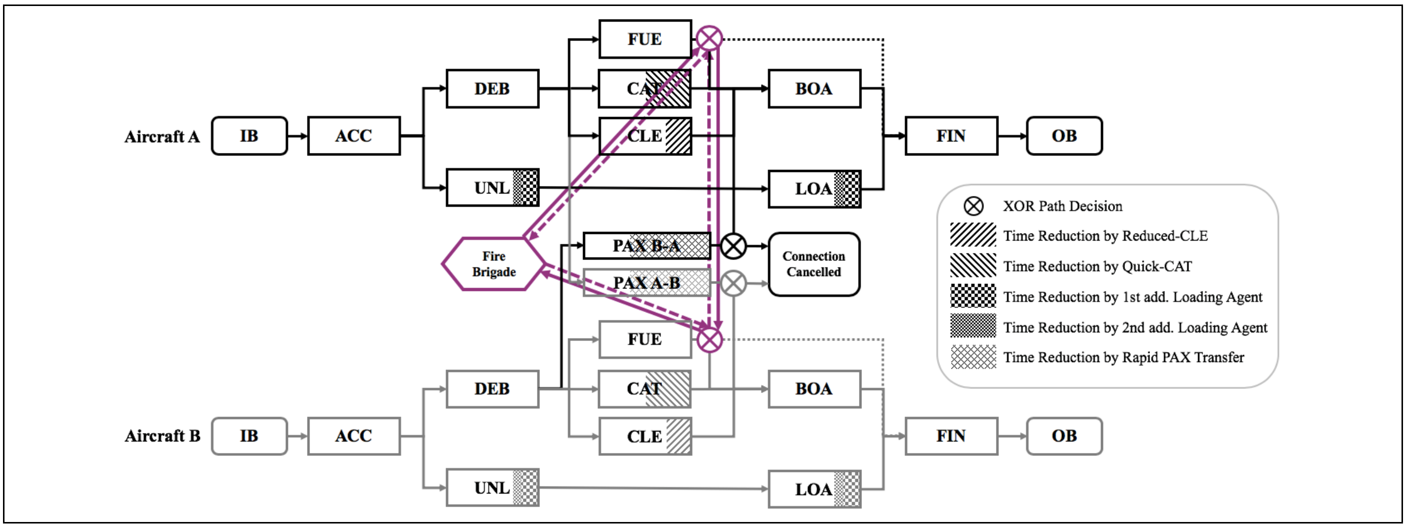

Figure 4. Control Graph for Two Parallel Turnarounds

V. Implementation Approach of Deterministic Optimization in a Stochastic HUB-Airport Setting

For the merger of the two functionalities – stochastic TOBT prediction presented in chapter 3 and deterministic optimization presented in chapter 4 – an implementation setting at a HUB-airport was configured. A scenario situation which requires operational control is introduced and analyzed within this chapter in order to showcase the operating principle that the new stochastic turnaround model is supposed to work with.

A) Assumptions for the HUB-Airport

The example airport with three letter-code "HUB" provides five walk-boarding positions directly adjacent to its terminal. The terminal comprises five boarding gates and a connected transfer area. The example network carrier "TU" operates a flight schedule which includes four feeder flights from domestic out-stations A, B, C and D as well as an intercontinental flight to station E (see Table III). The long-haul flight from E carries 250 passengers, of which 40% are connecting equally-distributed to four spoke-stations on flights 006 to 009 ($Num_{CP_{001*}} = 25$). In return, flights 002 to 005 each bring 125 passengers to the HUB, of which 25 each are continuing their journey with flight 010 ($Num_{CP_{*010}} = 25$). Thus, the schedule resembles a typical wave of arriving and departing aircraft of a network carrier.

TABLE III. Filght Schedule of HUB Airport

Flg.No.	Aircraft	Origin	Destination	Arrival	Departure
TU001	e	E	HUB	8:00	
TU002	a	A	HUB	8:15	
TU003	b	B	HUB	8:45	
TU004	c	C	HUB	9:00	
TU005	d	D	HUB	9:25	
TU006	a	HUB	A		9:13
TU007	b	HUB	B		9:31
TU008	c	HUB	C		9:46
TU009	d	HUB	D		10:11
TU010	e	HUB	E		10:57

It needs to be mentioned at this point that the odd departure times originate from the fact that no additional slack was put into the turnaround network. Thus, the AVGT resembles the MGT for each aircraft (based on the deterministic mean process time values in Table I) with addition of potential network dependencies through transfer passengers as depicted in Fig. 5.

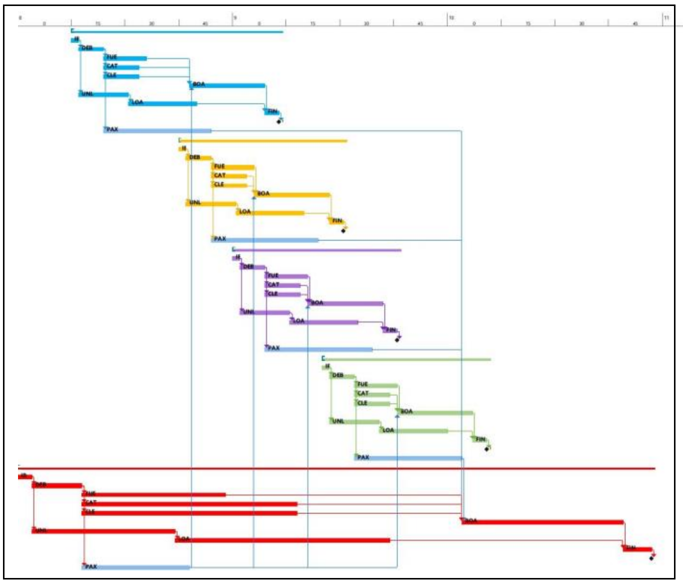

Figure 5. GANTT Chart of Parallel Turnaround Activities at HUB-Airport

Delay costs are determined at $C_{v_j} = 100$ monetary units $(MU) \,\middle|\, j \in \{\text{aircraft } a, b, c, d\}$ and $C_{v_j} = 200\ MU \,\middle|\, j \in \{e\}$ per minute. Costs for schedule recovery actions are set at $C_{Para} = 200\ MU$ for parallel FUE/BOA, $C_{CAT} = 100\ MU$ as operating costs per catering vehicle, $C_{GH} = 50\ MU$ as wage costs per loading agent, $C_{CLE} = 100\ MU$ as penalty costs for *Reduced-Cleaning*, $C_{RPT} = 100\ MU$ for each rapid transfer process, and $C_{CAN} = 200\ MU$ per passenger that misses the scheduled transfer connection. Factors for process acceleration are defined as $m = 0.5$ and $n = 0.4$. Airport resources are limited to $Num_{CAT} = 8$, $Num_{GH} = 20$ and $Num_{FB} = 1$. The transition time for the fire trucks is $t = 5\ min$.

B) Deterministic Optimization with Stochastic Processes

The exemplary scenario describes arrival delays in four different dimensions (15, 30, 60, 90 minutes) for flight TU003. All other arrivals in the described flight schedule (see Table III) arrive on-time. For each of the five parallel aircraft turnarounds, random durations are generated in 1,000 iterations for each activity, according to the respective process parameters in Table I. Per iteration, the generated set of process durations is then used as deterministic input for a single optimization run within the branch-and-cut solver SCIP. Solutions are retrieved from the solver once without the application of recovery actions (which basically corresponds to a prediction of the delayed TOBT) and once when all control options are available, so that the decision is left to the solver which combined actions might result in an optimal solution. Since the optimization algorithm is applied 1,000 per scenario dimension, probabilities can be estimated as to which set of turnaround recovery actions might be the best for which arrival delay situation.

C) Scenario Analysis

First of all, it needs to be emphasized that the analyzed off-block times of flight TU007 (see Table IV and Fig. 6) clearly prove a correct working procedure of the new simulation model, as the average total turnaround time of roughly 47 min with a standard deviation of 4.5 min corresponds to the one calculated in Chapter 3 (see Table II). As process parameters are not changing with the amount of arrival delay, which might be the case in reality [11] but goes beyond the scope of this paper, the distributions of the OB-time are similar for all four arrival delay dimensions.

TABLE IV. ANALYSIS OF OFF-BLOCK TIMES (FLIGHT TU007) WITH AND WITHOUT APPLIED RECOVERY ACTIONS AFTER ARRIVAL DELAY

Arr.Delay TU003	15min		30min		60min		90min	
OBT TU007	*w/o*	*with*	*w/o*	*with*	*w/o*	*with*	*w/o*	*with*
Min	9:35	9:31	9:50	9:42	10:21	9:52	10:46	10:44
Median	9:47	9:40	10:02	9:55	10:32	10:26	11:02	10:55
75%-Q.	9:50	9:43	10:05	9:58	10:35	10:28	11:05	10:58
90%-Q.	9:53	9:46	10:08	10:01	10:38	10:31	11:08	11:01
Max	10:03	9:57	10:16	10:11	10:50	10:40	11:16	11:09
Mean	9:47	9:40	10:02	9:55	10:32	10:25	11:02	10:55
St.Dev.	4.5	4.3	4.4	4.4	4.5	4.5	4.5	4.4

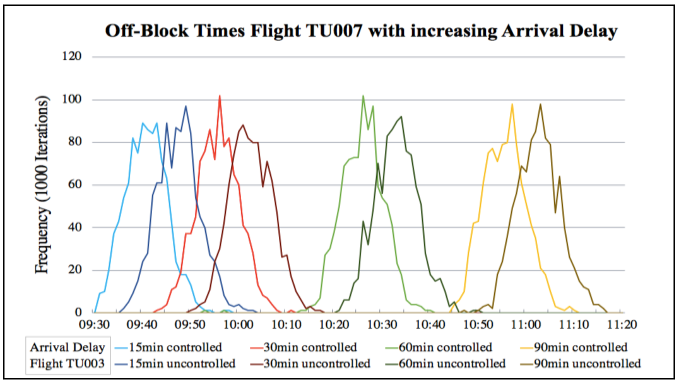

Figure 6. Distributions of OBT (Flight TU007) with and without applied Recovery Actions after Arrival Delay (Flight TU003)

In the ideal case that for each of the 1,000 simulation runs the optimal set of recovery actions would be applied, ceteris paribus the TTT is reduced by up to 7 min at each level of arrival delay (see Table IV). Solely, maximum and minimum TTT values show high variances, while mean values, 75%- and 90%-quantiles reveal stable time reductions of 6 to 7 min and a general left-shift of the controlled OBT distribution (see Fig. 6).

In terms of network costs, it was the objective to minimize the sum of delay costs and schedule recovery costs over all flights (10). As one might expect, the optimization potential with only 15 min of arrival delay is very low (average reduction by 200 MU from 3,245 to 3,045) in comparison to a 90 min delay (average reduction by 4490 MU from 19,836 to 15,346 – see Table V). This is largely depended on the fact that schedule deviations at 15 min delay are smaller and result in lower delay costs, while the costs for recovery actions constitute a larger part of overall costs. Once delay increases, there is also an increasing network effect, which explains that, while delay triples from 30 min to 90 min, average network costs rise more than fourfold. This effect, also defined as delay multiplier [22], is likely to be even greater if more than one flight would receive passengers or crew members from the delayed aircraft and is therefore dependent on the individual interconnection of the flight in the airline network. Another interesting observation in Table V and Fig. 7 is that the application of recovery actions significantly decreases the standard deviation in resulting network costs and, hence, provides a higher certainty for the overall cost prediction.

TABLE V. ANALYSIS OF NETWORK COSTS – ARRIVAL DELAY LEVELS WITH AND WITHOUT APPLIED RECOVERY ACTIONS

Arr.Delay TU003	15 min		30 min		60 min		90 min	
Network Cost	*w/o*	*with*	*w/o*	*with*	*w/o*	*with*	*w/o*	*with*
10%-Q.	1,663	2,427	3,225	3,904	7,788	7,175	16,513	14,497
Mean	3,245	3,045	4,871	4,539	10,940	8,612	19,836	15,346
90%-Q.	5,258	3,669	7,104	5,206	13,957	10,710	23,032	16,203
St.Dev.	1,485	527	1,574	551	2,342	1,397	2,474	871

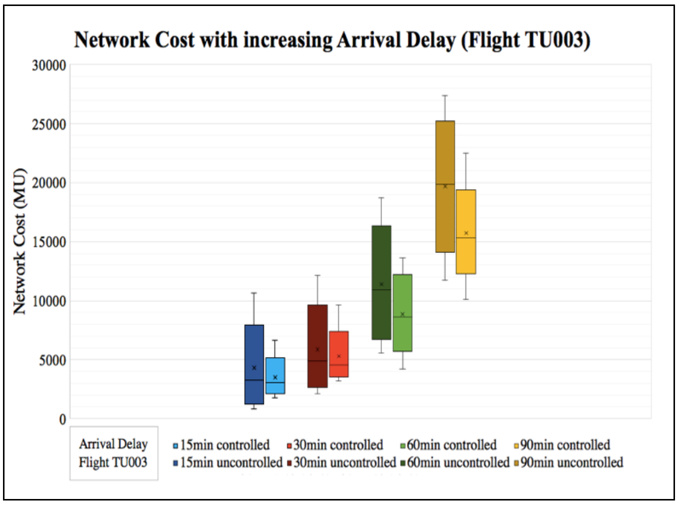

Figure 7. Network Cost Development with and without applied Recovery Actions after Arrival Delay (Flight TU003)

Regarding the individual recovery actions, Fig. 8 reveals that a simultaneous application of *Parallelization*, *Quick-Catering* and *Reduced-Cleaning* was the optimal strategy in more than 80% of all cases for each scenario dimension. This corresponds to the fact that in 80-90% of all turnarounds the critical path goes via path 1-3 (see Table II). In all other cases and also once control options are applied for FUE/CLE/CAT, path 4 becomes critical, so that in roughly 20-30% of all cases more loading agents are needed to accelerate the cargo processes. Thus, a so-called Quick-Turnaround with increased resources for CAT and LOA, a shorter CLE procedure and parallel FUE/ BOA is always the best solution for a delayed aircraft – no matter how big the arrival delay is. In case some of those four control options are not available, results might be very different, so that a sensitivity analysis of the individual impact of turnaround recovery actions needs to be done in further research, as well as a cost calibration between the different options and delay costs.

In contrast to the first four measures, the two network control options *RPT* and *Cancelled Connection* show a very heterogenetic development when the arrival delay grows larger. Judging from Fig. 8, in about 15% of all cases the allocation of a *RPT* for passengers connecting from flight TU003 to TU010 would result in optimal solutions when TU003 has 30 min Arrival Delay. Once the Arrival Delay increases to 60 min, *RPT* almost always yields the best network solution. However, at 90 min Arrival Delay, it is the most efficient solution in only 20% of all cases, while cancelling the connection has an 80% probability of yielding the best overall outcome. Depending on the airline´s recovery policy, an AOC in the OCC would decide based on these numbers whether to push back the TOBT of flight TU010 or to release the aircraft as scheduled without the passengers from TU003. The first would only be efficient until 11:22 (see Fig. 9) and has an 80% probability of resulting in higher network costs for the airline. The latter would ensure on-time departure for flight TU010 with 20% risk of higher costs.

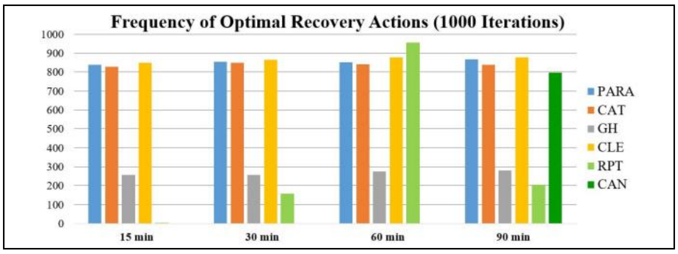

Figure 8. Frequency of Optimal Recovery Actions applied on the Turnaround of Aircraft b after Arrival Delay (Flight TU003)

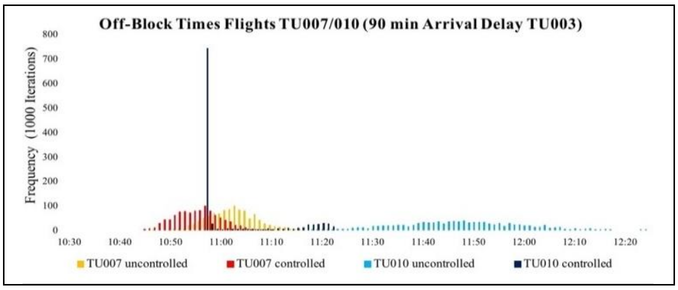

Figure 9. Distribution of OBT (Flights TU007/010) with and without applied Recovery Actions after 90 min Arrival Delay (Flight TU003)

VI. Conclusions

An initial stochastic turnaround optimization model is introduced in this paper with its two core elements – stochastic prediction of the TOBT and deterministic optimization of parallel turnaround operations using RCPSP. The stochastic TOBT prediction is taken up from previous research using Monte Carlo Simulation of network processes, while, for the first time, analytical convolution is presented to produce equal prediction results with less calculation effort. Within the optimization problem, various sequencing approaches are extended from earlier studies into a microscopic, multi-stakeholder model under the objective of minimizing network-wide costs for ground operations. Both procedures are combined into a simulation algorithm and are implemented at an exemplary HUB-airport with assumed costs and process parameters. The methodological showcase provides extensive insights into the possibilities of the new model, which aims to act as tactical decision support system for the selection of robust schedule recovery actions by an AOC in the airline´s OCC. By doing so, it calculates cost-benefit-comparisons between the network consequences of uncontrolled and controlled schedule disruptions. The effectiveness of the method is proven to work especially once larger arrival delays propagate from one aircraft to multiple parallel turnarounds and increase network costs in a non-linear fashion. The non-existence of a standardized turnaround control algorithm results in huge inefficiencies in day-to-day ground operations, which is why this new approach is deemed appropriate for the expansion of the literature in the field of developing (semi-)automated tools for the future of digital aviation.

Starting from the theoretical concept of this article, further research will expand the model to include a broader variety of control options which can be adapted to airline´s individual recovery policies. Additional control options may comprise flexible boarding strategies, gate dependencies among aircraft and aircraft swaps between two flights (so-called tail swaps). More network dimensions might be introduced by adding crew dependencies and passengers connecting from all flights to one another or by taking into consideration that some of the recovery actions may be influenced by further restrictions originating from the operating schedule of GSE or by the turnaround of aircraft from other carriers. The expansion of the basic flight schedule to multiple airports in the airline´s network might further bring network control options which include downstream effects in their cost consideration. Such options may cover flight cancellations; passenger re-routings; the trade-off between a quicker turnaround on ground and an in-flight trajectory acceleration; or the trade-off between recovery actions at the first or a later station in the aircraft´s daily routing.

Regarding the methodology, future steps will deepen the approach of using analytical convolution as a substitute to time-consuming simulation procedures and in order to describe the fundamental mathematics of the controlled network processes. Likewise, stochastic features will be tested directly inside the optimization model through the application of chance constraints. Furthermore, it will be an aim to substitute the normal-distributed dummy processes with fitted distributions from operational analytics and calibrate the costs in order to replicate a real-life operational environment. Once this validation is done, it will be the ultimate goal to perform sensitivity analyses for different disruption scenarios under the objective of determining the ideal amount and lead time of schedule interventions.

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