Delay Impacts onto Turnaround Performance

Optimal Time Buffering for Minimizing Delay Propagation

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***Abstract*— During 2007, 19% of all European flights were more than 15 min late. One contributor to this delay is the insufficient ground operation performance inducing excessive process durations. Whenever these processes are part of the critical Turnaround (TA) path, such as de-boarding, fuelling, cleaning, catering and boarding, the effects immediately propagate an accumulating delay through the ATM network. Recent studies have investigated into the effects of technical aircraft deficiencies onto TA reliability, and could show that significant potential is given for improvement. Field analyses at German airlines showed that pre-set quality standards for punctuality can actually not be met. This paper extends that analysis by considering the individual inbound delay measured at the gate, revealing the correlation between TA process duration and stability versus a given delay with an analytical model. The concept of dynamically scheduling buffer times to compensate for potential delays into the ground time of aircraft turnaround operations is introduced into our model. It can be shown that dynamic buffering may overcome deficiencies of the currently applied buffer strategies for ground processes. The paper closes with a strategy on how to scale gate time to cope with demanding punctuality requirements from the customer's side. With regards to Airport CDM concepts, the dependencies found may be used in decision support tools to trigger ground handling resource (personnel and tools) planner and motivate for strategies specifically for Ground Handling Companies.**

Keywords-turnaround, delay propagation, critical path, ground handling operations, Monte Carlo simulation

I. Motivation – Need for Investigation

The Aircraft Turnaround has been identified to be crucial for airline schedule adherence, for high customer satisfaction, and economic productivity. Productivity is further measured not only by the airline but also by the airport operator, the ground handling companies and the air navigation service provider since all of them have to handle carefully scarce stuff and tool resources.

Consequently, the aircraft turnaround is complex in terms of participating parties (s. a.) and of given technical, legal and operational dependencies between individual activities or processes comprising the turnaround: Consequently grid locks are costly here. A number of ground operations have to be processed, in sequence, to service the aircraft. These comprise 1.) Placing of chocks (rubber blocks that prevent aircraft from moving) in front of the aircraft's wheels after it comes to full stop 2.) Unloading of passengers and baggage 3.) Post-flight administration 4.) Pre-flight administration 5.) Catering replenishment 6.) Aircraft cleaning 7.) Security checks 8.) Loading of passengers and baggage, and 9.) Removal of chocks for departure. Cleaners, ground handlers and engineers execute these processes and shall best coordinate their activities to provide a seamless aircraft turnaround.

All these processes are being scheduled against the Scheduled Time of Arrival (STA) and - by assuming a dedicated taxi-in time - scheduled against the “on block (chock)” times at the assigned aircraft stand, either remote or at the terminal building according to the airport’s stand allocation scheme. All disruptions occurring at the inbound sequence unavoidably cause gridlocks for the ground operations since personnel resources are tight and tools are partly specific for aircraft types so that switching concepts (reallocation to alternate stands) are limited. Therefore, the aircraft turnaround performance relies on a robust stand and aircraft allocation scheme over the day. All deviations increase the criticality of the following underlying requirements:

- Pressure to achieve the optimal long-haul passenger / cargo mix at hub airports.
- A shrinking window for receiving cargo prior to departure. This in turn affects e. g. fuel truck availability and fuel requirements.
- Reduced staff due to a specific economical pressure for ground handling agents due to small earnings (EBIT) figures.
- An increasing pressure from the aircraft operator to utilize aircraft more efficiently (seat load factors have been raised up to 80+% on average) and to limit ground time.
- A culture for zero excess fuel requirements – excess fuel is kept close to safe minimums, implying the need for reliable load figures and adherence to the expected geometric flight plan.

- Increased air traffic combined with limited airport expansions inducing busy situations over large time frames specifically at ramps of Hub airports.

E.g. Deutsche Lufthansa (DLH) and Lufthansa City Line (CLH) claim for high quality standards with 95% flight availability (continuity of service) and 92% on time service (less than 15 min deviation from schedule. Statistics gathered during a field evaluation in 2008 [1] show, that these may actually not be achieved (background = City Line figures of 2007, black/gray lines Lufthansa/City Line figures for 2008, ranging below target values):

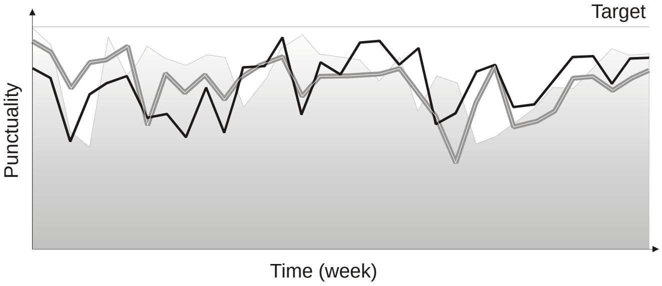

Figure 1. Achieved Punctuality Lufthansa City Line 2007 & 2008

To achieve these targets, the airline operator typically introduces time buffer onto technical minimum gate times (MGT), as published by the airport operator resp. ground handler. These buffers seem not to follow rigid rules but are calibrated to expert knowledge. Further, the MGT itself is not a constant value per type of aircraft but considers additional aspects such as

- Belly freight onboard or passengers only for in-, outbound or both.
- Inbound from a HUB airport or a secondary airport,
- Outbound to a HUB airport or a secondary airport.

Existing airport schedules show a variance of more than 100% depending on what type of operation takes place: As such, the MGT for an A320 family aircraft ranges from 30 min up to 55 min, for a B747 from 50 min up to 2:30 hrs. Consequently, we studied the relationship between found process stability and turnaround reliability [2] and deviations from STA. In this paper we additionally investigate into currently used time buffers, their capability of absorbing delays and propose a strategy on how to best scale buffers to minimize delay propagation (see also [3-6]).

The paper is structured as follows: Chapter 2 will recall these existing dependencies, chapter 3 reveals the set of collected ground operations data at Leipzig, Frankfurt and Munich Airport from 2003 until 2008 and presents the main process characteristics. Chapter 4 hosts the stochastic modeling for arrival (on block) and departure (off block) distribution and empirical correlations found between the punctuality and turnaround performance. Chapter 5 uses the model as stochastic input into a Monte Carlo Simulation to determining the dependencies between additional buffer times which are introduce to improve schedule reliability at the expense of reducing aircraft productivity. Chapter 6 collects the major findings and discusses the stochastic model's potential for implementation into Airport CDM decision support tools such as SMAN and DMAN to best support a reliable scheduling and planning.

II. Factors Impacting Turnaround Reliability

A. Tactical Aspects

Reasons for flight delays can be allocated to six main categories (type of reason): Rotation, ATFM/ATC, Airport Authorities, Handling, Technical, and Weather [1] these major categories cover up to 85% of potential flight delays (see Tab. I. For CLH, the following distribution could be analyzed:

TABLE I. Registered Delay Causes

Reason		**(%)**
Rotation	Delayed flight cycles	30
ATFM/ATC	Restrictions according to crowed ATC sectors, traffic flow restrictions	25
Airport Authorities	Problems due to runway capacities, occupied parking positions, etc.	15
Handling	Delayed ground processes (late passengers, handling agent disposition)	10
Technical	Malfunction of technical systems (e.g. aircraft)	3
Weather	Negative weather influences (rain, snow, wind, etc.)	2
Other	Aircraft damage, Strike, No delay code given, etc.	15

These categories are highly independent as regression analyses can show. The only exception is found for the category "ATFM/ATC" which mainly appears in line with a rotation delay (e. g. losing a slot).

According to Tab. I, the category that impacts most punctuality is „rotation", reflecting delayed inbounds, imposed from previous flight legs: Since especially short haul aircraft fly more than one, often several legs per day, every delay occurring during a leg or a turnaround accumulates over the day (delay propagation), as the following figure depicts:

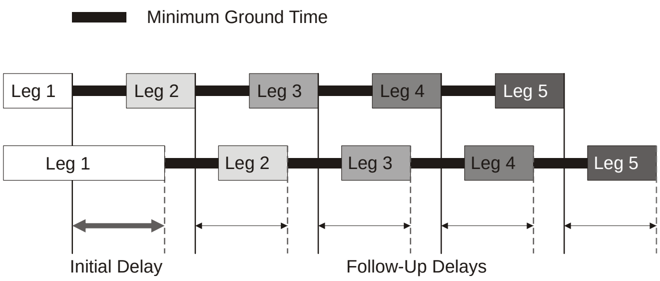

Figure 2. Delay Propagation from Off-Schedule Rotation

One obvious strategy to overcome these deficiencies and help to increase turnaround reliability consists in introducing buffer times for the turnaround as a whole or, more specifically, in between the processes along the critical path. Those have been identified by statistical analyses as consisting of de-boarding, then fuelling, catering or cleaning, and finally boarding [10].

TABLE II. PROCESSES ON CRITICAL PATH

Process	fuelling	catering	cleaning
Frequency of occurrence on critical path	57%	35%	8%

On a simplified view, these findings correlate with the manufacturer's Aircraft Operations Manual (AOM) documentation, which represents process durations and start times as deterministic parameters with various dependencies, splitting the activities in sequential and parallel ones:

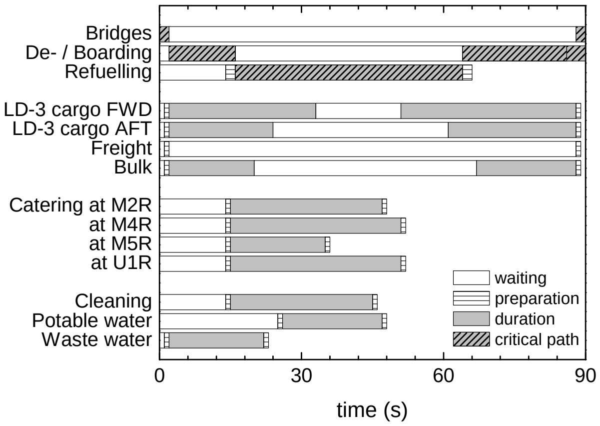

Figure 3. Turnaround Time Schedule (A380, 90min, baseline)[7]

The overall turnaround time is measured with the termination of the last process. According to Fig. 3 moving of passenger bridges, boarding and refueling are part of the critical path, similar to the author's findings in Tab. II. Only shortening the processes on the critical path allows reducing the turnaround time, resulting in reduced idle times and ground related handling costs for airlines as well as in benefits for the airport through increased gate productivity.

So, time buffer introduction along the critical path results in planned extended turnaround times above the MGT and so look contra productive on a first intent. On the other hand, compensation for delay so will become possible, resulting in reduced delay propagation effects. The question of the "best" time buffer to cope with both aspects is obviously crucial. As argued, the appropriate buffer size does depend from the MGT characteristics as listed above. According to queuing theory, the buffer will further be dependent on the delay magnitude of an individual turnaround, expressing the fact that late aircraft may most probably need less buffer time due to an increasing pressure on all actors to catch up with the schedule.

Finally, there are additional distortions that may occur and may not be covered by a standardized, even delay depending buffer strategy: These cover technical failures along with the aircraft (typically system faults to be resolved prior the next leg as they belong to the Minimum Equipment List of the aircraft) or follow up effects induced by excessive delay.

To better understand these effects, a comprehensive field analysis at an Airline dispatch center, located at a large German airport was executed in 2008 [1]. It could be learned, that these safety related technical occurrences are being handled up to 72 hours prior scheduled time of departure (STD), comprising the following activities:

1. Equipment change (ECH): Technical issues impacting the Minimum Equipment list of the aircraft require maintenance on short notice
2. Aircraft change (ACH): Aircraft availability on short notice, the aircraft is take off sequence, the turnaround consists of a twofold procedure
3. Missing a Slot: Late aircraft not being capable of using their assigned slot will be served with an alternate slot upon availability, ideally a slot (exchange shall be achieved so to allow another flight to use it)
4. Crew change: Late aircraft may impose limitation to the crew working times according to regulations. Only a crew change can solve this issue.

These actions are complex and require a significant set of coordinating activities beforehand such as negotiation with the responsible flow management unit with regard to slots, with the airport operator to overcome stand compatibility constraints, or with the ground handler to grant availability of handling tools at alternate aircraft stands and times. Although individual system support is available for all these actors, central coordination systems are hardly provided at most airports, leading to numerous process disruptions, as shown later in this paper. To increase the process reliability, Collaborative Decision Making (CDM) strategies are now being explored. The first Airport CDM application running operational was initiated at Munich Airport leading to a successful inbound delay compensation during turnaround for more than 50% of all flights in 2008 [9].

B. *Operational Aspects*

To finally understand why process stability is quite limited, another field study was performed by the authors from 2006 until 2008 at Munich Airport's ground handling premises [2]. It is pointed out that technical deficiencies at the aircraft body do clearly hamper the process efficiency.

From the process time line perspective, single ground handling processes do not seems to influence each other. But looking at the A320 airplane service arrangements according to Fig. 4, geometric and logistical dependencies seem obvious. This is especially true, since various security and safety related regulations in Europe such EG 300/2008 [14], EASA CS 25 [12], and IATA AHM [15] do apply to the service arrangements. Those requirements have to be taken into consideration as well. As an example, the fuelling process is typically performed isolated (on the right hand side of the aircraft) from passenger related processes (left hand) to grant an escape route be free of vehicles or other obstacles. Especially refueling with onboard passengers requires safety precautions, set in EU-OPS [13] Chapter 1.305. The ground area beneath the exits intended for emergency evacuation and slide deployment areas must be kept clear and therefore some ground procedures are influenced in space and/or time.

For the turnaround processes several ground units are necessary and must be arranged around the aircraft. Fig. 4 depicts the general process and utility layout around the aircraft, parking at gate position. The passengers will use the left front door to board and de-board the airplane. In the case of a remote parking position, the passengers will typically use left front and rear door to de-board.

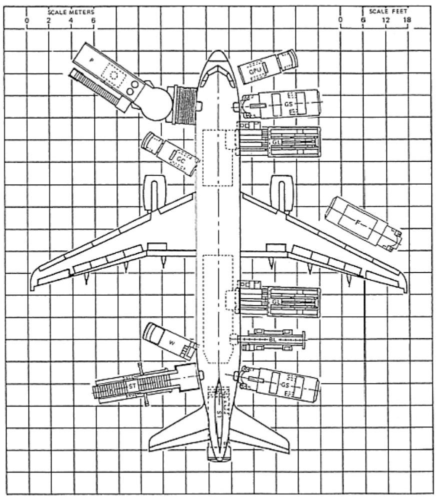

Figure 4. Airplane Service Arrangements

While the passengers access the aircraft at the left side, the ground units use the right side for approaching. Typical ground units arranged at the aircraft are listed at the following Tab. III.

TABLE III. GROUND UNITS

Abbreviation	Ground unit
AS	Air Starting Unit
BL	Bulk Loader
D	Dolly
F	Fuel Tanker
GL	Ground Loader
GS	Galley Service Truck
P	Passenger Loading Bridge
ST	Stairway
LS	Lavatory Service Truck
W	Water Service Truck
GC	Ground Air Preconditioning Unit
GPU	Ground Power Unit

Each ground vehicle is assigned to a specific ground process. Beginning with passenger de-boarding a passenger loading bridge or a stairway is connected to the main left hand exit(s). The rear exit can also be used to provide access for the cleaning crew. When the aircraft is connected to a GPU, electric power is applied by the ground service as well as air conditioning aid (GC). For loading and unloading cargo and baggage, a ground loader vehicle is typically used, while bulk cargo is deplaned via bulk loaders. Transport of cargo and baggage to and from the parking position is done with dollies (D) and trucks, depending if containerised or bulked. Catering service is ensured with a galley service truck, while lavatory and water service trucks emptying and refilling the used/usable water for the toilets and galleys. The fuel tanker (F) is necessary for refuelling, either as a tanker or as dispenser vehicle when under floor tanks are available. The air starting units (AS) are used for pneumatic engine start-up assistance, e. g. when the auxiliary power unit (APU) is not available or not allowed for noise reasons before pushback.

The ground processes depend on a spatiotemporal level. At first, all necessary ground units must have adequate clearances to the airplane and have to consider the space and maneuver requirements of adjacent units. Furthermore, some turnaround processes have preceding processes which need to be finished before: E.g. de-boarding must be finished before cleaning and catering can start. Considering all these dependencies and requirements, planning tools will be used for process optimization of the turnaround. Due to delays at daily operations, the planned process sequence is often disturbed and will so impact the airport performance largely.

For a reliable planning of the turnaround through prediction of expected delays and so allocation of the needed resources at the right time at place, each single turnaround process has to be evaluated. This evaluation is the basis for a turnaround model. As we presented in [2] the reduction of process variances is one important step to achieved higher confidence intervals for process prediction. The operative flight planning and controlling processes are primarily focused on airlines. A systematic and reliable prediction of all corresponding processes is necessary for a sustained economic growth.

III. DATA COLLECTION OF GROUND OPERATIONS

Almost in [2] a collection of 120 turnaround operations was used to determine statistically turnaround process characteristics. The dataset was meanwhile significantly extended with kind support of DLH to a total of 24,740 flight operations to allow not only for post analysis but also for reliable predictions and to study interdependencies between the turnaround and schedule adherence. This additional data was taken from the ALLEGRO database (**A**scending to a higher **Le**ve**l** of **E**xcellence in **Gro**und operations) operated by DLH to trace ground operations at Frankfurt (FRA) and Munich (MUC) airport. For further detailed analyses the dataset was refined by considering only flights with a flight time (in- and outbound) less than 120 min (short and mid range). Furthermore the scheduled turnaround time is set to equal to or less than 75 minutes (see Fig. 5) at those hubs. Flights that will arrive at the airport before scheduled time are not taken into consideration. Based on finally 1,048 valid datasets [1], the

1 It may be noted that few operations were found with a turnaround time up to 2 hrs, which were not considered

following distribution with a mean time of μ = 61.1 min (σ = 8.9 min) was found:

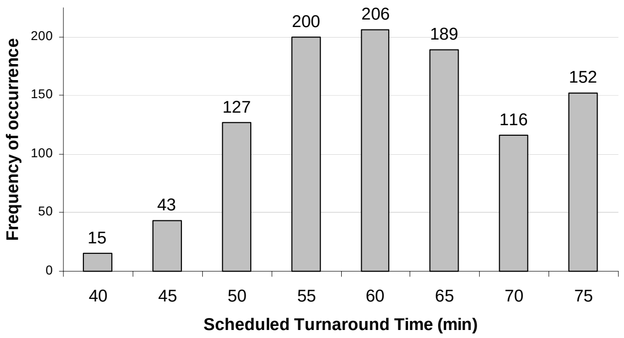

Figure 5. Scheduled Turnaround Time distribution for the A320 family

Further on, this data set was analyzed against the individual delays of each operation to allow correlating turnaround durations and. Fig. 6 shows the results of that analysis, with an average arrival delay of $\mu_{ARR} = 2.4$ min and an average departure delay $\mu_{DEP} = 8.4$ min. It was further found that departures leave the airport "early" for only 1% of all cases. The delay distribution shows 56% being less than 5 min late, 24% more than 5 and less than 15 min late and 19% being more than 15 min late.

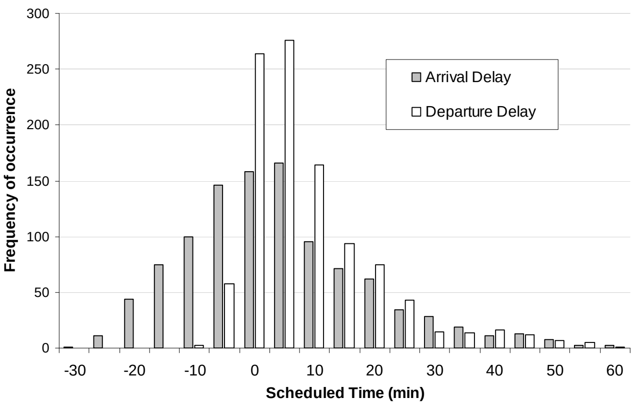

Figure 6. Arrival vs. Departure Delay Distribution

Departure delays result from various reasons such as "brought-in" arrival delays, delayed ground processes and/or disturbed ground processes [3,11]. As discussed, interdependencies do exist and may affect the delay chain: it can happen that existing delay results in an even increased follow-up delay due to scarce resources at the airport. On the other hand, in most of the cases delay was partly compensated by means of improved ground process efficiency and/or - to a limited extent - an accelerated en-route flight phase on the next flight leg (see below).

Analysis of the in- and outbound delays of aircraft rotations point out, that the delay could be reduced during en-route on average by μ = -4.5 min (σ = 9.5 min). Considered flights at the refined dataset took a mean flight time μ = 78.6 min with a standard deviation of σ = 19.9 min at those hubs, focusing on medium haul operations. The characteristics of delay compensation on those flight legs are shown in Fig. 7.

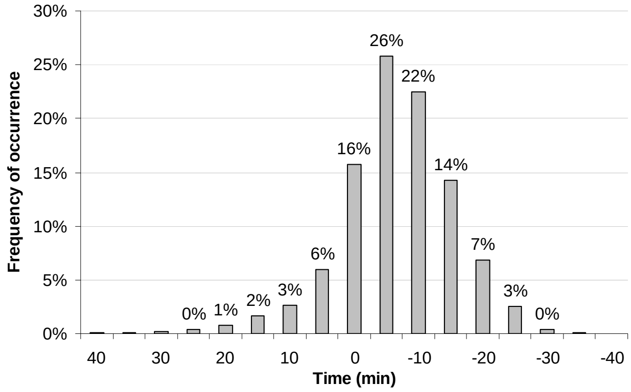

Figure 7. Delay Compensation during flight legs

The delay compensation potential on ground will be discussed in the following paragraph.

IV. Stochastic Correlation Analysis of Delay to Process Reliability

The evaluation of the turnaround delay reduction potential must tackle all processes running along the critical path, so de-boarding, cleaning, catering, fueling, and boarding. To fit the analyzed process duration and process kick off time distributions, three different statistical functions were found to be candidates: Weibull (1), Gamma (2) and Normal-Distribution (3), being expressed with the following probability density functions.

$$f_{WEIBULL}(x,\alpha,\beta) = \frac{\alpha}{\beta^{\alpha}} x^{\beta-1} e^{-(x/\beta)^{\alpha}} \quad (1)$$

$$f_{GAMMA}(x,\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-(x/\beta)} \quad (2)$$

$$f_{NORMAL}(x,\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(\frac{x-\mu}{2\sigma}\right)^2} \quad (3)$$

For each process distribution, all candidates are evaluated for best fit. This is achieved with a chi-square test at 95% significance level (confidence interval) and with 7 degrees of freedom. This procedure was already found efficient in [2], for the smaller dataset.

A. Process Duration Analysis

Further it was found that ground process duration times reflects a statistical behavior which is best be fitted with a

for further analysis as a "parking" was supposed to happen.

Weibull distribution according to equation (1). Fig. 8 depicts the fit quality for the sample process “cleaning” confirming that Weibull is the most appropriate distribution for the extended dataset used here as well. Based on a dataset of n = 841 values, the real data is successfully (chi square test positive) fitted with a Weibull distribution with the following parameter: $\alpha = 2.16$, $\beta = 2.76$, $\Delta x = 5$ (10 classes). The corresponding chi-square value of $\chi^2 = 6.4$ is smaller than the required value $\chi^2(95\%, 7) = 14.1$.

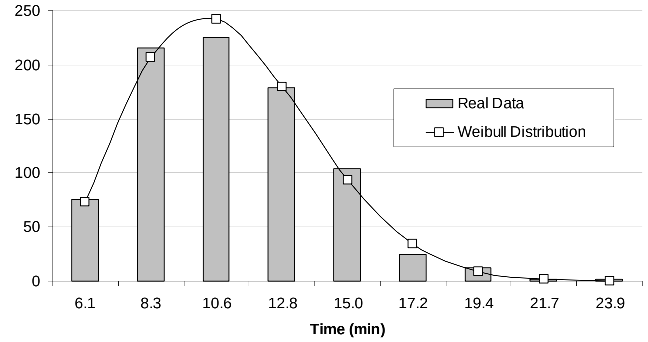

Figure 8. Cleaning process fitted with Weibull Distribution

This proof of good fit could be performed for all remaining three ground processes de-boarding, catering, and boarding, too. However, for the fuelling process, the chi–square test failed for all attempts to fit with Weibull, here a Gamma distribution (2) was finally found for acceptable fitting, as the Gamma distribution could deliver the required higher peak value. Tab. IV collects all parameter sets (α, β, Δx) found appropriate for the individual processes. To better allow comparing the processes among each other, the mean value μ and standard deviation σ for each process are also listed.

TABLE IV. STATISTICAL DISTRIBUTION PARAMETER FOR PROCESS DURATION

Process	α	β	Δx	μ	σ
De-boarding	2.07	4.04	1	4.57	1.81
Cleaning	2.16	6.76	5	10.99	2.94
Catering	2.18	17.37	0	15.38	7.51
Fueling (Gamma)	1.64	9.12	2	10.16	5.06
Boarding	3.42	16.74	3	18.05	4.85

B. *Process Kick Off Time Analysis*

To determine the delay to stability ratio during the turnaround, the process durations for all processes along the critical path will have to be evaluated against their start time to correctly model the process chain. In contrast to process durations, process kick off times were found by the same statistical means to be rather Normal distributed. As shown in Fig. 9, the start time of the boarding process can adequately be represented by a Normal distribution.

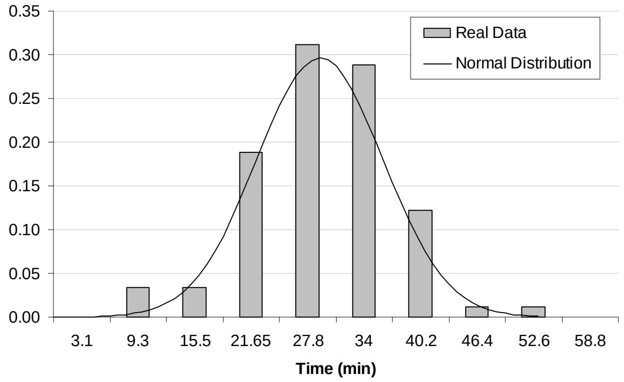

Figure 9. Dataset fitting for Boarding Process with Normal-Distribution (Arrival Delay 5-10 minutes, $\mu = 32.5$, $\sigma = 7.9$, n = 90)

To evaluate the correlation between the inbound delay and the so modeled ground process sequences, six delay categories with 5 minutes step size were defined: On time (0 to 5 minutes), 5-10 minutes, 10-15 minutes, 15-20 minutes, 20-25 minutes, and 25-30 minutes. For the evaluation of the process starting times 550 valid datasets were available, whereas each category consists respectively of 290, 90, 60, 55, 30, and 25 values[2].

The following characteristics were found across these categories: With increasing inbound delay, the ground processes tend to start earlier with regard to the on block time. However, one interesting exception was found for the de-boarding process, which tended to start later and with an increased standard deviation. Compared to the scheduled turnaround, the starting times μ_{min} were found to have an approx. 30% lower minimum (so starting earlier) with an approx. 50% smaller minimum standard deviation σ_{min}. This trend is only unreliable for the second highest delay category “20-25 minutes” for some processes, an also interesting but so far unexplainable effect, pointed out in Tab. V.:

TABLE V. PROCESS STARTING TIMES REGARDING TO ARRIAVAL DELAY

Process		**Arrival Delay (min)**					
		on time	***5-10***	***10-15***	***15-20***	***20-25***	***25-30***
De-boarding	μ	1.65	1.78	1.64	2.19	2.67	1.89
	σ	0.63	0.55	0.60	1.29	1.31	1.15
Cleaning	μ	11.84	9.79	9.74	8.76	8.65	8.94
	σ	4.51	3.46	2.43	2.26	2.58	2.65
Catering	μ	12.43	12.49	10.37	10.70	10.47	9.83
	σ	4.96	5.74	3.39	2.98	2.92	2.86
Fueling	μ	18.02	15.34	15.43	13.45	13.76	11.98

[2] The other datasets do not contain complete information about starting times or have only specific information about process duration. So a valid dataset is characterized by a complete set of all ground process data (starting time und duration).

Process		Arrival Delay (min)					
		on time	*5-10*	*10-15*	*15-20*	*20-25*	*25-30*
	σ	8.03	5.37	5.64	4.80	6.47	5.12
Boarding	μ	36.52	32.51	28.68	26.83	28.96	24.98
	σ	11.01	7.86	6.43	4.76	7.41	8.31

The found correlation between arrival delay and process characteristics is depicted in Fig. 10. With regard to process duration, an obvious dependency to the individual preceding process can be seen. Further, the variance of the process kick offs and its duration is marked with an extended thin line (whisker) on the left (based on the start time) and the right (based on process duration) at each process. The left side whiskers have a length of 2σ referring to the Normal-distributed start process, so 95.45% of all cases are covered. The whiskers on the right also cover a range of 95.45% of the corresponding Weibull distributed process duration time. The dark line between the whiskers represents the expected start time and duration of the ground process. Contrary to the common understanding that all processes start immediately after de-boarding, our analysis clearly shows that in most cases a time shift (buffer) is found between the end of the boarding and the beginning of the following ground processes. We assume that this is the airline and ground handler current strategy to claim for the demanding reliability standards according to Fig. 1.

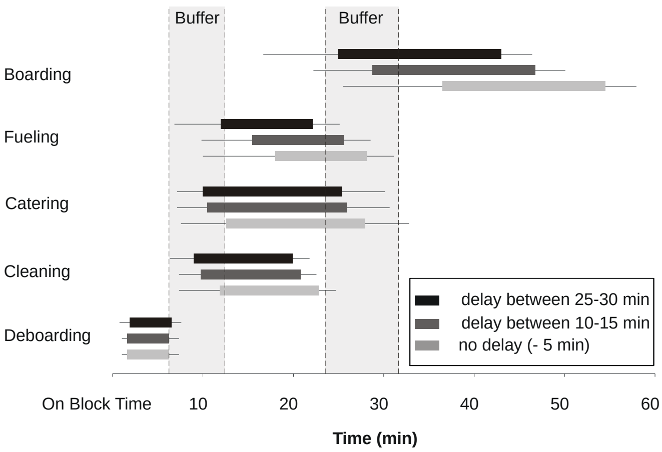

Figure 10. Process Start Times and Duration correlating with Delay

Comparing the parallel run processes catering, cleaning, and fueling, different variances for the starting times are observed (compare to Tab. V). Whereas the turnaround is normally restricted by the fueling processes [8], our analysis shows a further time restriction imposed by the catering process. As a result of all preceding process characteristics, the final de-boarding accumulates all uncertainties and so possesses a significant higher variance for the starting time. The fueling process may be used as an example how process starting times do change along the critical path. Fig. 11 points out, that increasing inbound delay leads to an earlier start of the fueling process (with reference to on block time) along with a significantly reduced standard deviation. On scheduled flights the expected starting time is at μ = 18.02 min (σ = 8.03 min) and decreases to μ = 11.98 min (σ = 5.12 min) for the highest delay category.

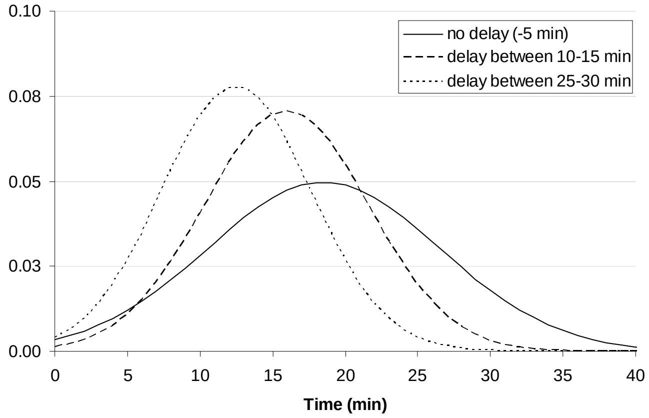

Figure 11. Process Starting Times versus inbound Delay (Fueling)

As Fig. 10 shows, ground processes tend to start earlier with increasing arrival delay. Consequently, the overall turnaround time should also decrease compared to the scheduled figures. Looking for a correlation of inbound and outbound delay (Fig. 12), a linear or polynomial regression is found. Assuming the linear dependency, ground processes can cover up 1/3 of the delay at average, with decreasing tendency (polynomial function). This effect is primary caused by a saturation of the discussed planned time buffers at a given delay intensity:

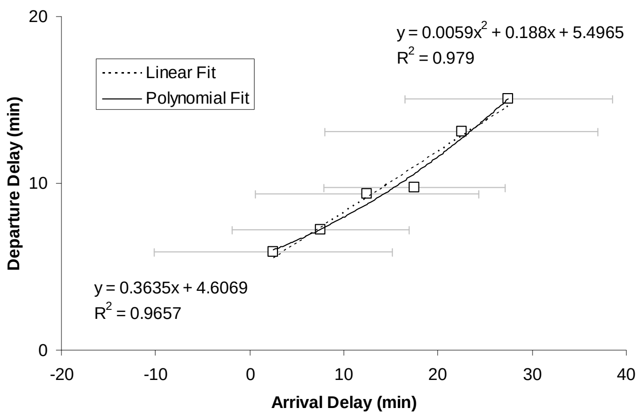

Figure 12. Inbound vs. Outbound Delay Correlation

These results – in order of magnitude –reflect partly the findings from the European CDM project [9].

After having understood the dependency between process reliability, turnaround planning with regard to the MGT and the effect of delay onto the process behavior, it becomes obvious, that dynamic time buffers are required to optimize tactically the turnaround. The next chapter presents our so developed model covering all of these ground process characteristics.

V. DELAY MODELING

The delay modeling will be formulated with respect to the findings for statistical distributions for each ground process duration according to Tab. IV and for their starting times (according to Tab. V). Further the following process constraints are obeyed:

1. The turnaround starts always with de-boarding (unloading of baggage neglected);
2. Catering, cleaning, and fueling are run in parallel without influencing each other. These processes can only start after completion of de-boarding; and
3. Boarding will always be the last ground process and can start only if all other processes are completed (loading of baggage neglected).

The model is implemented in a software environment, which uses a Monte Carlo (MC) Simulation approach to achieve statistically significant results. For each delay category, 10^6 MC runs are performed. Taking into consideration, that process duration for each ground process is independent from the arrival delay, different from the starting times tending to earlier kick offs, the turnaround process is being MC modeled using the various distribution functions found for process and process starting times, all concatenated according to the statistically found process sequences.

This is achieved in the model as follows: Each simulation run starts with the determination of the de-boarding starting time and its process duration. Then the starting times of the following ground processes (cleaning, catering, and fueling) are calculated dependently. If the processes would start before de-boarding ends (what appeared for few data sets), the starting time is reset to the end of de-boarding by default. Concerning the specific process durations, the corresponding completion times are then determined. Finally, the start of boarding will be calculated and “attached” to the longest of all parallel processes running beforehand. With completion of the boarding process, the turnaround conceptually ends.

To understand how a single ground process can influence the overall turnaround performance, its individual contribution to the critical path is needed to be known. Due to the fact that the boarding process is always at the critical path, only the four remaining ground processes need to be analyzed consequently. As shown in Fig. 13 the catering and the fueling process have a significantly higher influence onto the turnaround compared to all other processes. Starting with the on time flights (category 1), 58% of all MC processed turnarounds are not affected by any ground process, since the preset (planned) buffer times fully compensate any process delay within the turnaround. With increasing delay, these buffers will consecutively be consumed. At a delay of 25-30 minutes, this effect becomes dominant, as only 34% of all turnarounds could then only be handled without process interference, meaning inter process disturbance. The following picture concludes the found buffer consumption with increasing delay.

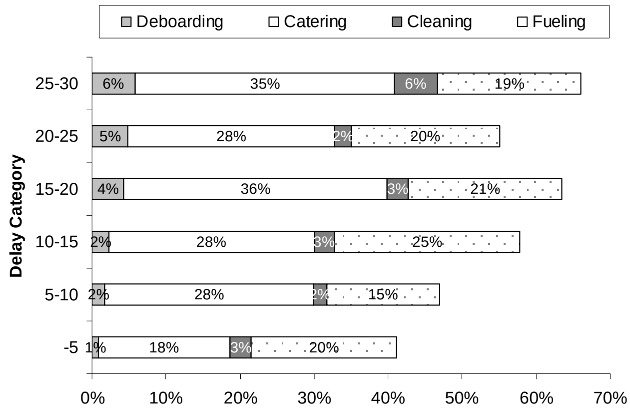

Figure 13. Processes on Critical Path

Even in case of a high arrival delay, the ground processes should be able to compensate as much delay as possible, to prevent a delay propagation into the next flight leg. From the turnaround point of view its performance increases (by means of increasing expected values μ and standard deviation σ, see Tab. VI) with growing arrival delay. This tendency is driven as stated by consuming time buffers.

TABLE VI. TURNAROUND DURATION

Delay	Mean Value μ (min)	Standard Deviation σ (min)
Scheduled	57.93	8.84
5 – 10 minutes	54.03	7.64
10 – 15 minutes	50.97	7.11
15 – 20 minutes	49.31	7.02
20 – 25 minutes	51.03	7.32
25 – 30 minutes	48.83	7.42

When considering the mean process durations from Tab. IV, de-boarding contributes 4.57 min, catering 15.38 min, and boarding 18.05 min to the turnaround, all located on the critical path. The resulting theoretical minimum turnaround time based on these averages equals the sum of those values ($\Sigma = 38$ min). Differences to this average minimum time are determined by buffer times and ground process interferences.

As explained, the reduction in turnaround duration is achieved in the expense of buffer consumption. Considering the found critical path constellation, the MC turnaround model leads to currently contained planned buffers of approx. 9 min as taken from Tab. IV when comparing “scheduled” to delay category “25-30 minutes”. The buffer size decreases continuously, whereas the buffer before the boarding reaches a minimum of 1.3 min on average for the delay category “25-30 minutes”. As the buffer time after de-boarding is depended on the longest of three parallel processes, this buffer is only reduced to 4.2 min minimum on average.

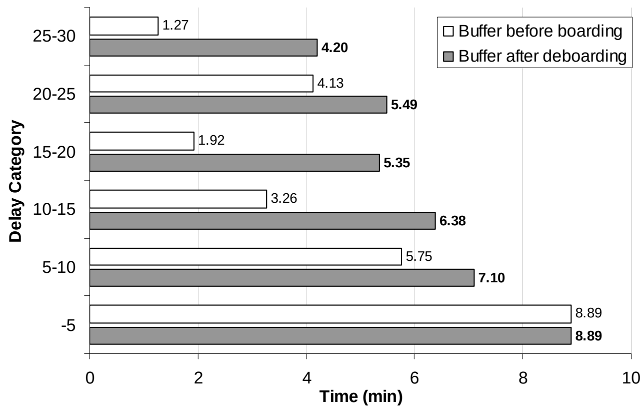

Figure 14. Derived Time Buffer Size for Turnarounds

The buffer time will only explain one part of the variations between the minimum average and the expected turnaround time. Considering the aggregated buffer times and the minimum average turnaround time, the consequential turnaround time referring to each delay category are depicted in the following Tab. VII. It is concluded, that the difference to the expected turnaround time is caused by the dynamic interferences of single ground processes. It can be clearly seen that reduced buffer times indicate increasing process interference times. The process interferences will reduce the buffer compensation.

TABLE VII. PROCESS INTERFERENCE TIME

Delay	Min. TA (min)	Total Buffer (min)	TA with Buffer (min)	Expected TA (min)	Process Inter-actions (min)
Scheduled	38	17.78	55.78	57.93	2.15
5 – 10 minutes	38	12.85	50.85	54.03	3.18
10 – 15 minutes	38	9.64	47.64	50.97	3.33
15 – 20 minutes	38	7.27	45.27	49.31	4.04
20 – 25 minutes	38	9.62	47.62	51.03	3.41
25 – 30 minutes	38	5.47	43.47	48.83	5.36

The process interference times become naturally more important with increasing arrival delay (as pressure to catch up increases, following the measurements gathered in above). The characteristics of the buffer time and the process interference times are shown in Fig. 15. When neglecting the outlier found for the delay category “20-25 minutes” a linear/ polynomial fitting does excellently correlate buffer and interference times with regard to delay. Whereas the aggregated buffer times hold a square dependency ($R^2 = 0.999$) the process interference time do follow a linear relationship ($R^2 = 0.976$). From the planning perspective, buffer times are embedded elements to allow for process disturbances compensation and to ensure increased system reliability. In addition to these static buffers, delays due to process interferences have to be taken into consideration as well. To estimate the interference a polynomial relationship comparing to Fig. 16 was found appropriate. This allows us to immediately calculate the process interference time versus planned buffer time.

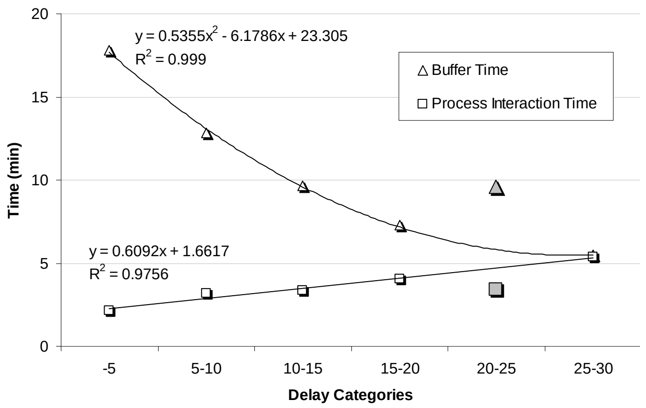

Figure 15. Buffer Time vs. Process Interference Time over Delay Category

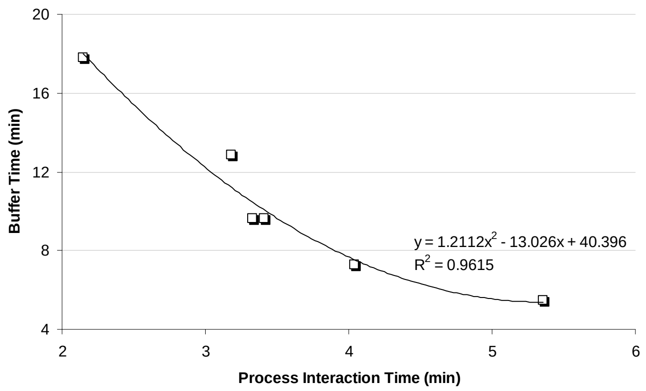

Figure 16. Buffer versus Process Interference Time

VI. CONCLUSION

The scheduled turnaround process is always disturbed if the airplane does not arrive at the allocated gate or apron position on time. This is true for every 5th flight operation on average. Ground handling agents have to consider the possible delays to ensure reliable ground processes aiming to not let this delay propagate into the next flight leg. This is a crucial goal, since there is only limited capability of compensating delay on the flight leg itself, the analyzed Munich Hub data showed an average of $\mu = 4.5$ min en-route delay reduction. But this is also a realistic goal, as MC simulations performed with the presented stochastic turnaround model proved a potential to reduce arrival delay of 33% on average. It is suggested to continue integrating inter-process time buffers during the gate allocation planning phase as those allow a higher system reliability. Hence, it could be found, that there is no systematic buffer concept applied. Rather, empirical experiences seem to trigger this process. The presented model may improve this procedure, allowing to optimize the time buffer size with regard to the expected average delay at a specific airport. It allows to find a balance between minimized buffer times with regard to given arrival delays on one hand (to shorten the turnaround), and an acceptable level of interference between the ground processes which tend to increase and counteract the buffer consumption (to keep reliability high). This is a core quality element for efficient Airport CDM, aiming at agreeing on a commonly accepted Target Start Up Approval Time. The order of magnitude for a given, very significant arrival delay of 25-30 minutes e.g. lays at an average of $\mu_{Buffer} = 5.5$ min cumulated buffer time at a process interference time $\mu_{Interference} = 5.4$ min.

VII. Outlook

The turnaround is embedded into the airport apron processes with a major influence onto the air transport performance. The next step we focus will consist in evaluating the precision of existing and used ground handling process databases such as ALLEGRO. This will be done with further field measurements focusing on the sensor side, ranging from Wifi (WLAN) hand held systems with manual process tracing to fixed installations based on RFID technology. Respective evaluation arrangements are under preparation, again with kind support of various airport operators in Germany. Further the airplane service arrangement concepts currently following the IATA Aircraft Handling Manual (AHM) [15] standards will be further investigated at more detailed level by means of microscopic simulations of apron traffic around the aircraft stand (see Fig. 17).

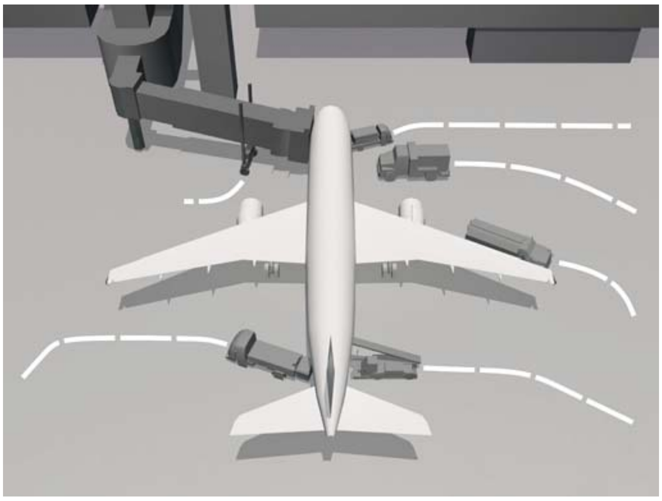

Figure 17. Turnaround Processes Inside an Airport Environment

An innovative simulation software has been developed in the past years at the Chair of Air Transport and Logistics at Dresden University of Technology. This software allows for simulating various constellations in fast time and to search logistically for optimized concepts to arrange service units in the light of highly reliable turnaround processes.

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