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Boarding on the critical path of the turnaround

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Abstract—**Due to the fact, that the boarding is always on the critical path of the aircraft turnaround, efficient boarding strategies are an essential for a reliable turnaround progress. Since the boarding time mainly depends on the amount of passengers, arrival rate, passenger boarding sequence and aircraft type we investigate different boarding scenarios on three reference aircraft: Airbus A320 (single aisle), Boeing B777 and Airbus A380 (both with a twin aisle configuration). The proposed microscopic approach of modeling the passenger behavior is primarily based on the asymmetric simple exclusion process, where the passenger motion is defined as a one dimensional, stochastic, and time/space discrete transition process. The provided analysis focuses on substantial boarding strategies and the scenarios are evaluated with common statistical criteria (e.g. expected value, variance, quantiles). In the context of both reliable boarding progress and delay compensation during the turnaround our results basically emphasize the use of an additional door for the boarding process (20 - 25 % savings), followed by a change of the boarding strategy (10 - 15 % savings), and the potential application of different seat layouts (3 % savings). First validation checks are performed against measurements of field trials with Airberlin. These tests point out the high reliability of the proposed stochastic aircraft boarding model.**

Keywords-aircraft boarding; efficient turnaround; microscopic passenger behavior; stochastic transition; critical path; optimization

I. INTRODUCTION

Economic systems have to be efficient in both cost and operational strategies. If a passenger gets in contact with the dispatch processes in an airport terminal, he will recognize that finally the boarding to the airplane is one of the characteristic processes. Nearly all passengers are brought to one location, to pass the boarding card control station, enter the gate and try to access their seat. Obviously, there is no significant chance to act tactically to improve the individual position and the overall system performance seems to be associated with the sequence of the passengers. Whereas first class and business passengers enjoy a smooth transition to their seats, the economy passengers compete against each other for an acceptable transfer to their seats. Not only will passengers benefit from a smooth boarding strategy but also the airline itself. From the airline point of view, the boarding is the last process to complete the turnaround of the aircraft. An optimized boarding strategy ensures short boarding times and a reliable predictability of the duration.

The *turnaround* is a generic term for the aggregated aircraft ground processes and the turnaround time is commonly defined as the aircraft parking time, between on-block and off-block. While the aircraft is at its gate or apron position the major ground processes of (un-)loading, catering, cleaning, refueling, and (de-)boarding are executed. Due to safety regulations and logistic requirements some processes run parallel to others and some processes have to be sequentially executed. Consequently, the actual turnaround time is reached with the termination of the last ground process. All ground processes which are able to influence the turnaround time are determine as critical. Keeping the focus on the passenger boarding process, it is quite evident that the efficiency of boarding could directly influence the overall turnaround progress. To achieve reliable improvements to the turnaround, optimizations have to ensure both a reduced expected value and variance of the process duration, which are expected to come along with an increased level of standardization. The process variances are often neglected, or only used as a second-rate value of system performance. But regarding to the stochastic nature of the real progress of the ground processes, investigations aiming on reliable performance enhancements have to cope with process variances. Various research studies were performed on the field of efficient boarding strategies [1-11].

These studies use the Airbus A320 layout as a typical reference for a single aisle aircraft. As the proposed investigations points out, particularly the single aisle layout significantly benefits from the improvements of changes in boarding strategies. From this vantage point and considering both the current amount of single aisle airplanes in operations (about two thirds of the total jet fleet) and the forecast of the aircraft manufactures Airbus and Boeing, that they expect a high business volume of single aisle aircraft, with a majority to be delivered within the next 20 years [12, 13]. These aircraft often come into operation for low cost carrier (LCC), where the market pressure forces the airlines to be highly competitive and to achieve high efficiency at all operational levels. The spread of the LCC business models and the expected rapid expansion of the air service in the emerging economies (e.g. Asia, Africa) [13] additionally emphasizes this trend. The single aisle aircraft represents a broad segment, which covers capacities from about 100 seats to 210 seats and is used at 87% of all routes and nearly 80% of all globally offered seats [12]. In the context of the current market share and the future expectations about the single aisle aircraft trend efficient boarding strategies will be an important competitive factor.

There are different disturbances during the passenger boarding process that significantly increase the process duration. These disturbances are mainly divided into three operational parts: calling passengers at the gate, boarding pass control, and passenger seating within the aircraft [6]. An adequate strategy for reducing the boarding time is to split the passengers into groups, whereas these groups are separately called to sequentially enter the aircraft (*block boarding*). Due to the high quantity of possible parameter variations, such as the size and the sequence of these blocks, a model-driven evaluation of the boarding strategies is necessary to achieve reliable results [7]. These evaluations provide a detailed insight into the associated boarding progress. However, a simulation environment to run the model is only capable to run pre-defined scenarios, but they normally do not provide autonomous algorithms for developing the most efficient strategy [3].

Since the scientific driven analyses of the boarding progress often disregards operational facts (e.g. seat load factors, arrival rates, or acceptance of boarding strategies, caused by separation of groups/families and delay arrival), the range of boarding duration (only average boarding times are calculated), and the practicability of the proposed boarding sequences (e.g. passenger specific boarding sequence), we consequently consider the operationally essential boundary conditions. Driven by the generally demand for reliable and fast boarding strategies, the presented research will cope with both realistic and scientific reliable scenario evaluations by using a sensitivity analysis. To cover the naturally varying boarding behavior of the individual passenger, a stochastic behavior approach is proposed for walking, storing the baggage and taking the assigned seat.

II. Aircraft Seat Layout

The proposed research mainly focuses on disturbances occurring during passenger boarding, namely the congestion in the aisle, the storage of hand baggage, and number of occupied seats between the aisle and the assigned passenger seat. However, disturbances based on missed rows, congested overhead compartments and overtaking of other passengers are not taken into account. For the analysis of the boarding sequences three different kinds of aircrafts are considered: a single aisle (Airbus A320-200), a twin aisle (Boeing B777-200) and a wide body aircraft (Airbus A380) (see fig. 1). Beside the different number of passengers, each aircraft is used to point out one special research aspect of boarding strategies. The investigations on the A320 provide information on the nature of the different boarding strategies and their potential benefits by means of reduced boarding time and time fluctuation. Using the twin aisle configuration, the portability of the A320 results will be verified and further aspects of different seat layout configuration will be analyzed. Finally the A380, as the aircraft with the highest capacity of passenger, is used to allow an outlook for potential future challenges.

For the simulation of a single aisle aircraft the Airbus A320-200 has been chosen, whereas a common seat layout of an Airberlin aircraft is used [14]. The aircraft is characterized with three seats on each side of the aisle and possesses a seating capacity of 174 economy seats in 29 rows (fig. 1, left). Due to the fact that first and business seats are not available in this specific configuration, priority boarding strategies do not have to be considered. This seat layout significantly differs from the following twin aisle seat configuration of the Boeing B777-200 (fig. 1, center) and the Airbus A380 (fig. 1, right), which provide a configuration up to 10 seats per row.

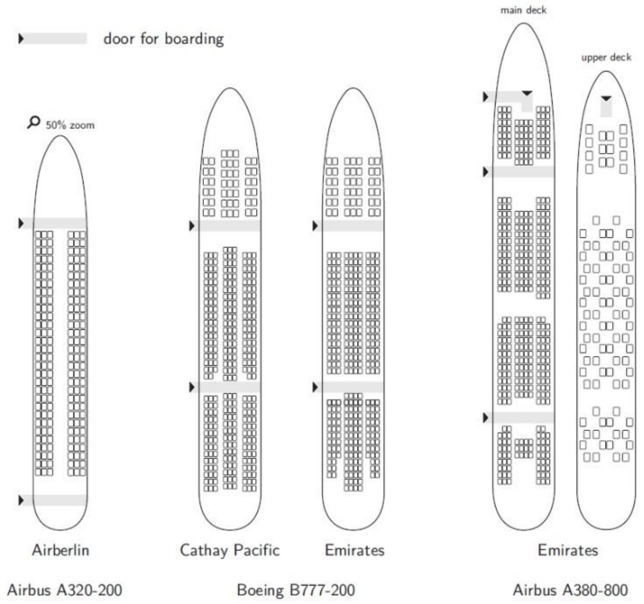

Figure 1. Schematic layout of aircraft used for the analyses

The Boeing B777-200 is a middle/long range aircraft with a (design) capacity of 440 passengers at maximum. Three different seat layouts are identified for the following analyses, where only 2-class configurations with premium and economy class seats are selected. The layouts are taken from the airlines Cathay Pacific [15] and Emirates [16], whereas the third layout is a general seat plan layout provided by the corresponding aircraft manufacturer Boeing [17]. These layouts differ in the seat allocation per row in the economy section, so Cathay Pacific has a 3-3-3 layout (read as: 3 seats on the left, 3 seats in the center, 3 seats on the right), Emirates has a 3-4-3 layout and Boeing propose a 2-5-2 layout. To ensure comparable calculation results of the boarding time, all three B777 layouts are harmonized by (minor) changes in the seat configuration. So finally, all layouts contain 36 business class seats and 320/322 economy seats. The different amount of seats per row at the seat layout of Emirates airlines (10 seats per row) results in 39 rows and 42 rows are used for the other configurations with 9 seats per row. The premium class is located in the front section of the airplane and will be boarded via the first door. In the case that only one door is available for the boarding process, the middle section with 198/200 seats and end section with 122 seats are boarded via the first door as well. If the second/rear door is available for boarding, all passengers seated in the end section, as well as passengers from the last rows of the middle section, will use this door (details available at the simulation section). For the evaluation of the boarding process the economy seats are divided into 8 equal sections. In contrast to the Airbus A320, the priority boarding of first class passengers has to be taken into account in these scenarios. In case only one door is used for boarding, the premium class passengers will board first, followed by the economy passengers. In the two door scenario the premium class passengers board separately, but at the same time economy passengers will use the second door for boarding. Similar to the B777, the Airbus A380 is a middle/long range aircraft with a twin aisle configuration. The A380 additionally has an upper deck section, so the maximum number of passengers is between 555 and 853 passengers (depending on aircraft and airline specification [2]). For the evaluation of the boarding progress, the aircraft seat layout from Emirates is used, which is characterized by a clear, deck-wise separation of premium and economy class: all economy seats are located on the main deck and the premium seats are located on the upper deck. The fact that different doors are used for the boarding of premium and economy passengers leads to an independent boarding progress for the upper and main deck section. The following boarding evaluation focuses on the lower deck, where 399 economy seats exist using the Emirates seat layout. We are aware of the current A380 gangway configuration using 3 gangways (one upper front door and two front doors at main deck), but for reasons of comparability we use the rear door at the main deck as the second boarding door scenario.

III. STOCHASTIC MODEL OF PASSENGER BOARDING

In contrast to the mixed integer linear program approach [2] or the multi-parameter discrete random process [1], the proposed simulation model is based on the asymmetric simple exclusion process (ASEP). The ASEP was successfully used for road traffic investigations. In a close analogy, the boarding can also be described as a stochastic, forward directed, one dimensional, and discrete (time and space) process [4, 5, 8]. For this purpose the seat layout is transferred into a regular grid as shown in fig. 3. This regular grid consists of equal cells with a size of 0.4 x 0.4 m, whereas a cell can either be empty or contain exactly one passenger [19, 23].

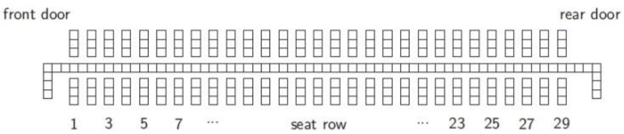

Figure 2. Grid based simulation environment for a Airbus A320 seat layout

During the movement process a passenger enters an empty cell at each simulated time step (v_{max} = 1 model, max 1 cell per time step). If the cell in front of the passenger is occupied the passenger has to wait (probability to overtake passengers is set to zero, comparable to the assumption of a one-dimensional transition process). Assuming a maximum speed of 0.8 ms^{-1} at the aisle (60% of maximum passenger speed) [19], the time step has a width of 0.5 s. At each time step during the simulation run the position of all passengers is updated via a shuffled sequential update strategy [20-23]. The boarding progress consists of a simple set of rules: a) passengers enter the aircraft at the assigned door (based on the current scenario), b) they move from cell to cell along the aisle until they reach the assigned seat row, and c) they store their baggage (block the aisle) and take their seat. Whereas the movement process is only dependent on the next cell state, the storage of the baggage is a stochastic process considering the individual amount of baggage pieces and the seating process has to take into account the occupied state of the associated seat row. This stochastic process requires for a minimum of simulation runs for each selected scenario, to derive reliable results. In this context, a scenario is mainly defined by the seat layout, the number of passengers to board, the arrival frequency of the passengers, the number of available doors, the boarding strategy and the conformance of passengers to follow these strategies. Other potential disturbances, such as blocked overhead compartments or wrong seat selection are excluded in the proposed model. The arrival frequency at the aircraft is deterministic for each simulation run (defined as n passengers per minute). Before the passengers enter the aircraft, they are stored in an additional queue, to ensure that congestions insides the aircraft aisle will not reject arriving passengers. This will cover both possible aircraft parking positions, a gate position where passengers queue arise at the gangway and remote positions where passengers use transfer vehicles to get access to the aircraft. If this pre-aircraft queue is empty, the passengers directly enter the aircraft, otherwise they have to wait until all passengers arrived earlier have entered the aircraft (first in first out behavior, no preemptive rules). The proposed ASEP model is used to model the movement and the interactions of the passengers in the aisle and they leave this one dimensional process, if their associated seating process frees the aisle.

A. Passenger interactions at the seat row

During the baggage storage and seating progress (e.g. other passengers have to leave their seats to allow access) the aisle is blocked by the passenger. The time t, which the passenger needs to take his seat, depends on several factors. First, t depends on time of baggage storage t_B, (related to the number of baggage) as well as on the time for handling occupied seats t_S and on the response time t_R of all involved passengers. These times are covered by stochastic probabilities, defined by a Simpson distribution [4, 6]. This distribution demands for three significant values: minimum, maximum and mode (cf. three-point estimation techniques using best, worst and most likely estimates). The cumulative distribution function for the Simpson distribution is defined in the interval of [min, max] as follows:

$$F(t) = \begin{cases} \frac{(t-min)^2}{(max-min)(mode-min)}, \text{if } min \leq t \leq mode \\ 1 - \frac{(max-t)^2}{(max-min)(max-mode)}, \text{if } mode < t \leq max. \end{cases}$$

The appropriate distribution values are determined as follows {min, mode, max}: {5 s, 10 s, 20 s} for time to store one piece of baggage, {1.8 s, 2.4 s, 3 s} for one movement from seat to seat, and {6 s, 9 s, 20 s} as the response time for all involved passengers. It may be noticed, that these values (and the following values) are initial assumptions which usually allow for a scenario comparison on a relative basis and that they have to be evaluated in the field to derive absolute time values for the boarding process. While the response time t_R is directly calculated from the given probability distribution, the time for baggage storage t_B is determine by the sum of the specific times for each piece of baggage, generated with the determined baggage storage distribution function. It is assumed, that each passenger stores at least one piece of baggage (e.g. coat), and the amount of individual pieces of baggage is determine by the following probability rates: 1 piece 60%, 2 pieces 30%, and 3 pieces 10% [19]. Fig. 3 shows the resulting distribution for the required individual time to store the baggage in the overhead compartment and under the front seat.

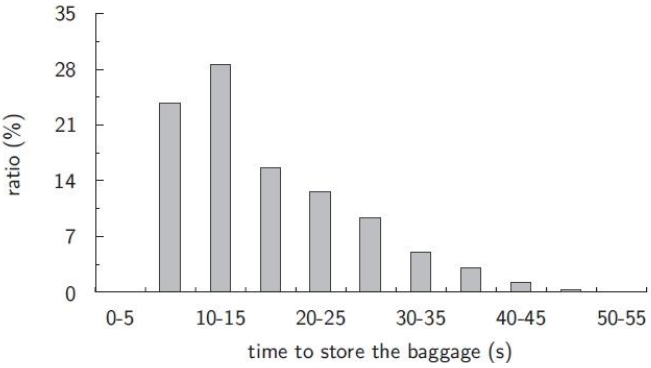

Figure 3. Distribution for individual baggage storage process

To determine the time t_S for handling the occupied seats, the character of the seat row states has to be clarified. At the chosen A320 layout, which consists of a 3-3 seat configuration, four relevant kinds of seat row states exist:

- seat access without any disturbances (state A),
- blocked aisle seat (state B),
- blocked middle seat (state C), and
- blocked aisle and blocked middle seat (state D).

This list of seat row states is sorted by the degree of complexity of seat replacements (by meaning of increasing time consumption). As an example, to take a seat at the window with a blocked middle seat (state C), the passenger at the middle seat has to move to the aisle seat and from there to the aisle itself. Now the window-seated passenger enters the seat row followed by the middle seat passenger, which finally results in 7 movements. During this seat replacement, the aisle is blocked as long as one involved passenger occupies the aisle. Hence, the number of required movements to ensure the availability of the aisle is lower than 7, because following passengers can pass the row 2 movements earlier: the prior passenger (on middle seat) needs 2 moves to the aisle, the arriving passenger enters the row and reaches the middle seat (2 moves), at the next moment the prior passenger clears the aisle by entering the seat row as well (1 move). Finally, the following seat row replacements, where the passengers get their corresponding window and middle seat, will be done without influencing the other passengers on the aisle. Considering a parallel update strategy, a passenger only needs 1 movement to enter the row in the simplest case (state A), state B requires 4 movements, state C requires 5, and the most complex row state D requires 9 movements. Finally, the overall time t_S for handling the occupied seats is determined as the sum of the required movement times using the proposed probability distribution for a single movement.

B. *Boarding strategies*

In order to speed up the boarding process, it seems obvious to eliminate the required interactions of the seat replacements using defined boarding calls. For arranging the arrival of the passengers a call-off system is used to ensure an appropriate passenger sequence already at the boarding counter. To determine the efficiency of specific boarding strategies, the progress of four different strategies will be evaluated: *random* - the passengers access the aircraft without a special order, *outside-in* - passengers with window seats enter the aircraft first, followed by passengers with middle seats and finally the passengers with aisle seats enter the aircraft, *back-to-front* - the aircraft is parted into blocks, whereas passengers allocated to the block with the highest distance is boarded at first, and *block boarding* - the aircraft is parted into blocks, whereas the fastest sequence considering all block configurations is used for the boarding. The *random* strategy is used as the baseline scenario to allow a target-performance analysis. Former studies pointed out, that the *outside-in* strategy is one of the fastest and (scientifically) suitable boarding strategies [3], even if this strategy possesses implementation issues in the field. Since passengers at airport terminals show clear group statistics, these groups (e.g. families) are often seat next to each other and are not willing to be separated [19, 22]. There is clear trend of groups with 2 or more members (78%) at the tourist classification whereas the business travelers often travel alone (73%).

It is expected that these group constellations decrease the actual efficiency of all boarding strategies and the *outside-in* strategy in particular (see fig. 4, bottom, for the associated seat allocation). Despite this fact, the *outside-in* is used to mark the benchmark value of the boarding time. The *back-to-front* method is often used by airlines (two blocks, where the rear block is boarded first). Based on this, the more general *block* boarding is part of the analysis. An example of the proposed block classification with 6 blocks is given at the following figure (fig. 4). Attention should be paid to the numbering sequence, which starts at the end of the aircraft. Consequently, the *back-to-front* strategy is equivalent to a block boarding strategy with the ascending sequence of seat blocks: 123456.

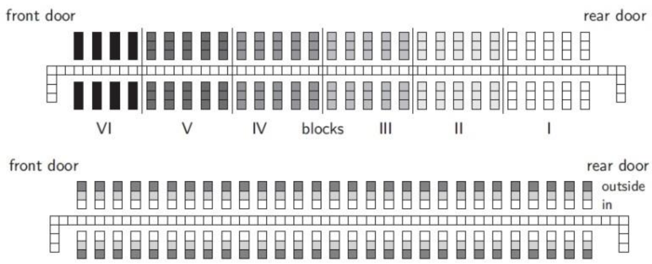

Figure 4. Classification of seats regarding to the *block* (top) and *outside-in* (bottom) strategy

C. *Parameter variation at the simulation runs*

The evaluation of the boarding strategies considers the common parameters conformance rate of boarding strategy (CR), seat load factor (SLF), the passenger arrival rate (PR), the amount of available boarding doors as well as the specific parameters for the *block* boarding: block size and sequence. Whereas the SLF (amount of passengers in proportion to the maximum seat capacity) and the AR (passenger per minutes arriving the aircraft, cf. [2, 18, 19]) are easily to derive from standards and operational figures, the conformance rate of the boarding strategy is defined as the percentage of passengers not taking the assigned position at the boarding sequence. This behavior may be intentionally caused, but also a result of late arrivals at the boarding gate. In the simulation environment the passenger conformance is implemented using two-stage procedure: a) the passengers are sorted according to the current boarding strategy, and b) the given percentage of passengers is reallocated. Thus, at the *block* strategy the passengers are using another blocks or at the outside-in strategy they use another sequence (e.g. window seated passenger located at aisle seated passenger group). This shuffle procedure ensures that the passengers are fully reallocated, which finally results in a contrary strategy. As an example, a block strategy with two blocks (block 1 and 2) turns from 1-2 sequence (assuming 100% conformance) to a 2-1 sequence as the consequential result of a total non-conformance (CR = 0%). The seat load factor depends on several factors, such as destination, region, or range. Deutsche Lufthansa (DLH) as the largest European airline published in the annual report of the financial year 2011 an average SLF of 77.6% (Europe 71.6%, America 83.5%, Asia/Pacific 81.1%, and Mideast/Africa 72.8%). In this context, the Air France-KLM group reports an average SLF of 82%, British Airways reports 79.1%, and Emirates reports 80% for the year 2011. In summary, the simulation scenarios are generated by the combination of the following set of parameters, whereas the default values are conservatively set. To allow a reliable and significant statistical analysis of the simulation results, each scenario consists of 10^4 simulation runs.

- SLF and CR ranging from 20% to 100% (default: 85%)
- AR ranging from 1 to 40 passengers per minute (default: 14 passengers per minute)
- 4 different boarding strategies (default: random)
- One and two door configuration (default: one door)

IV. Results

As the simulation for each chosen aircraft (Airbus A320, Boeing B777, and Airbus A380) aims at different aspects of the boarding, the result section is subdivided in three parts. The A320 simulations focus the boarding strategies and the sensitivity of input parameters, the B777 simulations are used for the comparison of seat layouts (2-5-2 vs. 3-3-3 vs. 3-4-3), and the A380 simulations point out the portability of these results to (new) wide body aircraft. Although the input parameter indicates absolute results using a time unit of seconds (minutes), the following results are explicitly outlined as relative values against the default boarding strategy.

A. Airbus A320-200

The *outside-in* strategy eliminates the required rearrangements of passengers at the seat row. The probability of seat row state A (no blocked seats) is about 66% using the random strategy and 91% if the *outside-in* strategy is used with the default input parameters. Although the *outside-in* strategy is adopted to real boarding conditions (CR = 85%), the significant smaller probabilities of the time consuming seat row states B, C, and D still results in an up to 20% faster boarding process. Since the effects of local seat row arrangements are not locally limited but also result in waiting queues at the aisle (negative side effect), the amount of arriving passengers is critical for the waiting queue length. For the default scenario using a random boarding sequence with a one door configuration, CR = 85%, and SLF = 85%, the queue length exponential increases if the arrival rate exceeds 9 passengers per minute. To efficiently handle the resulting increase of the individual waiting time, the use of the rear door is an appropriate solution. If passengers seated in rows from 15 to 29 are able to use the rear door, the arrival rate increases from 9 to 14 passengers per minutes without exhibiting the exponential queue growth [19].

During the boarding progress the number of seated passengers characteristically increases. In fig. 5 the center line represents the expected time embedded by the corresponding quantiles ($Q_{0.1}$, $Q_{0.25}$, $Q_{0.75}$, $Q_{0.9}$). Depending on the proposed stochastic model the boarding time using the default boarding parameters varies between ± 9% and ± 5% for $Q_{0.1}/Q_{0.9}$ and for $Q_{0.25}/Q_{0.75}$ respectively. The statistic evaluation of the boarding time suggest a normal distributed behavior which is confirmed by a chi-square test using a standard deviation of σ = 7% for the expected boarding time (μ=100%).

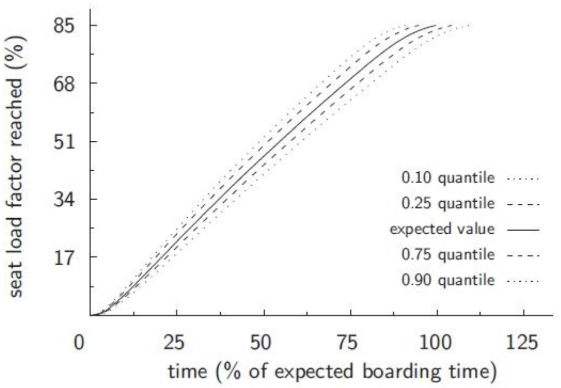

Figure 5. Boarding progress using the default boarding parameters

The expected boarding time of the fastest block sequence is shown in fig. 6 and points out a significant relevance of the number of blocks. Whereas the *back-to-front* strategy only benefits from 2 and 3 block classification. In this context, only the fastest block sequence determines the efficiency of the *block* strategy. From the view of the *block* strategy, a classification with 4 blocks clearly points out an increased boarding time. At this point, the characteristics of the *back-to-front* strategy diverge from the block strategy. Using a block size of 6 blocks (approx. 5 rows per block with 30 passengers) the expected boarding time of the *back-to-front* strategy increases to 110.7% and the (fastest) *block* strategy results in a decreased time of 96.1%. A further increase to 15 blocks finally results in an expected boarding time of 140.6% and 90% for *back-to-front* and *block* strategy respectively.

The evaluation of the different block sizes points out that alternating block sequences are much faster than other sequences. So, if the passengers of block 1 (rear block) enter the aircraft, they naturally block the corresponding aisle segment of block 2. Considering this consistent behavior, block 3 with an unoccupied aisle should be used as the following boarding block in the block boarding sequence. Furthermore, the most efficient sequence at the 29 row layout of the A320 always starts even numbered (246...) followed by the odd numbered blocks (...135), resulting from the fact, that the block 6 only contains 4 rows [cf. 19].

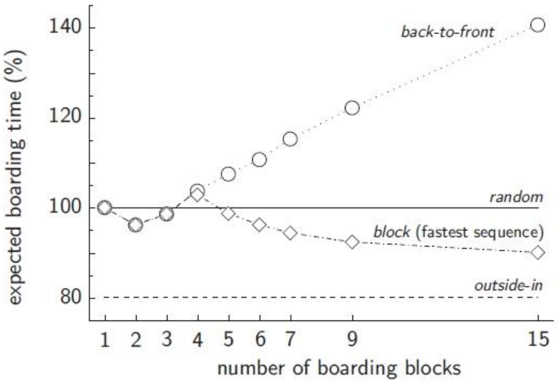

Figure 6. Efficiency of block strategies using different block numbers

The next evaluations are fully based on the 6 block classification, where the block sequence of the *back-to-front* and the *block* strategy is defined as 123456 and 246135 respectively. For the two door configuration this nomenclature has to be slightly adapted. The blocks 123 are boarded through the rear door and 456 are boarded at the same time through the front door. Hence, the sequences for back-to-front and for block are 34-25-16 (rear-center-front) and 25-34-16 (center-rear-front) respectively, where the separation of boarding doors allows a simultaneously boarding call for the corresponding blocks. In contrast to the one door boarding passengers, the effective block size is reduced to 3 and it is assumed, that the passenger from blocks 4, 5, and 6 (front door) do not disturb passengers from blocks 1, 2, and 3 (rear door).

To analyze the different boarding strategies one parameter has been varied (CR, SLF, AR, and number of doors) whereas the other parameters are kept constant at their default values. In the following figures the random strategy is always marked as a reference with a solid line to easily compare the different boarding strategies. In the fig. 7 the expected boarding time is shown, where the one door and the two door configuration are put next to each other followed by the progress of the corresponding standard deviation. As expected, the *random* strategy points out a constant behavior, whereas the two door configuration shows an average decrease of both the expected boarding time (74.2%) and the standard deviation (from 7.1% to 4.7%). The *block* boarding points out a slight parabolic behavior with a minimum of 96.1% expected boarding time at 85% CR using the one door configuration. This behavior is stronger pronounced at the *back-to-front* strategy, where the minimum of 98.2% is at 48% CR and a CR greater than 62% results in significant slower expected boarding times. With the increasing conformance of the provided boarding strategy (fig. 7) the expected boarding time of the *outside-in* boarding strategy decreases nearly linear with an average slope of 3.7% and 1.9% per 10% conformance rate steps for the one and the two door configuration respectively. Furthermore, a minimum of 32% CR has to be reached at both configurations, to ensure that the *outside-in* sequence is faster than the corresponding *random* strategy. Looking at the two door configuration a nearly linear behavior is seen for all strategies, whereas *back-to-front* points out no significant advantages (±1.5%) and the *block* strategy is always slower than the *random* strategy. The behavior of the standard deviation reflects the behavior of the expected boarding time.

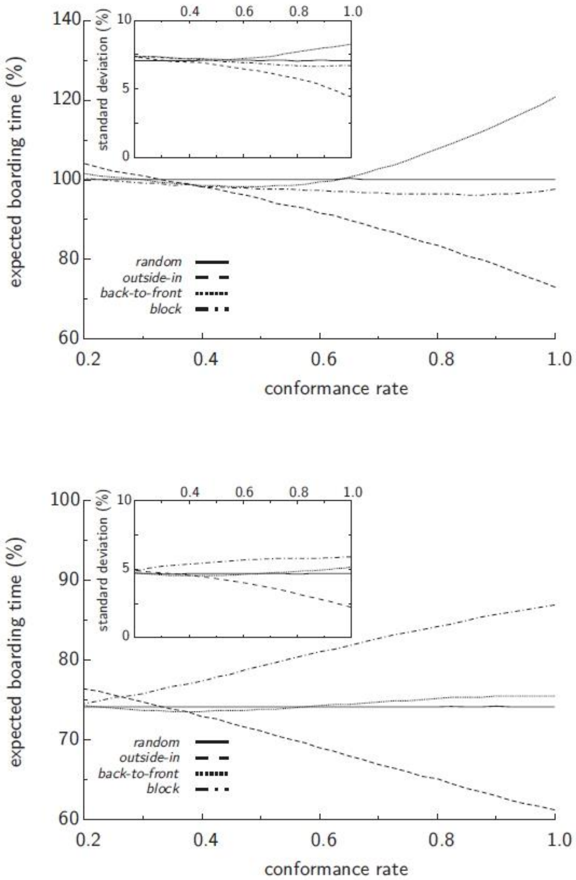

Figure 7. A320. Variation of conformance rate (CR) using for one door (top) and two door configuration (bottom).

The analysis of the SLF variation shows nearly linear correlations between the SLF and the expected boarding times, except the *back-to-front* strategy at the one door configuration. Analogue to the behavior of the conformance rate variation, the behavior of the *back-to-front* strategy is parabolic and the expected boarding time exceed the reference for SLF >68%. Even for small SLF (<45%) the *back-to-front* strategy is the fastest strategy and additionally points out the smallest standard deviation at SLF < 38%.

The analysis of increasing arrival rates provides no additional information about the comparison of different boarding strategies regarding to the expected boarding time and the corresponding standard deviation. However, the direct comparison of the one door versus the two door configuration shows that an AR of about 11 (one door) and 16 passengers per minute (two doors) determines an upper value for the arrival rate regarding to the expected boarding time. From these points a further increase of the arrival will only result in a marginal decrease of the expected boarding time. This result corresponds to the waiting time analysis at the beginning of this result section, where an AR > 9 results in an exponential increase of the waiting time. The summary of the evaluation of the A320 boarding process is shown in tab. I. The simulation results are based on the default configuration of the input parameter CR, SLF and AR with 85%, 85% and 14 passengers per minute respectively. Furthermore, the result points out that the *back-to-front* strategy is a not recommended boarding strategy. Also the application of the *block* boarding is not recommended, because the expected boarding time only marginal decreases accompanied by a nearly unchanged standard deviation. Though, the utilization of the second aircraft door significantly accelerates the boarding processes by 25.9%, without even considering particular boarding strategies. In comparison to this, the fastest strategy using the one-door configuration only provides an enhancement of 18.7%. The combination of the promising candidates, two-door configuration and *outside-in* strategy finally result in the minimum expected boarding time of 63.9% with a standard deviation of 3.0% towards the defined reference boarding procedure.

TABLE I. RESULTS OF A320 BOARDING

configuration	sequence	expected boarding time (%)	standard deviation (%)
1 door	*random*	100.0	7.1
	outside-in	80.9	5.5
	back-to-front	110.6	7.9
	block	96.1	6.1
2 doors	*random*	74.1	4.7
	outside-in	63.9	3.0
	back-to-front	75.4	4.9
	block	85.0	5.8

B. Boeing B777-200

In contrast to the single aisle configuration of the A320, the B777 seat layout contains two aisles and a nearly doubled seat capacity. The economy section is divided into 8 equal blocks (fig. 8) considering both the given B777 seat layouts and the results of the A320 evaluations. The harmonization of the different layouts are taken from Emirates, Cathay Pacific, and Boeing reference result in 198 (200 for Emirates) seats in the center and 122 seats in the rear section.

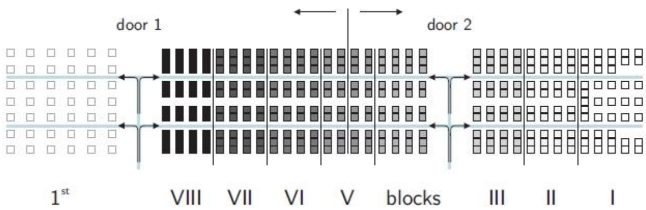

Figure 8. Model of B777 aircraft

Since the B777 seat layout additionally contains a section for premium passengers, this section is always boarded first. Consistently, the block sequence for the one-door configuration is 1st-24681357. As a consequence, the sequence for two-door configuration is 1st-6857 and 24513 for the front and rear door, respectively. The block V is divided into two parts, whereas the first two rows boarded via the front door and last two rows board via the rear door. This separation line results from specific calculations, where the boarding time shows a minimum for all used boarding strategies. As the back-to-front strategy points out no significant enhancements at the A320 evaluations and for reasons of clarity, this strategy is skipped for the following analyses. The seat configuration 2-5-2 (2 seats left, 5 centered seats, 2 seats right) of Boeing is used as a reference for the B777 simulation runs. The developed model is extended for the application of the twin aisle layout to cover all available seat configurations (fig. 9).

Whereas the passengers at the A320 only have one aisle for boarding, the twin aisle configuration results in an additional choice. It is assumed that the passenger use the aisle which ensure the shortest distance without counterflow situations.

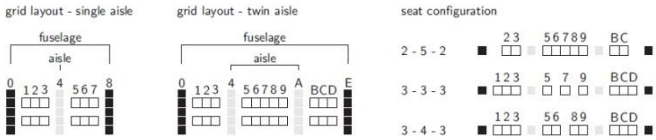

Figure 9. Model extension for the twin aisle configuration

According to fig. 10, the passengers with seats at position 1, 2, 3, 5, and 6 are using a different aisle than the passengers with seats at position 8, 9, B, C, and D. If an odd number of seats are located at the middle section of the row, the seat at position 7 is stochastically assigned to one aisle. Further on, fig. 10 points out the seat allocation for the outside-in strategy.

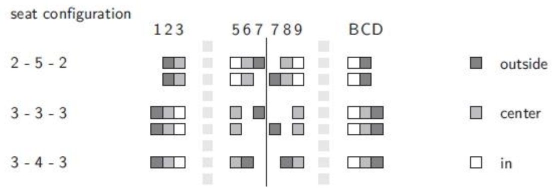

Figure 10. Stochastic allocation of aisle for the center seat at position 7 considering different seat configurations

Whereas an arrival rate greater than 9 (14) passengers per minute for a one (two) door configuration at the A320 will not additionally decrease the expected boarding time, the analysis of the boarding process of the B777 points out a different behavior (fig. 11).

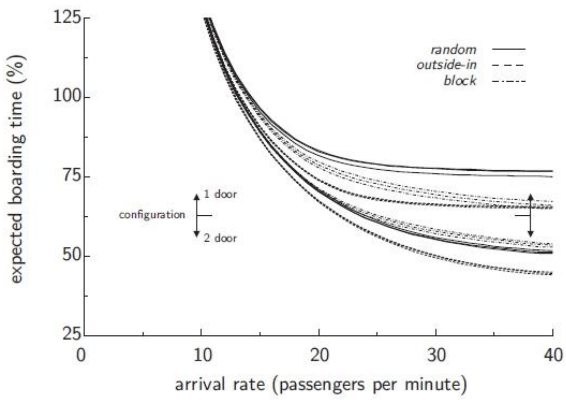

Figure 11. Boarding time using Boeing B777-200 with increasing arrival time

Particularly the block strategy benefits from the higher amount of arriving passengers and nearly reaches the performance of the outside-in strategy at AR = 40 passengers per minute with a one-door configuration. As a result of the significantly increased capability of handling arriving passengers, the default arrival rate is changed from 14 to 28 passengers per minute for the following twin aisle configurations. The behavior of the standard deviation directly corresponds to the behavior of the expected boarding time and points out no further indications for efficiency of the boarding strategies. The expected boarding time of the boarding strategies points out a comparable behavior against the A320 boarding scenarios. The 2-5-2 seat configuration gains a time benefit, whereas the expected boarding time of the 3-4-3 and the 3-3-3 seat configuration points out only minor differences (0.1% at average).

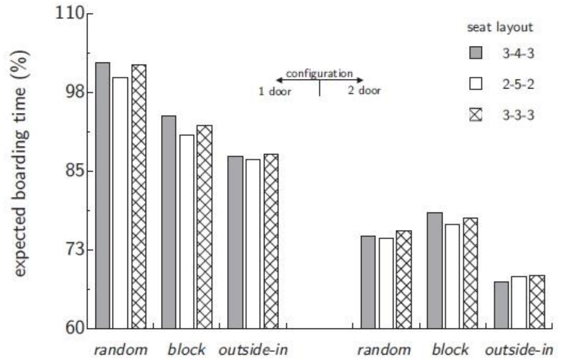

Figure 12. Boarding efficiency using Boeing B777-200 considering random, outside-in, and block strategies, as well as 3 seat (3-3-3, 3-4-3, 2-5-2) and door configurations (1, 2) at standard values for CR = 85%, SLF = 85% , AR = 28 passengers per minute, using random strategy and 2-5-2 seat layout as reference.

Even at the outside-in strategy using a two-door configuration the 3-4-3 is the fastest strategy with 67.5% (2-5-2 with 68.2% and 3-3-3 with 68.5%). The different seat configurations only have a minor influence on the expected boarding time (1-3%) against the time savings due the implementation of boarding strategies (10-15%) or the use of a two-door configuration (25%) (fig. 12).

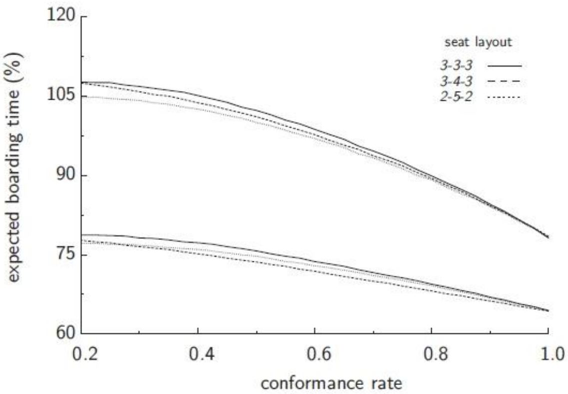

Figure 13. Boarding time using Boeing B777-200, outside-in sequence, 3 seat configuration, 1 and 2 door

As directly compared to the *outside-in* sequence (fig. 13) the *block* sequence (fig. 14) shows a modest influence against changing CR. All seat layouts possess are nearly linear behavior with slight variations, except a minor increase at higher CR (>80%), particularly remarkable for the 3-4-3 seat layout. The evaluation of the varying SLF provides no new findings, so the analyzed seat layouts expectably possess a linear decreasing boarding time associated with a decreasing SLF.

The results of the boarding progress using the B777 are summarized at tab. II. Consistent to the A320 results, decreasing boarding times come along with smaller standard deviations. Further on, the evaluation of the B777 boarding confirms that the application of boarding strategies holds the potential to improve the boarding progress. Furthermore the single aisle configuration results in a halved standard deviation, which leads to a more stable/reliable boarding progress.

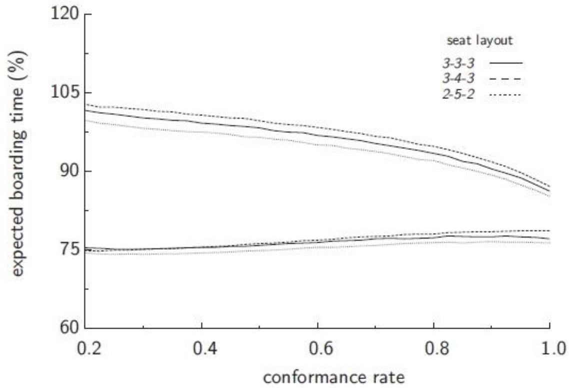

Figure 14. Boarding time using Boeing B777-200, block sequence, 3 seat configurations, 1 and 2 door

The results of the arrival rate analysis suggests a high arrival rate by using a two-door configuration with at least 3 parallel boarding counters assuming an average time for the board card checking of 5s [19].

TABLE II. RESULTS OF B777 BOARDING

configuration	sequence	expected boarding time (%)	standard deviation (%)
1 door	*random*	100.0	2.9
	outside-in	86.0	2.1
	block	91.0	2.7
2 doors	*random*	73.8	2.2
	outside-in	67.1	1.7
	block	76.4	2.1

C. *Airbus A380*

The selected A380 seat layout from Emirates is divided into two parts, where the premium passengers are located at the upper deck, the economy passengers are located at the main deck. Due to this separation and the facts that a) the premium passengers at the upper deck passengers will use a different door for the boarding and b) the dominant ratio of the 399 economy passengers against 90 premium passengers, the expected boarding time mainly depends on the boarding progress at the main deck. As the seat blocks at the A320 and B777 contain 5 seat rows, the layout of the A380 will be divided into 10 seat blocks using at the one door configuration (fig. 15).

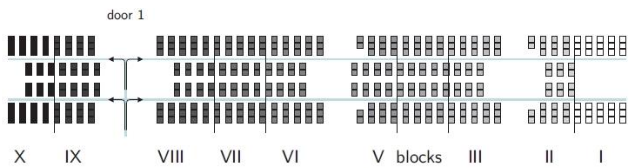

Figure 15. A380 seat layouts with 10 blocks for the one door configuration

Because this segmentation results in an inefficient boarding behavior using two doors for boarding, a slightly different block allocation is developed (fig. 16). The results of the A320 points out the *back-to-front* strategy as appropriate against the *random* strategy and will be consequently transferred. The seat layout is mainly parted by the seats allocated the doors and is further subdivided into a separate front bock (II, IV) and rear block (I, III)

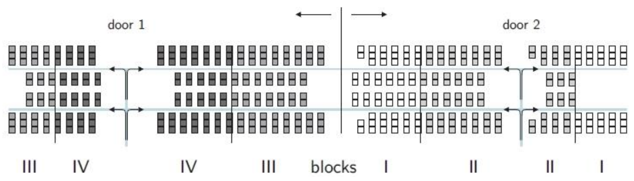

Figure 16. A380 seat layouts with 8 blocks for the two door configuration.

The boarding of the one-door configuration using the prior identified alternating block sequence (246...135…) and for the two-door configuration the 1324 sequence is implemented. In comparison to the A320 and B777 analysis, the characteristic shape of the expected boarding time against the increasing conformance rate will be also achieved for the A380 boarding (fig. 17).

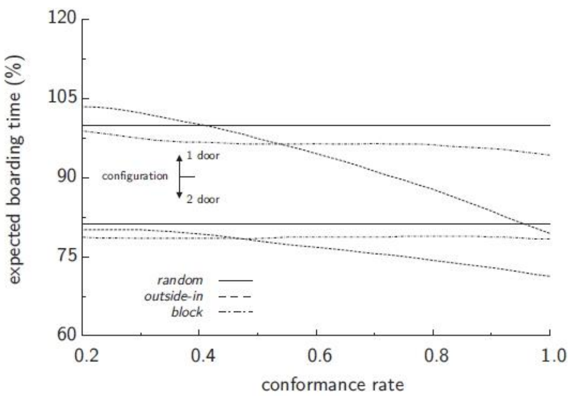

Figure 17. A380. Three boarding sequences (*random*, *outside-in*, *block*), 1 and 2 door configuration at AR = 28 passenger per minute and SLF = 0.85.

The results of the A380 boarding scenarios are shown at tab. III. Although the good results of the B777 boarding progress could not be reached and the standard deviation in particular is significantly higher (but smaller than the A320 results), the A380 boarding possesses a comparable boarding behavior (keeping in mind the slight deviations from the prior proposed block classification of A320/B777).

TABLE III. RESULTS OF A380 BOARDING

configuration	sequence	expected boarding time (%)	standard deviation (%)
1 door	*random*	100.0	5.9
	outside-in	85.9	4.3
	block	95.9	5.3
2 doors	*random*	81.4	3.7
	outside-in	73.7	2.3
	block	79.1	3.2

V. OUTLOOK

Current measurements at Airberlin aircraft emphasize the high consistency of the chosen input parameter (e.g. walking speed, amount of baggage, or interaction times). Consequently, additional field trials are planned to validate the achieved results against the real progress of the passenger boarding processes. The presented results will be further used as an input into current research on turnaround optimization and the introduction of a decision support system for airline and ground handler personnel. The turnaround is modeled using stochastic input parameters and specific process properties, which directly influence process progression as shown with boarding strategies in this paper. A main aspect of the research is the reduction of delays resulting from disturbances en-route (weather) or previous flight legs. As shown with the results of this paper, the boarding process has a high potential in time savings. Additionally, the turnaround process always includes the passenger boarding as part of the critical turnaround process path, whereas other processes may be left out in a specific flight leg and cannot be used for further optimization. However, changing boarding strategies also implies higher costs for airlines in personnel or equipment (transfer busses, passenger stairs, etc.). Therefore cost functions will be developed for opposing delay cost and additional resource costs, allowing the simulation system to find an optimal solution in terms of delay minimization and cost savings.

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