Invited Review

Airplane boarding

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The time required to board an airplane directly influences an airplane’s turn-around time, i.e., the time that the airplane requires at the gate between two flights. Thus, the turn-around time can be reduced by using efficient boarding methods and such actions may also result in cost savings. The main contribution of this paper is fourfold. First, we provide a general problem description including partly established and partly new definitions of relevant terms. Next, we survey boarding methods known from theory and practice and provide an according classification scheme. Third, we present a broad overview on the current literature in this field and we describe 12 most relevant papers in detail and juxtapose their results. Fourth, we summarize the state-of-the-art of research in this field showing e.g., that the commonly used strategy back-to-front generally requires more time than other easy to implement strategies such as random boarding. Further concepts and approaches that can help speed up the boarding process are also presented and these can be studied in future research.

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1. Introduction

The boarding of an airplane is a process that many of us have personally experienced. It happens many thousands of times every day at airports in almost every country in the world. Nevertheless, the problem of getting passengers into an airplane is often not optimally organized. Many airlines use boarding methods that perform rather poorly concerning boarding time (Nyquist & McFadden, 2008). The principle objective of studies on the boarding problem is to minimize boarding time. Three key parties benefit from reduced boarding times: airlines, airport operators and passengers.

Airlines can save money when the ground processes involved in the turn-around time (see p. 3) take less time and result in a quicker turn-around time. The literature provides various evidence regarding possible cost savings due to a reduction in turn-around time. According to Nyquist and McFadden (2008), a 1-minute reduction in the turn-around time saves US$30 at each turn-around. Other estimations range from US$77 (Steiner & Philipp, 2009) to US$250 per minute (Horstmeier & Haan, 2001). FMT, a Swedish supplier of boarding bridges, has stated with every saved minute of turn-around time saves US$30 at each turn-around. Other estimations range from US$77 (Steiner & Philipp, 2009) to US$250 per minute (Horstmeier & Haan, 2001).

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2. Problem description

To the boarding procedure. However, personnel responsible for boarding soon became unhappy with the new procedure, and the boarding strategy then changed several times until the airline finally returned to the outside-in method in 2013.

Reduced boarding times and turn-around times can also benefit airport operators. Because a reduction in turn-around times implies that an airplane sits at a gate for a shorter time, fewer gates are necessary for a given number of flights (Steffen, 2008b), and it is possible to offer more flights per day per gate. Gates are a scarce resource at airports (Dordorff, Drexl, Nikulin, & Pesch, 2007), and thus the benefits for airport operators are obvious.

Passengers generally take advantage of shorter boarding times because a reduction in total boarding time implies a reduction of the average individual boarding time for passengers (van Landeghem & Beuselinck, 2002). Waiting time at the gate, in the bridge or in the aisle during boarding is reduced and the whole process is likely to be perceived as more relaxed. Nevertheless, there are fast boarding methods that are not very passenger-friendly. Hence, with greater passenger convenience viewed as a competitive advantage for airlines, it is not enough to simply implement faster boarding methods. The identified methods also have to allow for a comfortable boarding process, and this factor must be included in the objective function.

Although the boarding problem is a central and important part of air traffic, there are rather few research papers dealing with the problem. To the best of our knowledge, there is no paper that provides a complete survey of the relevant literature and of existing and possible boarding strategies.

Our aim is to offer a broad insight into the airplane boarding problem and to identify and present the current state of research. First, we classify the boarding procedure in terms of the ground handling processes at an airport, study the different problems that influence the boarding time and present various boarding methods. Our comprehensive introduction to the boarding problem is followed by an overview of the existing literature, and we classify and compare a number of studies and present their key findings. The structure of the paper is as follows. In Section 2 we outline the airplane boarding problem. Moreover, we define the term turn-around time, chronologically classify the boarding process and provide an overview of the other processes involved. We also focus on the difficulties that emerge during the boarding process and explain the occurrence of seat and aisle interferences. In Section 3 we define the scope of the literature review. In the following section we present common boarding strategies like random, back-to-front and outside-in as well as non-traditional strategies, analyze them and list their main advantages and drawbacks. In Section 5 we focus on the current literature on the boarding problem. The main results are presented in Section 6. In Section 7 new ideas as a starting point for future research are presented and discussed.

2. Problem description

Boarding is part of the passenger handling process at airports. It is usually the responsibility of the airlines but often passenger handling is outsourced to service providers, so-called handling agents, who conduct the whole process from check-in to boarding (except for the security check that is performed by members of the police or an airport security service).

The typical procedure a passenger goes through from arrival at the airport until aircraft takeoff can be summarized as follows. After arriving at the airport, the first step for passengers is to check-in if they have not already done so online. For this passengers can use a self-service check-in kiosk or they go to a check-in counter staffed by the airline's ground crew. In both cases, passengers with most airlines can choose their own seats, sometimes passports are controlled, and the passengers receive their boarding passes. If passengers have used the online or the self-service check-in, they then go to a facility where the baggage is weighed, tagged, checked and sent to the baggage handling system from where it is later transported to the plane. If passengers check-in at a staffed check-in counter, they can drop off their baggage there. The next step of the passenger handling process is the security check that ensures that no weapons or explosives are taken on board. Every passenger has to walk through a metal detector and carry-on baggage and all other items carried onto the plane are screened. This security check separates the public domain (i.e., the terminal area with the check-in counters) from the departure hall, a secure area with direct access to the gates of the respective aircraft. In most countries only passengers with boarding passes are allowed to stay in this area. Commonly, passengers must arrive at the gate from which their plane is leaving at least 30 minutes before departure time. This time, also called the latest boarding time, and the gate number are normally printed on the boarding pass. The boarding of passengers, which we now consider in detail, is the final step of the passenger handling process at airports for out-bound flights. It is important here to first clarify the terminology.

The boarding problem comprises all decisions and activities that influence the passengers’ experience from the gate to their seats, including decisions regarding which boarding strategy to use and its implementation, announcements by the gate agent, the handling of carry-on baggage, lining up in front of the gate, the ticket check, the walk from the gate to the plane and the search for a seat, the stowing of carry-on baggage and settling into one’s seat.

We define boarding as the process of passengers entering an airplane.

Contrary to boarding in general, boarding time “starts when the first passenger enters the plane and ends when the last passenger is seated in his assigned seat” (van Landeghem & Beuselinck, 2002, p. 296). The middle aisle of an airplane with six seats per row (the standard configuration for medium-haul flights) is no wider than 50 centimeters, and hence it is difficult to pass other passengers that no weapons or explosives are taken on board. Every passenger that influence the passengers’ experience from the gate to their seats, including decisions regarding which boarding strategy to use and its implementation, announcements by the gate agent, the handling of carry-on baggage, lining up in front of the gate, the ticket check, the walk from the gate to the plane and the search for a seat, the stowing of carry-on baggage and settling into one’s seat.

We define boarding as the process of passengers entering an airplane.

A boarding strategy or boarding method influences or even determines the sequence in which passengers board the plane. Boarding usually starts with a call from the ramp agent (the person who commonly controls all ground handling processes) informing the gate agents that the airplane crew is ready for boarding. However, some airlines do not make this call, but—unless there is delay information—start boarding at the boarding time written on the boarding pass. For single-aisle airplanes this call is usually made 30 minutes before the departure time. The gate agents then announce boarding via speakers and ask passengers to line up in front of the gate. A signal often appears at this time on a screen above the gate. It is common for special passengers (such as disabled passengers, families with young children, and first or business class passengers and those with priority boarding) to board first. When reaching the gate agent, passengers must show their boarding pass (and with some airlines or flights, their passport). The gate agents scan the boarding pass to confirm which passengers have boarded. They also take a quick glance at passengers’ carry-on luggage to
determine whether it complies with the airline’s size limits. After passing the gate agents, the passengers walk over the passenger boarding bridge (also known as the jetway, jetty, airbridge or finger), which directly connects the gate with the airplane door, and enter the plane. Sometimes when the airplane is parked on the apron, passengers have to use buses or walk across the apron to the airplane and board it via a gangway. When entering the plane, the boarding pass is sometimes shown again to the cabin crew to double check passenger numbers. Inside the airplane, the passengers search for their assigned seats, the number and letter of which are written on the boarding pass.

The numbers denote the different rows starting with 1 at the front of the plane. As many people consider numbers 13 and 17 to be bad luck, these numbers are sometimes omitted. The letters, determining the location of the seat in a row, in single-aisle airplanes usually range from A to F with A being the window seat at the port side and F the window seat at the starboard side of the airplane. When the passengers have reached their assigned seats, they stow their baggage in the overhead lockers or under the seat and sit down.

If, in the meantime, not all passengers have yet arrived at the gate, the gate agent will once more make a boarding announcement. If after some time there are still missing passengers, the gate agent will make the final boarding call by specifically calling out the names of those passengers, asking them to immediately proceed to the gate. A few minutes later the gate agents call the ramp agent and cabin crew to inform them that boarding is complete and as soon as there are no more passengers on the boarding bridge the airplane door is locked. At this point, the flight status on the flight information boards in the terminal building switches from “final call” to “departed” and passengers can no longer board. The subsequent activities like the push-back (tractors towing the plane backward away from the gate), which cannot start before all passengers are seated, or taxiing (travel to the runway) are considered aspects of the block time (flight time) that starts as soon as the chocks are removed, and are not included in the turn-around time (Schlegel, 2010, p. 110).

When it comes to airplane boarding, the primary objective of airlines and, therefore related research, is to minimize the time required to board a plane. This is the only objective that is quantifiable. It also could be argued that it is sufficient to remove boarding from the critical path, but in consideration of the fact that missed time slots because of unexpected longer boarding times result in much higher cost, airlines also have an interest in further reducing boarding time and not only removing it from the critical path. A further objective that is also important but more difficult to measure is passenger comfort. Airlines want to please passengers to gain or retain them as satisfied loyal customers. Therefore, one has to bear in mind the following: passengers wish to avoid feeling stressed when boarding (e.g., if there are no assigned seats and everyone wants to enter the plane first), they do not want to feel disadvantaged, and they do not like procedures that are too complicated (e.g., if they do not understand at what time they are allowed to board). The success of a strategy largely depends on the cooperation of the passengers. Thus, to ensure passenger satisfaction, the procedure needs to be easily understood and accepted by passengers and to not result in customer avoidance. Moreover, a solution that is fast and passenger-friendly but not possible to realize (e.g., because of essential personal data or passenger characteristics that are not possible to collect) is only of theoretical interest. This means that certain restrictions, for example, safety rules or constructional circumstances at the gate or plane have to be followed. And, of course, there is no benefit from a fast strategy that saves money by reducing the turn-around time if it brings with it many extra expenses. In summary, airlines have to trade off different aspects against each other as they are searching for a boarding method that boards passengers quickly and comfortably, without too much additional effort and is practically applicable.

To achieve these goals there are a number of issues on which airlines have to make decisions. Theoretically, airlines can adjust aspects of the boarding process that are not fixed by the circumstances of the airport or airplane.

It starts with the decision on seat assignments (open seating or assigned seats, and whether or not the passengers choose their seats or whether seats are assigned according to a special system), the rules on carry-on baggage and the boarding strategy. Furthermore, the number of gate agents can be varied as can the number of doors that are used for boarding (provided that the infrastructure of the gates permits boarding with two doors). The mode of announcing passengers at the gate must also be chosen, because this procedure can be carried out by signals (numbers or colors) on a screen above the gate, by calls made by the gate agents or a combination of both. The most common way is to make an announcement and to simultaneously show the numbers (e.g., the rows that are to board next). As for color coding, each passenger gets a colored card when arriving at the gate area that assigns them to a boarding group. The screen above the gate then shows the color of the current boarding group and all passengers with that color are allowed to board (van Lansegem & Beuselinck, 2002). Instead of using colored cards, the color of the different boarding groups can also be printed on the boarding pass.

Even if it is just one of the many possibilities to speed up the boarding process, the choice of boarding method is a very important decision as it can lead to substantial savings of boarding time. As stated above, boarding methods influence or even determine the sequence in which the passengers board. Most methods divide passengers into different boarding groups for which the boarding sequence between the groups is given. The boarding groups usually consist of passengers who are allocated to this respective group because of their seats. Within these groups there is no given order for the passengers to board. When the airplane is ready for boarding, gate agents call the first group and after this group has boarded the next group is asked to board and so on.

This leads us to the main research question of the boarding problem:

How and to what degree should the sequence in which passengers board an airplane be influenced to reduce boarding time while also offering a high level of customer comfort? In other words: which boarding method is best, considering the trade-off between boarding time and passenger convenience?

Although we talk about boarding strategies, this decision is made on a tactical level. It has to be decided by the airline management and then the chosen strategy is applied on their flights. Basically, different boarding strategies can be applied (depending on the kind of flight and airplane), but usually an airline decides on a single strategy and boards all of their flights in this manner. As the success of the boarding method—and thus the needed time for boarding—is highly dependent on the comprehension, acceptance and realization of the passengers and the expertise of the gate agents who have to instruct the passengers, it is not reasonable to frequently change the boarding method. The boarding itself is an operational task and the gate agents with every new flight have to make decisions on issues such as how to handle late passengers, special requests and other problems.

To enable a better understanding of the boarding problem, we now introduce two terms that are strongly related to the boarding process.

The first is airplane turn-around time. Boarding is one aspect of an airplane’s turn-around time (also called turn time, turn round time or minimum ground time), which can be regarded as the idle time of an airplane. The turn-around time is the time that an airplane spends at the gate or at the handling position on the apron between two flights while being prepared for the next take-off. Other turn-around time processes include deboarding, refueling, cabin cleaning, handling of catering, wastewater and potable water, and the offloading and...
loading of baggage and freight containers (and line maintenance services). Some of these processes are not possible or permitted to be performed simultaneously. Safety rules, for example, only allow refueling with passengers on board under certain circumstances. Moreover, catering and cleaning are timed before or after deboarding and boarding to prevent obstructions in the cabin and inconveniencing passengers. Fig. 1 illustrates the sequence of these processes. Of course, all these activities are strongly connected. In order to reduce turn-around time, all of them have to be examined and dependencies have to be analyzed. Minimized boarding times have much more impact on turn-around time if other processes, which are part of it are also adjusted. For further information on this see Wu and Caves (2002) and Ashford (2013). Depending on the airplane model, the type of flights and other factors, the turn-around time averages from 30 to 60 minutes. Three time-critical processes are deboarding (10–15 minutes), cabin cleaning (15–20 minutes), and boarding. Often only 10 minutes are reserved for the entire boarding time, but up to 30 minutes are required. In reality, the boarding process could begin by asking passengers to line up and allowing them to walk to the airplane door even though cabin cleaning has not been completed; airlines usually wait until the airplane has been cleaned completely (Ferrari & Nagel, 2005; van Landeghem & Beuselinck, 2002).

The second term relevant to the boarding process is interference. When passengers are boarding an airplane, they often block each other and cannot get to their seats without having to wait for other passengers who are stowing their carry-on baggage to leave the aisle or who are already sitting in the row and block access to other seats. These so-called interferences have a significant influence on boarding.

Fig. 1. Airplane turn-around time (according to Horstmeier & Haan, 2001).
boarding of wide-body aircraft see Bazargan (2011). Throughout this paper we only consider economy class passengers. Business and first class passengers and those with special needs (e.g., disabled passengers or adults with young children) are usually asked to board first and do not influence the decision regarding the best boarding method for regular passengers. The boarding procedures of these passengers are rarely changed because either those passengers would block all other passengers as they require extra time or they have paid for such privileges and would not accept having to board with regular passengers. Thus, the boarding times detailed later only refer to a simplified airplane model with economy class seats. We assume that in the basic case the plane is full. In this worst-case scenario, boarding is a bottleneck procedure that does not necessarily materialize with lower occupancy levels. For studies on the influence of the load factor on boarding time see Ferrari and Nagel (2005). If boarding is not on the critical path, it is not that important to reduce boarding time because it does not have a direct influence on turn-around time. Furthermore, all passengers arrive at the gate on time. This means that we do not have to consider the case where passengers do not appear at the gate and consequently their baggage has to be identified and taken off the plane. It is given by laws that only the baggage of boarded passengers is to be carried. We also act on the assumption that the passengers board over a boarding bridge through one door at the front of the aircraft and that the passengers have assigned seats. The possibility of letting passengers choose their seats inside the aircraft, i.e., open seating, is not considered as it is not very popular among customers and hence only some low cost airlines use this method.

Most of the studies included in the literature review in Section 5 also make the same assumptions as used in our basic case. We mainly focus on those papers that concern the boarding problem in general. Research with a key focus on other problems such as the boarding of wide-body twin-aisle airplanes (Bazargan, 2011) or open seating (Steffen, 2008a) are not emphasized in this study.

We only study the boarding problem as it relates to airplanes because there are, for example, significant distinctions between the boarding of a bus or train. In contrast to the boarding of a bus or train, all airplane passengers must have a seat, usually an assigned seat, and the aircraft must not start moving until all passengers are seated. The boarding process is time-critical for airplanes. Passenger loading time is not as important for buses and trains because the impact of a schedule delay for a bus or train is not as serious as for an airplane. A further difference is the possibility of passengers to pass one another in buses or trains. This is not possible in planes because the aisles are very narrow.

The airplane boarding problem is chronologically located between the check-in and departure. Problems regarding the passenger handling process such as check-in and security check or certain ground handling activities (deboarding, Cimler & Oševičová, 2013; catering, Jones, 2004; cleaning, Longmuir & Ahmed, 2009; Stern & Hersh, 1980; fueling) as well as problems like gate assignment (Bolat, 2000; Dorndorf, Jaehn, & Pesch, 2008; Lim & Wang, 2005; Yan & Tang, 2007), scheduling of push-backs and taxiing (Marín, 2006; Smeltink, Soomer, Waal, & van der Mei, 2004), runway control (Atkin, Burke, Greenwood, & Reeson, 2007; Briskorn & Stolletz, 2014), handling of passengers with reduced mobility (Reinhardt, Clausen, & Pisinger, 2013) or baggage handling (Barth & Pisinger, 2012; Frey & Kolisch, 2010) are not included in this review. The problem of transporting passengers to an airplane parked on the apron has been studied by Diepen, Pieters, van den Akker, and Hoogeveen (2013) and Kuhn and Loth (2009). For a general overview of air transportation problems and ground operations see Barnhart, Belobaba, and Odoni (2003), Schmidberger, Bals, Hartmann, and Jahns (2009), Ashford (2013) and Andersson, Carr, Feron, and Hall (2000), for OR methods concerning the security check see Lange, Samoilovich, and van der Rhee (2013), Lazar Babu, Batta, and Lin (2006) and Nie, Batta, Drury, and Lin (2009). For a synopsis of the airport ground handling processes that are part of the turn-around

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time see Horstmeier and Haan (2001) and Mirza (2008). Although it is important to address efficient methods to quickly disembark passengers and this issue appears related to the boarding problem, the deboarding process is not considered here because it is a completely different problem that can be classified as an evacuation issue (Cimler & Ošlešíková, 2013).

A number of studies try to find optimal boarding strategies by searching for increasing subsequences and assume that passengers are infinitely thin, for example, Bachmat, Berend, Sapir, and Skiena (2007), Baek, Ha, and Jeong (2013), Brics, Kaupužs, and Mahnke (2013) and Frette and Hemmer (2012) (see here also Bernstein, 2012). Bachmat and Elkin (2008) and Bachmat, Khachaturov, and Kuperman (2013) mathematically study back-to-front boarding strategies to determine which method concerning the number of boarding groups performs best. Steffen (2008a) studies the open seating method, that is, the case where passengers do not have assigned seats. He analyzes the problem using physical methods where each seat is assigned a particular energy. He states that boarding without seat assignment is as fast as the best practical boarding methods with assigned seats. Using Boltzmann statistics he also studies the seating arrangements of flights with lower occupancy levels.

With a focus on research papers, publications such as working papers, student/graduate papers and newspapers articles are not included in our review. The following studies include simulation models and were not considered for various reasons: Audenaert, Verbeek, and Vanden Berghe (2009) (multi-agent based simulation), Cimler, Kautzka, Ošlešíková, and Gavalec (2012), Mas, Juan, Arias, and Fonseca P. (2013), Schultz, Kunze, and Fricke (2013) (single-aisle and wide-body twin-aisle aircraft) and Wang and Ma (2009) (MINLP, solved with genetic algorithms).

4. Airplane boarding strategies

In the following section, we give a general overview of boarding strategies as they can be found in practice and scientific and non-scientific literature. We differentiate the three main ways of boarding an airplane: random, by group and by seat. The latter two each consist of various boarding strategies (see Fig. 3). Note that we will not consider the possibility of open seating, that is, where passengers do not have assigned seats.

The first way of boarding is to let passengers enter randomly without any given order. For this method, no extra announcements or signs asking a passenger group to board are necessary, but all passengers are allowed to board as soon as the gate agents announce that boarding has started (Ferrari & Nagel, 2005; van Landeghem & Beuselinck, 2002). Random boarding is different to open seating where the seats are not assigned, and in this study we only consider ordinary economy class passengers and no special cases that are allowed to board first.

The second category, by group, allows several passengers to board simultaneously. A group boarding method typically defines two to six boarding groups. Gate agents announce these groups one after another by calling the respective rows, letters, group number, or color, and ask them to board. After the first group, the passengers from the next group are announced and may board as soon as everyone from the previous group has boarded and so on. Within the groups there is no fixed order, that is, within their group the passengers board randomly. Generally, the boarding groups can comprise any possible assemblage of passengers boarding at the same time, even with seating that is completely unrelated. The boarding groups are not required to be of the same size, but usually they are similar in size. A common classification of the group boarding strategies distinguishes by block strategies (multiple, complete rows board together), by row strategies (each row boards on its own, leading to a large number of boarding groups), by half-block and by half-row strategies (leading to twice as many boarding groups as by row) (see e.g., Ferrari & Nagel, 2005; Nyquist & McFadden, 2008; van Landeghem & Beuselinck, 2002). For the latter two strategies, each boarding group encompasses passengers with seats at one side of the middle aisle. Furthermore, the strategies outside-in and reverse-pyramid (see below) belong to the category by group. The most frequently used group boarding strategy is back-to-front where, for example, passengers in rows in the last third of the plane board first, followed by those in the middle rows and then those in the front third (Bachmat et al., 2013; Bazargan, 2007; Steffen, 2008b; van den Briel et al., 2005). Note that boarding from the back to the front could also mean that the passengers board by seat, all in order, starting at the back of the plane. However, with the term back-to-front, we always refer to the described block strategy where at least two rows, usually about five to seven rows, board simultaneously. The boarding strategy outside-in, also known as window-middle-aisle (wma), WilMA, or by letter, builds groups according to the position of the seats in the rows (window, middle and aisle seats). It leads to three boarding groups with the first group consisting of all passengers with window seats, the second group of those in middle seats and the third group of passengers with aisle seats (Bachmat, Berend, Sapir, Skiena, & Stolyarov, 2009; Bazargan, 2007; Ferrari & Nagel, 2005; Marelli, Mattocks, & Merry, 1998; Nyquist & McFadden, 2008; Steiner & Philipp, 2009). By mixing back-to-front and outside-in, the boarding method reverse-pyramid can be generated. It was developed by van den Briel et al. (2005) and attempts to board passengers diagonally from the window seats at the back of the plane to the aisle seats at the front.

A boarding strategy can occur with different variants depending on the size and number of boarding groups and the boarding sequence.
of these groups. For example, the by block method allows for boarding in two groups, with one group consisting of rear seats and the other with seats in the front half of the plane. However, boarding by block also can allow boarding in small blocks of only two adjacent rows. In this case, the number of boarding groups would be much higher. The exact design, that is, the number of boarding groups and the sequence

van Landeghem and Beuselinck (2002) structure the design of the strategies by introducing a notation that specifies these properties. The notation determines the type of boarding strategy (e.g., by block or by row); for block strategies the number of boarding groups (i.e., the number of blocks) and the sequence of the different boarding groups. It is assumed that each boarding strategy begins at the back of the plane. The sequence then can be descending (des) or alternating (alt), which means that all groups are boarded step-by-step in a descending order or that a given number of groups is always skipped. By_row_alt_1 denotes a boarding strategy where each boarding group only consists of a single row. Boarding begins at the back of the plane and one row is always skipped. When the front of the plane is reached, the rows that have been skipped are filled, again beginning at the rear.

The third possibility, by seat, defines an exact sequence of the passengers. Every passenger has to board at a given position that is planned in advance (see e.g., Steffen, 2008b; Steffen & Hotchkiss, 2012; Tang, Wu, Huang, & Caccetta, 2012b; van Landeghem & Beuselinck, 2002). This strategy provides the chance to board passengers in the optimal order.

Random boarding and by seat can also be regarded as special cases of the group strategies. Random boarding corresponds to boarding by one group only, that is, all of the passengers. In contrast, deterministic boarding by seat provides as many boarding groups as there are passengers, with every group consisting of only one passenger.

The literature review contains many references, analyses and discussions regarding various boarding strategies. Fig. 4 provides a schematic representation of some of the boarding strategies, illustrated using an airplane model with 20 rows. The numbers denote the boarding groups in which the passengers of the respective seats should board. For clarity, the numbers are merely alluded to for the Steffen method. The modified optimal method is a strategy deduced from the Steffen method, offering a fast and practical way of boarding an airplane (see Steffen, 2008b, p. 26). Table 1 lists the most important aspects of each strategy.

Generally, boarding strategies should be easily understood by passengers, and although a reduction in the boarding time is the key objective, costs, customer friendliness and feasibility must also be considered (see Section 2). The most common boarding strategies are random and back-to-front.

The boarding times given in the literature review are purely theoretical; that is, they operate under the assumption that the respective boarding strategy works as planned. If passengers do not board in the correct order (because they arrive late, do not understand the strategy or do not want to board in the given sequence) then good strategies usually perform worse. Thus, when only looking at the aim of minimizing boarding time, it would have been better to choose another boarding method from the beginning. Surprisingly, this is not the case for the strategy back-to-front, which performs better with an increasing number of passengers boarding too late (Ferrari & Nagel, 2005).

The risk of a poor performance is lower with simple boarding strategies that separate passengers into a few boarding groups. As for boarding by seat, where each passenger boards individually and an exact sequence is given, there is a high probability for disturbances because of passengers arriving late. Furthermore, complicated strategies lead to overwhelmed passengers who may negatively remember their experiences with the airline.

For the sake of completeness, Table 1 also includes the policy of open seating, which is not a boarding method in its original sense because the passengers, when getting on the plane, may choose any free seat. Although the number of airlines with free seat choice has decreased (e.g., the British airline easyjet dropped this policy in
November 2012) there are still some that do not assign seats. However, since open seating is rather uncomfortable for passengers and often perceived as stressful it is only used by low-cost carriers such as Southwest Airlines or Ryanair.

A completely different approach to boarding passengers efficiently was developed by the Australian design engineer Rob Wallace (2013). He invented the Flying Carpet, which is 2.0 by 5.6 meters in size, and was developed by the AustraliandesignengineerRobWallace(2013). Thiscarpet hastobeplaceddirectlyinfrontofthegate.Whenboarding starts, the passengers have to stand on the field of the carpet that starts, the passengers have to stand on the field of the carpet thatCongestions are concentrated on a small area of the plane; rather slow Rare (e.g., United Airlines)

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<th>Drawbacks</th>
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<tr>
<td>Random</td>
<td>Just one boarding group; there is no given sequence for the passengers to board, but every passenger is assigned to a particular seat</td>
<td>No organizational effort with calling groups; easy to understand; passengers who are traveling in a group can board together; rather fast; late passengers do not influence efficiency</td>
<td>Very bad worst case performance</td>
<td>Common (e.g., American Airlines, Lufthansa)</td>
</tr>
<tr>
<td>By group</td>
<td>Back-to-front</td>
<td>Boarding in blocks from the back of the plane to the front</td>
<td>Easy to realize; passengers who are traveling in a group can board together</td>
<td>Congestions are concentrated on a small area of the plane; rather slow</td>
</tr>
<tr>
<td></td>
<td>Outside-in/WillMA</td>
<td>First all window seats, then middle seats, finally aisle seats</td>
<td>Fast because of no seat interferences</td>
<td>Separation of passengers who are traveling in a group</td>
</tr>
<tr>
<td></td>
<td>Reverse-pyramid</td>
<td>Mixture of back-to-front and outside-in</td>
<td>Fast</td>
<td>Rather complicated; separation of passengers who are traveling in a group possible</td>
</tr>
<tr>
<td>By block</td>
<td>Passengers of some consecutive rows board together; generalization of back-to-front; also possible front-to-back; possible to skip rows/blocks and board them later</td>
<td>Passengers who are traveling in a group can board together</td>
<td>Congestions are concentrated on small areas of the plane; slow if more than one block (&gt;random), the more blocks, the slower</td>
<td>Other variants than back-to-front are rare</td>
</tr>
<tr>
<td>By half-block</td>
<td>Passengers of some consecutive rows and one side of the aisle board together</td>
<td>Passengers who are traveling in a group can board together</td>
<td>Rather slow</td>
<td>No usage known</td>
</tr>
<tr>
<td>By row</td>
<td>Passengers of one row board together</td>
<td>Passengers who are traveling in a group can board together</td>
<td>Slow; many boarding groups</td>
<td>No usage known</td>
</tr>
<tr>
<td>By half-row</td>
<td>Passengers of one row and one side of the aisle board together</td>
<td>Fast if rows are skipped; passengers who are traveling in a group can board together</td>
<td>Rather complicated</td>
<td>No usage known</td>
</tr>
<tr>
<td>By seat</td>
<td>Passengers board individually in given optimal order; number of boarding groups = number of passengers</td>
<td>Optimal sequence (\rightarrow) fastest possibility</td>
<td>Complicated; difficult to realize/to explain to passengers; separation of passengers who are traveling in a group</td>
<td>Rare (e.g., Southwest Airlines)</td>
</tr>
<tr>
<td>Steffen method</td>
<td>Exactly two rows distance between adjacent passengers (23A, 21A, 19A, …)</td>
<td>Very fast because of no seat and just few aisle interferences (maximum number of passengers can stow baggage simultaneously)</td>
<td>Separation of passengers who are traveling in a group; rather complicated</td>
<td>No usage known</td>
</tr>
<tr>
<td>Open seating</td>
<td>There are no assigned seats; passengers can choose any free seat when entering the plane</td>
<td>No organizational effort with calling groups; traveling groups can board together; passengers can avoid interferen ces by thoroughly choosing their seats</td>
<td>Often perceived as stressful by the passengers; disadvantages of first-come, first served principle: last passengers who are traveling in groups probably do not get adjacent seats</td>
<td>Relatively common at low-cost carriers (e.g., Southwest Airlines, Ryanair)</td>
</tr>
</tbody>
</table>

5. Literature on the boarding problem

Our literature search included the use of Google Scholar and the websites of several journals that publish papers concerning airplane boarding (e.g., Management Science, Operations Research, EJOR, Mathem. Programming, Transp. Science, SIAM J. on Computing, Discrete Applied Mathematics, OR Spectrum, INFORMSJ. on Computing, Mathem. of OR, J. of Operations Management, Annals of OR, Transp. Res. Part A – F, Comp. and OR, JORS, Omega, OR Letters, and Mathem. Methods of OR). Among others, we employed the search criteria ‘airplane boarding’, ‘aircraft boarding’ and ‘aeroplane boarding’. The same criteria were used to scan the library networks of Bavarian universities. The next step was to inspect the references of the found papers for further relevant research. We also searched the websites of authors with relevant publications.

There is a manageable amount of literature on the subject of airplane boarding. The first study was carried out by Marelli et al. (1998) for Boeing and was published in the Boeing Aero Magazine. van Landeghem and Beuselinck (2002) state that before 2002 attempts were made to improve the infrastructure or land-side
processes of airports and there were hardly any studies on the boarding problem. Since then there have been a number of publications covering the airplane boarding problem. We found 12 papers that are highly relevant to our topic. These papers are described in detail and for each, the approach, chosen method and main results are presented in this paper. Table 2 (p. 17) provides an overview of these 12 papers.

The papers follow different approaches and hence are assigned to the categories computer simulation and analytical model. Some authors try to find fast boarding strategies by setting up an analytical model. They use linear or nonlinear programming (MILP or MINLP) and minimize the number of interferences. Others just take common boarding strategies and use computer simulation (discrete-event simulation, e.g., with Arena) to reproduce the boarding process and compare the different boarding times. Some authors also empirically test various boarding strategies. Furthermore, there are studies where the boarding problem is analyzed from a physical perspective or considering passenger behavior. One paper by Nyquist and McFadden (2008) merely summarizes current papers and does not provide any mathematical models or simulations. It is the only paper that can be viewed as a review of the boarding problem, although it only comprises four studies on the boarding problem. This paper is discussed first.


The authors illustrate the boarding problem and its importance, and review four studies. Moreover, they address and calculate potential cost savings due to a reduction in the boarding time.

Methodology: Literature review (Ferrari & Nagel, 2005; Marelli et al., 1998; van den Briel et al., 2005; van Landeghem & Beuselinck, 2002).

Assumptions: –

Studied strategies: Traditional methods (by block, by half-block, by row, by half-row), non-traditional methods (outside-in, reverse-pyramid).

Main results: With each minute on the ground an airplane induces cost of US$30; with non-traditional methods (outside-in, reverse-pyramid) boarding time can be reduced by more than 30 percent; by restricting carry-on baggage to one piece, boarding time can be reduced by 15 percent, by forbidding carry-on baggage by nearly 40 percent.

After a short introduction including an outline of the boarding strategies used by US airlines and explanations regarding the turn-around time, the four reviewed papers are presented in detail with explanations concerning their approach, implemented methods and results. Clear summaries of these studies are provided in helpful tables. Subsequent to the literature review, the impacts of the use of efficient boarding strategies on boarding time as well as possible cost savings are shown. For this Nyquist and McFadden (2008) divide the boarding strategies into traditional and non-traditional ones. Traditional boarding methods include by block, by half-block, by row and by half-row, and non-traditional ones include outside-in and reverse-pyramid. Based on data from van Landeghem and Beuselinck (2002), Nyquist and McFadden (2008) determine the average boarding time of the traditional boarding methods used in the discussed studies, which is 30.33 minutes. For non-traditional boarding methods they state an average boarding time of 19.78 minutes, which is determined based on the four cited studies. Hence, airlines could save 10 minutes in boarding time if they used non-traditional methods instead of traditional ones like the back-to-front method.

In addition, based on van Landeghem and Beuselinck (2002) and van den Briel et al. (2005), they conduct calculations concerning time savings if carry-on baggage is reduced or prohibited. They estimate a reduction of 4.6 minutes in boarding time when allowing one piece of carry-on baggage and a reduction of 11.6 minutes by eliminating all carry-on baggage. The authors state that according to these values airlines could reduce their boarding times by up to 50 percent and thereby costs when using non-traditional boarding methods and limiting the number of carry-on baggage to one piece (when compared with the use of traditional boarding methods and allowing several pieces of carry-on baggage). By also using two doors instead of one door, a saving of 66 percent could be realized: Marelli et al. (1998) determine a 5-minute reduction in the boarding time when using two doors. Further savings, up to 90 percent, could be realized when boarding with a non-traditional method, using two doors and completely eliminating carry-on baggage. The authors met with a major US airline and found that every minute an airplane is on the ground it costs US$30. Consequently, they estimate an airline with 1500 flights per day could save approximately US$446 million per year when realizing all of the possible changes discussed above.

5.2. Papers focusing on simulation models

In this section we describe papers that study the boarding problem using simulations. Although papers that use optimization models often include simulation studies, their main focus mostly lies with analytical models and as such these papers are included in Section 5.3.

5.2.1. Marelli et al. (1998): The role of computer simulation in reducing airplane turn time, Boeing Aero Magazine

The study conducted by Boeing was the first to examine the airplane boarding problem in detail. First, the development of the airplane turn-around time over recent decades is discussed. Second, the authors describe their self-developed computer simulation, apply it to the boarding of a Boeing 757 and present the results.

Methodology: Computer simulation (Boeing Passenger Enplane/Deplane Simulation, PEDS); empirical tests to validate simulation.

Assumptions: Airplane models: Boeing 757–300 with 240 seats and two classes (simulation study), Boeing 757–200 (empirical tests).

Studied strategies: Traditional methods (not specified more precisely), outside-in.

Main results: With alternative boarding strategies (e.g., outside-in) boarding time can be reduced by 46 percent; usage of two doors can reduce boarding time by 20 percent.

In the first part of the paper, the authors explain the increase in the airplane turn-around time since the 1970s. Boeing has kept
records that show a decrease of more than 50 percent in the passenger enplane rate between 1970 (20 passengers per minute) and the 1990s (9 passengers per minute). They state that the reasons for this slowdown and thus increased turn-around time are mainly due to more carry-on baggage and improved passengers services.

To test various potential changes concerning the interior configuration of airplanes and boarding procedure, the authors develop a computer simulation program called Boeing Passenger Enplane/Deplane Simulation (PEDS). The program uses discrete event simulation and randomly assigns each passenger particular characteristics such as walking speed or number and size of carry-on baggage. The process of boarding the plane then is simulated with various actions like entering the plane, moving forward step-by-step, stowing the baggage and sitting down. Interruptions like waiting for the previous passenger to clear the aisle, which forces the passenger to stop, are considered. The simulation starts with the first passenger entering the airplane and ends when the last passenger is seated. To validate the simulation, Boeing observed real boarding processes and conducted empirical tests with 600 volunteers. The overall results show that PEDS was configured well, but some unexpected behavior like passengers stowing their baggage in overhead lockers not directly located above their seats has to be included in the simulation.

Applying the simulation tool PEDS resulted in a boarding time of 26 minutes and 12.5 minutes to deboard. The authors do not mention the boarding method used but state that when applying alternative boarding strategies like outside-in and using two doors, the overall time for boarding and deboarding (enplaning and deplaning) could be reduced by 17 minutes. By using two doors, with all other factors remaining constant, 5 minutes could be saved. As the choice of boarding method only influences the boarding process and not the time required for deboarding, the saved 12 minutes must result entirely from the reduced boarding time (enplaning time). Consequently, the boarding time can be reduced from 26 to 14 minutes (46 percent) by using alternative boarding methods.

5.2.2. van Landeghem and Beuselinck (2002): Reducing passenger boarding time in airplanes: A simulation based approach, European Journal of Operational Research

A computer simulation of different boarding strategies is provided. The authors explain the boarding process, different boarding methods, and the structure of the methods. The simulation results are clearly represented.

Methodology: Computer simulation (Arena).

Assumptions: Airplane model: 132 seats in 23 rows (3 seats in the first and the last row, 6 seats in all other rows); process times in the airplane (passing one row, settling into one’s seat and exiting from the seat into the aisle) follow triangular distribution; number of carry-on baggage after frequency distribution ranging from one to three pieces per passenger; 10 passengers can be controlled every minute by the gate agent (every 6 seconds a passenger arrives at the airplane door).

Studied strategies: Random, various variants of back-to-front, by block, by half-block, by row, by half-row, outside-in, by seat.

Main results: By half-row_alt_2 is fastest boarding strategy outside by seat strategies (15.8 minutes); by block strategies take at least 27.7 minutes, best if no more than two boarding groups; random: 24.7 minutes; boarding strategies with low total boarding times also lead to good average and maximum individual boarding times.

After a short introduction to the boarding problem, reference to Marelli et al. (1998), and an explanation of the various aspects of airplane turn-around time, the authors divide the boarding process into three steps. In the first step a gate agent begins the boarding process by making an announcement and asking passengers to line up in front of the gate. Step 2 contains the control of the boarding passes and carry-on baggage and step 3 is the walk to the airplane through a passenger boarding bridge or over the apron and the entering of the plane, the stowing of carry-on baggage, and the seating of passengers. The authors build their simulation architecture based on observations of the boarding process at Brussels National Airport and numerical data provided by a Belgian airline. As the authors not only search for the boarding method with minimal total boarding times but also for one with high passenger comfort, they also conduct tests concerning the average and maximum individual boarding time as well as measuring the average total boarding time. The best values (starting from 10.4 minutes) are generated with the by seat strategies where for each single seat the exact boarding sequence is determined. However, these strategies are difficult to realize because not all passengers arrive at the gate on time or are willing to board in this given sequence. The fastest boarding strategy beyond the by seat strategies is by half-row_alt_2 (15.8 minutes), which boards all passengers in one row and on one side of the aisle together, always skipping two rows. Boarding passengers by half-row without skipping any rows is not recommended because the boarding time using this method is 41.8 minutes. A similar structure can be found with the by row strategies where the best values are attained if five rows are omitted. In contrast, the by seat strategies where the passengers are boarded from the window to the aisle and by descending row are faster if no rows are skipped. The reason for these results is that in this simulation model passengers always need the space of one row to stow their carry-on baggage in the locker over their seats. When boarding by half-row (by row), three (six) passengers enter the plane at the same time and to be able to stow their baggage simultaneously, they need the space of three (six) rows in the aisle, which is ensured by skipping two (five) rows. The best boarding times can be achieved by omitting exactly one row less than there are passengers in one boarding group. By omitting additional rows, the boarding time gets longer, which can be explained by the number of trains that are needed. Trains are sequences of a number of consecutive boarding groups of which passengers do not need to cross each other when boarding. The bigger the gap between the successive boarding groups, and thus the more trains are needed, the more time accrues for walking in the aisle and the total boarding time increases. Another boarding strategy that performs quite well is outside-in with alternating sides (A, F, B, E, C, D) with an average boarding time of 21.3 minutes. All by half-block strategies have an average total boarding time of at least 24.8 minutes and the by block strategies of at least 27.7 minutes. Regarding by block strategies, the best results are obtained by separating the passengers into no more than two boarding groups. Hence, it is reasonable that random boarding with an average total boarding time of 24.7 minutes performs quite well. It is clear then that a scheduled boarding time of 10 minutes is insufficient. Concerning individual boarding times, the simulation results show that the boarding strategies with low total boarding times also lead to good average and maximum individual boarding times.
5.2.3. Ferrari and Nagel (2005): Robustness of efficient passenger boarding strategies for airplanes, Transportation Research Record

Ferrari and Nagel (2005) conduct a computer simulation similar to van Landeghem and Beuselinck (2002), but with a simplified, cell-based simulation architecture. The same boarding methods are simulated and the results are compared with the latter paper. The authors examine robustness of boarding strategies in terms of early or late passengers, airplane layout and occupancy level as well as various alternative boarding methods and the case of unassigned seats. Some of the results are also presented in Nagel and Ferrari (2005).

Methodology: Cell-based computer simulation (self-designed simulation environment); comparison of results with those of van Landeghem and Beuselinck (2002); test of robustness.

Assumptions: Airplane model: 132 seats in 23 rows, divided into rectangular cells with each cell corresponding to one row; process times given in deterministic time steps; passenger with baggages occupies one cell and, given that the next cell is free, walks one cell further each time step (= 2.4 seconds); number of carry-on baggage after frequency distribution ranging from one to three pieces per passenger; time required to stow baggage depends on the number of pieces per person and occupancy level of locker; time passengers need to sit down strongly depends on other passengers already seated in same row.

Studied strategies: Random, back-to-front, by block, by half-block, by row, by half-row, outside-in, reverse-pyramid, by seat.

Main results: Late passengers improve performance of by block strategies; the higher the number of boarding groups, the worse the results; recommended strategies: outside-in (fast, few boarding groups, relatively robust concerning late passengers) or reverse-pyramid.

From the start the authors intend to base their simulation on that of van Landeghem and Beuselinck (2002) to enable the comparison of results. Although the simulation architecture of Ferrari and Nagel (2005) is much simpler than that of van Landeghem and Beuselinck (2002), their studies produce similar results. The best results are attained by by seat strategies, especially when passengers board by descending row numbers and one letter after another beginning with A and ending with F (with an average boarding time of 11.5 minutes for the strategy seat_des_row_letter). These by seat strategies, where each passenger has to be announced separately, are rather difficult to realize and are very costly. It has to be expected that not all passengers are at the gate on time and because by seat strategies are not very robust with regard to late passengers (for 20 percent of late passengers, seat_des_row_letter has an average boarding time of 15.1 minutes) the authors do not recommend using them. The simulation of early and late passengers shows that to minimize boarding time, passengers who arrive too early should be rejected and not allowed to board out of order. Concerning by block strategies, an interesting and surprising result is that late passengers improve the performance of the adopted strategy. This can be explained by the approximation of the by block boarding strategy to the somewhat faster random boarding due to passengers who do not board in the given sequence. The slowest simulated strategy is row_des (with an average boarding time of 38.7 minutes) where each row is boarded separately, beginning at the back of the plane. With 80 percent of late passengers, this strategy only requires 60 percent of the average boarding time, which is needed when all passengers board in the right order. Boarding by block also performs rather badly and the higher the number of boarding groups, the worse the results are. The strategies by half-block, by row and by half-row are not recommended either, because they require too many boarding groups and they complicate the boarding procedure. However, boarding outside-in is recommended as the plane is boarded relatively quickly (in about 18 minutes), although only few boarding groups are needed, and it is reasonably robust in terms of the exact configuration of the airplane and the ratio of late passengers. Regarding random boarding, the passengers are scattered over the whole aisle and a large number of passengers can stow their carry-on baggage simultaneously, which results in a fast average boarding time of approximately 21 minutes.

To find a strategy that is not too difficult but that considers some of the advantages of the fast by seat strategies, Ferrari and Nagel (2005) try to modify the strategy seat_des_row_letter. This attempt results in seat group strategies where passengers are divided into a manageable number of boarding groups, which makes the boarding procedure less complicated. Seat group strategies divide the rows into two to five blocks that are boarded from the back to the front of the plane. Once again, it begins with the boarding of all passengers sitting on one side of the aisle at the window, then with those sitting in the middle on the same side and so on until the passengers with window seats on the other side of the aisle have boarded. In addition to seat group strategies, Ferrari and Nagel (2005) also recommend using pyramid strategies (see reverse-pyramid, Section 4). Here, the groups from the seat group strategies can be combined into larger boarding groups, arranged in a pyramid shape. Pyramid_2_des for example consists of eight boarding groups and has an average boarding time of 17.3 minutes.

The authors also calculate the “average worst case” for each boarding strategy, with close to 95 percent of all boarding events being faster than this value. Strategies that have a high average boarding time also have high values for the average worst case boarding times. Hence, there is hardly any difference in the ranking of average and average worst boarding times.

This study also shows that good strategies perform well for different airplane layouts or occupancy levels. The ranking of the strategies is almost the same for occupancies of more than 50 percent. If an aircraft has an occupancy of less than 40 percent, then certain strategies work better, but in this case the boarding process is no longer part of the critical path of the turn-around time. Furthermore, occupancies under 50 percent are not very common.


By employing an optimization algorithm based upon a Markov Chain Monte Carlo algorithm, Steffen explores the basic properties that must be fulfilled by a boarding method that theoretically avoids all possible interferences. Steffen claims this to be an optimal method. Due to practicalities he recommends using the modified optimal method he presents later in his paper.

Methodology: Markov Chain Monte Carlo optimization algorithm; computer simulation.
Assumptions: Airplane model: 120 seats in 20 rows; no determination of aisle, middle or window seats; each passenger is randomly assigned number between 0 and 100 that determines time steps that are needed for stowing carry-on baggage; passengers require space of two cells to walk and stow baggage.

Studied strategies: Random, back-to-front, front-to-back, outside-in, by seat, Steffen method, modified optimal.

Main results: Optimal method (for this setting): boarding by seat, always 12 seats (2 rows) distance between passengers (= Steffen method).

The first part of the paper summarizes the results of van Landeghem and Beuselinck (2002), van den Briel et al. (2005) and Bachmat, Berend, Sapir, Skiena, and Stolyarov (2006). Moreover, the author states that boarding an airplane from the rear to the front with the passengers in order (i.e., by seat or by row) is one of the worst methods, being “topped” by boarding the passengers from the front to the rear. As he assumes that the stowing of carry-on baggage causes a bottleneck when boarding an airplane, he tries to let as many passengers as possible load their baggage simultaneously. This implies that the passengers are spread over the length of the airplane instead of only using a small area at one time.

Steffen (2008b) does not only run a computer simulation with different boarding methods. He also tries to find the optimal boarding method by using a variant of the Markov Chain Monte Carlo algorithm. He starts with a random initial order of the passengers and in each iteration the positions of two random passengers are swapped. He does not accept solutions that lead to slower boarding times and hence the optimal order of passengers. In contrast, random swaps of two passengers have significant impact on the boarding time and hence the optimal order of passengers. The fastest methods board adjacent passengers with a distance of two rows, that is, a seat distance of 12. This distance corresponds exactly to the space in the aisle that is assumed to be required to stow baggage. To avoid seat interferences, which are not considered in the optimization model, the passengers with window seats should board first, followed by those in the middle and finally by those with aisle seats. Following Steffen and Hotchkiss (2012) we will call this boarding method the Steffen method.

In testing the robustness of this strategy, Steffen (2008b) detects that the distribution of the baggage loading time does not influence the boarding time and hence the optimal order of passengers. In contrast, random swaps of two passengers have significant impact on the boarding time. If only 10 percent of the passengers swap their position in the queue and do not board according to the given order, boarding time increases by 20 percent.

Steffen admits that the Steffen method is difficult to realize and therefore he designs a more practical variant, the modified optimal method. This method consists of four boarding groups with each group encompassing every second half-row of one side of the aisle. That is, passengers who sit in a row with an even number on one side of the aisle board together and those who sit in a row with an odd number on the same side board as a group. The same works for the passengers sitting on the other side of the aisle.

Finally, the author conducts a computer simulation boarding the passengers in order from the front of the plane to the rear (worst case scenario) and from the rear to the front, with the method back-to-front with five rows in each group, outside-in, random, the Steffen method and the modified optimal strategy. Back-to-front performed quite badly with a boarding time equal to 74 percent of the worst case scenario. With outside-in, a reduction in the boarding time equal to 43 percent of the worst case scenario is achieved. Boarding passengers randomly leads to boarding times that are slightly worse than those of outside-in. In contrast, the modified optimal method boards passengers slightly faster than outside-in, especially for smaller planes. By using the Steffen method, boarding times can be reduced to nearly 20 percent of the worst case boarding time, which is only half of the time required by random, outside-in or the modified optimal method. For a plane with 240 seats, the improvement is even greater and boarding time can be reduced by a factor of seven compared with the worst case scenario. Consequently, even if some passengers do not board in the right order and although, as mentioned above, the Steffen method is not very robust concerning incorrectly boarding passengers, it Nevertheless outperforms all other boarding methods in this simulation. However, to successfully implement the Steffen method, a practical way of lining up passengers in the right order has to be found.

5.2.5. Steiner and Philipp (2009): Speeding up the airplane boarding process by using pre-boarding areas, 9th Swiss Transport Research Conference

Steiner and Philipp (2009) develop a simulation tool called the Airplane Boarding Simulator and study the influence of different factors on the boarding time. They examine different boarding strategies, the impact of the number of pieces of carry-on baggage, the use of pre-boarding areas and the number of gate agents.

Methodology: Computer simulation (Airplane Boarding Simulator, ABS).

Assumptions: Airplane model: Airbus A321 with approximately 200 seats; varying assumptions concerning carry-on baggage, pre-boarding areas, gate agents.

Studied strategies: Random, back-to-front.

Main results: Reduction of 1 minute turn-around time saves US$77; usage of pre-boarding area is recommended (1 minute saved).

The authors mention that a reduction in the turn-around time due to savings in boarding time is only possible if the boarding process is time critical. Unlike Nyquist and McFadden (2008), who imply a linear relationship between the boarding time, turn-around time and arising costs, the authors state that several factors impact on the turn-around time. If turn-around times can be reduced by at least several minutes and earlier time slots can be reached, then additional flights can be offered without increasing the number of airplanes and hence benefits can be realized. The authors also state that possible cost savings add up to a considerable sum (over US$700,000 per year if the turn-around time can be reduced by 5 minutes for 4 flights per day).

Their self-developed Airplane Boarding Simulator was calibrated with observations from eight flights and analyzes the impact of different variations concerning the boarding process. Their simulation approach considers data on the walking speed of passengers, the number of groups traveling together and the number of passengers who let others pass (pass rate). The authors simulate 24 different scenarios by varying the following factors: the number of pieces of carry-on baggage (average or low), the boarding strategy used (random or back-to-front), the use (yes or no) and starting time (0, 150 or 300 seconds before the gate announcement) of pre-boarding, the starting time (0 or 90 seconds after the gate announcement) of a second gate agent who also controls boarding passes (power boarding) and the
assignment of an additional gate agent dealing with problems (yes or no). Pre-boarding means that the first passenger group is controlled by the gate agents before the boarding time starts. If the airplane does not board randomly, the correct passenger order is already determined by first controlling the passengers belonging to the first boarding group. These passengers then go into the pre-boarding area and can walk directly to the airplane once the plane is ready for boarding.

As one might expect, a considerably shorter boarding time (about 2–4 minutes faster) can be achieved when there is very little carry-on baggage to be stowed in the overhead lockers. In accordance to the studies described above, random boarding clearly outperforms back-to-front (with a 1-minute time saving). Using a pre-boarding area can also save about 1 minute in boarding time and is therefore recommended. If no pre-boarding area is used, a second gate agent as well as an additional gate agent who deals with passengers who further impede the boarding process, can speed up the boarding time by approximately 30 seconds each. Although Steiner and Philipp (2009) emphasize that customer satisfaction must always be considered, they recommend contemplating a reduction in carry-on baggage and letting passengers board randomly because the possible savings are comparatively large. Thus, in addition to the described time savings, missing passengers, whose baggage has to be unloaded, can be determined earlier. This is very useful for airlines because the process of unloading baggage is a common reason for departure delays. With these actions, the boarding time of an Airbus type A321 can be reduced by 4–6 minutes. However, the authors state that the costs caused by implementing these processes should also be considered.


Steffen and Hotchkiss (2012) run empirical experiments with five different boarding methods. Their aim is to test the performance of these methods, including the Steffen method, in a real life situation where some assumptions made by Steffen (2008b) might not hold.

Methodology: Empirical tests of the performance of five boarding methods.

Assumptions: Airplane model: Boeing 757 with 12 rows, one middle aisle and six seats in each row.

Studied strategies: Random, back-to-front, outside-in, by seat, Steffen method.

Main results: Steffen method: boarding time is reduced by more than 20 percent compared to random; outside-in 10 percent faster than random.

The authors mention that previous studies mainly try to find a fast boarding method that boards passengers in groups, but no significant attempts have been made to find the optimal method. Steffen (2008b) claims that his method is optimal under certain assumptions. In this study, the authors want to test if Steffen method really performs better than all other common boarding strategies. For this purpose, they conduct real-world experiments where test passengers have to board a plane in five different ways: random, by seat beginning at the back of the plane and in each row the window seats first, and then middle seats followed by the aisle seats, back-to-front with three groups of four rows, outside-in and with the Steffen method.

The results indicate that the Steffen method is indeed the fastest of the five methods. The second-best method is outside-in, directly followed by random. Boarding by seat from the back of the plane to the front takes longer than random boarding and boarding in blocks back-to-front performs the worst.

Moreover, the experiments show that the impact of seat interferences on the boarding time depends on whether or not they cause aisle interferences. Seat interferences that do not result in an aisle interference are of minor importance only. There is also a difference concerning aisle interferences. The authors say that an interference where passengers are blocked near their seat is less serious than one where passengers still have to walk through the aisle. This information can be used to appropriately place groups who travel together to ensure that they have more time to stow their carry-on baggage and place themselves in their seat.

In this experiment, where passengers boarded in 12 trains (or waves), the Steffen method caused aisle interferences at the front of the plane, that is, the worst sort of aisle interference. Nevertheless, the time required for random boarding can be reduced by more than 20 percent.

5.3. Papers presenting analytical models

As simulation models are highly dependent on their implementation and are of no value for the development of new boarding methods, some authors build analytical models instead. As to determine the solutions to the models, various methods and algorithms are used.

5.3.1. van den Briel et al. (2005): America West Airlines develops efficient boarding strategies, Interfaces

The authors of this study, which was carried out in cooperation with America West Airlines, now US Airways, are the first to provide an analytical model for the boarding process. Moreover, computer simulations are conducted to validate the optimization model and the newly developed reverse-pyramid boarding strategy is tested and implemented at the airline.

Methodology: MINLP (minimization of interferences); computer simulation (ProModel); implementation of reverse-pyramid at America West Airlines.

Assumptions: Airplane model: single-aisle aircraft with six seats in each row, e.g., Airbus A320 or Boeing 737 with 23 rows (simulation study).


Main results: Back-to-front best with only two boarding groups; new boarding method: reverse-pyramid, best with three boarding groups, in this case equivalent to outside-in, total number of interferences can be reduced by nearly 50 percent compared to boarding back-to-front; implementation results: boarding time can be reduced by up to 26 percent compared to boarding back-to-front, leading to a decrease of 21 percent in departure delays; second gate agent: reduction of the boarding time by 18 percent.

van den Briel et al. (2005) first explain the importance of short turn-around times, provide the history and structure of America West Airlines and briefly summarize the studies of Marelli et al. (1998), van Landeghem and Beuselinck (2002) and Bachmat, Berend, Sapir, and Skiena (2005). They then demonstrate their procedure, which includes establishing an analytical model, verifying it with computer simulations, modifying the model, analyzing the results, and detecting fast boarding strategies that are subsequently tested and implemented at America West Airlines.
The provided nonlinear assignment model (see also van den Briel, Villalobos, & Hogg, 2003) minimizes the number of interferences using the binary decision variable $x_{ijk}$, which is 1 if passenger in row $i$ with seat $j$ is assigned to boarding group $k$ and 0 otherwise.

van den Briel et al. (2005) define an interference as an event where a passenger is blocked by another passenger and cannot reach his or her seat. Furthermore, they determine that aisle interference occurs only when passengers are blocked by another passenger who directly boarded in front of them. Hence, the number of blocking passengers is counted and not the number of passengers who are blocked.

The objective function considers the interferences that could occur during boarding: seat and aisle interferences within and between boarding groups. This results in a large objective function with a multitude of quadratic and cubic terms, each representing another combination of the assignment of two or three particular passengers to the boarding groups, which can lead to aisle or seat interferences. These terms are each weighted with a previously calculated factor representing the expected number of interferences caused by a particular constellation of passengers. The severity of the interference concerning the caused delay is not considered, that is, there is no particular weight for aisle or seat interferences and hence both have the same impact on the objective function value. The authors mention that it is difficult to determine such weights, however, they recommend including them. The model also contains constraints specifying the properties of the decision variable $x_{ijk}$ and the minimum and maximum size of the boarding groups.

Implementing an MINLP optimization solver, which uses a truncated (i.e., heuristic) branch-and-bound algorithm, the authors try to find a new, fast boarding strategy. They let the solver run for different numbers of boarding groups (from two to five groups in economy class) and obtain boarding patterns similar to outside-in with a trend to board back-to-front. They call this pattern a reverse-pyramid because of the V-shaped or reversed pyramid-shaped assignment of passengers to the boarding groups.

In addition, they calculate the number of interferences when boarding back-to-front with two, three, four and five boarding groups. When boarding back-to-front, the best method is to divide the passengers into just two boarding groups. Reverse-pyramid, in contrast, performs best with three boarding groups. Their pattern of reverse-pyramid with three boarding groups corresponds exactly to boarding outside-in. Using this method, the total number of interferences can be reduced by nearly 50 percent compared to boarding back-to-front.

Computer simulations confirm these results. The authors filmed some actual boardings and obtained data on, for instance, walking speed, distance between passengers and the time needed to stow carry-on baggage to construct the simulation model. For boarding by reverse-pyramid and back-to-front all variants from two to five boarding groups are simulated 100 times each. Just like the optimization model, the simulations show that boarding the passengers by reverse-pyramid is faster than by back-to-front. Moreover, the authors show that the shorter the inter-arrival time, the better the reverse-pyramid performs compared with back-to-front.

The new boarding method reverse-pyramid with five boarding groups in economy class is first tested and then implemented system-wide at America West Airlines. The authors state that according to estimates by America West Airlines, boarding times can be reduced up to 26 percent using the reverse-pyramid method compared with boarding back-to-front. Implementing this method could lead to a decrease in departure delays by 21 percent. If a second gate agent is assigned, boarding times can be reduced by 39 percent in total; thus, the use of a second gate agent can lead to a reduction in the boarding time of 18 percent.

5.3.2. Bazargan (2007): A linear programming approach for aircraft boarding strategy, European Journal of Operational Research

Bazargan (2007) provides an integer linear model to minimize the number of boarding interferences. He also takes into account the impact of passenger boarding velocity on the performance of particular boarding strategies. He solves his model with CPLEX, compares his results with those of van den Briel et al. (2005) and clearly presents his efficient solutions in a diagram. He then runs computer simulations to identify which values concerning the congestion caused by passengers from previous boarding groups are realistic and to recommend good boarding strategies.

Methodology: MILP (minimization of interferences); computer simulation (Arena).

Assumptions: Airplane model: Airbus A320 with 23 rows in economy class and six seats in each row; simulation study: data similar to those described in van Landeghem and Beuselinck (2002) and Ferrari and Nagel (2005).


Main results: Optimal boarding pattern outside-in, reverse-pyramid or back-to-front (depending on $\alpha$ and number of boarding groups); recommends using different variants of reverse-pyramid.

Similar to that in van den Briel et al. (2005), the analytical model in this paper tries to find the optimal assignment of passengers to boarding groups by minimizing seat and aisle interferences within and between groups. All of these interferences are explained in detail before the analytical model is set up.

The sum of all possible aisle interferences between groups—that is, the maximum number of aisle interferences that only can occur when all passengers from the previous group are still standing in the aisle—is multiplied by $\alpha$, the fraction of passengers from the previous boarding group still on their way to their seats and waiting on the boarding bridge or in the aisle. This parameter ranges between 0 and 1. If $\alpha = 0$, aisle interferences between groups do not occur at all because everyone from the previous boarding group is already seated. If $\alpha = 1$, all passengers from the previous boarding group are still standing and the expected number of aisle interferences between the groups is maximal. The value of $\alpha$ on the one hand depends on the walking speed of passengers and the time required to stow their carry-on baggage in the overhead lockers. However, this value also can be influenced by the number of gate agents who check the boarding passes before the passengers are allowed to enter the boarding bridge. According to Bazargan (2007), $\alpha$ is approximately 0.1 with one gate agent and 0.3 with two gate agents. The greater the time between the announcement of different boarding groups or the slower the ticket check of passengers, then the smaller the value is.

Bazargan (2007) solves the model for different group sizes and different values of $\alpha$ with CPLEX. For each case he determines the efficient solution, that is, the distribution of passengers among the boarding groups that minimizes the total expected number of interferences.

Depending on $\alpha$ and the number of boarding groups, the optimal boarding pattern shifts from boarding outside-in (if $\alpha = 0$, three boarding groups) over types of reverse-pyramid ($\alpha \leq 0.3$, three, four or five boarding groups) to mainly boarding back-to-front ($\alpha \geq 0.5$, three, four or five boarding groups).

For the value $\alpha = 0$ (i.e., there are no more passengers from the previous boarding group in the aisle and thus aisle interferences between groups cannot occur) these efficient solutions (outside-in for
three boarding groups and different patterns of reverse-pyramid for four and five boarding groups) correspond exactly to the boarding patterns obtained by van den Briel et al. (2005). The reason why there are so few aisle interferences between groups in van den Briel et al. (2005), which means that their results only can be compared with those of Bazargan (2007) for $\alpha = 0$, presumably lies in the various ways of defining aisle interferences. The smallest number of interferences, independent of the value of $\alpha$, can be reached when boarding by Bazargan’s efficient solutions with five boarding groups in economy class.

To determine which values of $\alpha$ actually occur when boarding an airplane, Bazargan (2007) also conducts computer simulations with Arena. This leads to the result that in the case where one gate agent controls the boarding passes, a value of $\alpha = 0.1$ should be assumed and in the case of two gate agents, it is $\alpha = 0.3$.

Hence, based on the results of the analytical model, Bazargan (2007) recommends using different variants of the reverse-pyramid. When boarding with one gate agent, the optimal pattern of the reverse-pyramid resembles boarding outside-in, whereas when boarding with two gate agents, the optimal pattern of the reverse-pyramid is similar to boarding back-to-front. Thus, Bazargan (2007) states that the higher the value of $\alpha$, the better the performance of the back-to-front method.

In contrast, van den Briel et al. (2005) obtain the result that for larger values of $\alpha$, the reverse-pyramid method outperforms back-to-front. One reason for this discrepancy could be the approach used by van den Briel et al. (2005) to count aisle interferences.

The big advantage of Bazargan’s boarding patterns over those recommended by van den Briel et al. (2005) is that passengers traveling in groups and sitting next to each other do not always have to board separately.

Based on this model, Bazargan (2011) analyzes the boarding problem for wide-body twin-aisle airplanes using a Boeing 767 configuration with seven seats per row and two aisles. His model is the first one to describe the boarding process for wide-body airplanes. It is very similar to the one of Bazargan (2007) but offers the flexibility to let neighboring passengers board together. After solving it with CPLEX and simulating the boarding process with Arena, he recommends using an efficient solution consisting of 10 boarding groups. This solution does not follow any common boarding pattern but the passengers of one boarding group rather are split over the whole airplane.

After outlining studies on the airplane boarding problem, the authors define the term interferences and their assumptions and decision variables concerning their model. They then deduce the various constraints for the interferences and explain them in detail.

The objective function contains all mentioned interferences: seat interferences within groups and aisle interferences within and between groups. Seat interferences between groups are prevented by assigning passengers to groups. Consistent with Bazargan (2007), aisle interferences are weighted with a penalty factor of 2.4 and seat interferences with a factor of 3.6. The decision variable of the model, $q_{i,k}$ is defined as the number of passengers in row $i$ who board in group $k$ with $q_{i,k} \in \{0, 1, 2, 3\}$. The constraints determine the expected number of interferences for all possible types of seat and aisle interferences. The aisle interferences between groups are—similar to the models of van den Briel et al. (2005) and Bazargan (2007)—multiplied with $\alpha$, the fraction of passengers from the previous boarding group still standing in the aisle.

Soolaki et al. (2012) solve the model using a genetic algorithm. In their paper, they extensively describe the approach of genetic algorithms in general and their application to the aircraft boarding problem. They use Matlab to develop the metaheuristic algorithm including a fitness function, selection and genetic operators such as crossovers and mutations and then try to find a (near) optimal boarding strategy by applying the algorithm to the problem.

They let the genetic algorithm run with different values of $\alpha$ and for three, four and five boarding groups in economy class. To compare results, they also list the performance of the boarding strategies presented by van den Briel et al. (2005) and Bazargan (2007). The obtained boarding patterns of Soolaki et al. (2012) as well as the corresponding values of the objective functions are very similar to those of Bazargan (2007). This approach leads to the result that, under the given circumstances, boarding passengers using variants of the reverse-pyramid method minimizes the number of interferences. For high values of $\alpha$, their solution is slightly better than that of Bazargan (2007), but generally the two studies produce similar results. Under the assumption that no passenger from the previous group is blocking the aisle, that is, for $\alpha = 0$, the solutions cited in Soolaki, van den Briel et al. (2005) and Bazargan (2007) coincide.

5.3.4. Bachmat et al. (2009): Analysis of airplane boarding times, Operations Research

Bachmat et al. (2009) study the airplane boarding process from a physical-mathematical point of view. The authors use Lorentzian space-time geometry and the critical path method to explain the boarding problem and calculate the estimated boarding time of different boarding strategies. They compare these boarding times with the simulation results of van Landeghem and Beuselinck (2002) and examine the impact of the congestion parameter $k$ on the performance of the strategies.

Methodology: Lorentzian space-time geometry and critical path method (physical-mathematical point of view).

Assumptions: Number of passengers tends to infinity.

Main results: 20 percent longer boarding times when splitting economy and first class; best strategy: variant of outside-in with additionally dividing the airplane into two parts.
The study by Bachmat et al. (2009) is based on the model presented in earlier research by the same authors (Bachmat et al., 2005, 2006). In the present study, they try to explain the physics-related model using terminology that is more common in operations research. The authors start with a short summary of existing literature and the current state of research regarding the airplane boarding problem. They then classify the boarding problem, which is considered a stochastic problem, into the mathematical context of critical paths. The variables used in the model are the queue and row position of passengers, which are represented by a distribution function in the unit square.

By assuming that the number of passengers tends to infinity, the authors then analyze the asymptotic behavior of the boarding process. The parameter $k$ describes the ratio between the length of the queue and the length of the airplane and is a measure of the occurring congestion. The authors define the sequence of passengers as well as precedence relations, use Lorentzian geometry (a part of differential geometry which is also used to model Einstein’s general theory of relativity) and search for the largest chain to determine an expression for the estimated boarding time.

To describe the boarding strategies, Bachmat et al. (2009) introduce a new notation including the number of boarding groups, the sequence of the groups and the number of classes. Several boarding strategies are then expressed using the distribution function mentioned above and estimated boarding times are calculated.

Bachmat et al. (2006) show that the asymptotic approach is only suitable for large systems and not for problems like the airplane boarding with only 100–200 passengers. In this case, calculations of the boarding time lead to overestimations by approximately 50 percent. Nevertheless, the results in Bachmat et al. (2009) are compared with those of the computer simulation conducted by van Landeghem and Beuselinck (2002).

The results show that boarding by seat is the fastest method; however, the authors state that it is nearly impossible to implement such complex strategies and therefore random boarding is a good option.

Furthermore, Bachmat et al. (2009) briefly examine boarding outside-in, describe its effect on the estimated boarding time, and present a new boarding strategy. This boarding strategy is a mix of back-to-front with two non-uniform boarding groups (the rear third of the plane and the front two-thirds) and outside-in. It is important that the plane is divided into two non-uniform parts because the combination of outside-in with uniform back-to-front does not yield significant improvements over the conventional outside-in method. This boarding pattern boards passengers outside-in with a separation of the plane into two non-uniform parts. Leading to six non-uniform boarding groups (i.e., all window seats in the rear third, all window seats at the front, all middle seats at the rear, then those in the front, the aisle seats in the rear and those in the front), this strategy is the best performer of all analyzed boarding methods with six or less boarding groups.

In addition, the authors analyze the impact of non-uniformly dividing the passengers, for example, into first class and economy class. Here, the boarding groups are of different sizes. They calculate that boarding the first class passengers before the economy class leads to a 20 percent longer boarding times than boarding all passengers together in one group. This result is similar to that of the simulation of van Landeghem and Beuselinck (2002).

5.3.5. Tang et al. (2012b): An aircraft boarding model accounting for passengers’ individual properties, Transportation Research Part C: Emerging Technologies

The analysis of Tang et al. (2012b) uses the pedestrian flow theory to model passengers’ motions during the boarding process (see also Tang, Huang, & Shang, 2012a) and presents a boarding strategy that considers the individual properties of passengers. This and other strategies are simulated with Matlab and then compared.

Methodology: Analytical model (Matlab) for finding fast boarding strategy by considering passengers’ individual properties.

Assumptions: Individual walking speed of passengers is known.

Studied strategies: Random, by seat, seat number and individual properties.

Main results: Boarding by seat does not work well because passengers pass each other and hence the given sequence is broken; strategy, which considers passengers’ individual properties, eliminates all interferences.

Before introducing their model, the authors review the literature on airport operations, the airplane boarding problem and pedestrian flows. The aircraft boarding model, which is based on a model presented in Tang et al. (2012a), is then described. It contains the two-dimensional first-order and the social force model, representing pedestrian flow and the impact of the environment on this flow. Interruptions such as waiting at the ticket check or settling into one’s seat are considered along with walking speed and safe distance. Because these variables are different for each passenger, the authors modify the model in Tang et al. (2012a) by including passengers’ individual properties.

Using Matlab, the authors simulate random boarding, boarding by seat (first all window seats, followed by middle and then aisle seats, always beginning at the rear of the plane and boarding one passenger after another to the front on both sides of the aisle) and boarding passengers by their seat number and their individual properties. This third, new approach explicitly considers the walking speed of passengers and the negative impact of their carry-on baggage on their individual boarding time. Generally, the passengers board in the same sequence as the by seat method (individually from the back to the front and from the window to the aisle), but the strategy also ensures that fast passengers board before slower ones. The assignment of passengers to seats (when passengers are told their row and seat number, usually at check-in) follows a distinct pattern. The seats are divided into three “groups” (not to be confused with boarding groups): window, middle and aisle seats. Within each group, the fast passengers are assigned to those seats at the rear of the plane (i.e., they board first) and the slower ones to the seats at the front (i.e., they board later). In this manner, all passengers can board at their own optimal speed. Once the passengers with window seats are seated, those with middle and then aisle seats board the plane.

The results show that with this boarding strategy, which considers passengers’ individual properties, interferences can be completely eliminated. By determining the boarding sequence described in the by seat strategy, boarding times can be reduced and theoretically interferences do not occur, but with passengers passing other passengers on the way to their seat (for example on the boarding bridge) the determined sequence is broken and seat and aisle interferences occur. In the simulation, this third strategy performs best, but its applicability is questionable especially as it is difficult to detect the walking speed of the passengers a priori.
Table 2
Literature presented in the literature review.

<table>
<thead>
<tr>
<th>Authors, Year</th>
<th>Methodology</th>
<th>Aircraft type</th>
<th>Tested strategies</th>
<th>Recommended boarding strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical model</td>
<td>Airbus A320</td>
<td>Boeing 757</td>
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<tr>
<td></td>
<td>Computer simulation</td>
<td>Airbus A321</td>
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<td></td>
<td>Empirical tests</td>
<td>Boeing 757</td>
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<tr>
<td>Bachmat et al. (2009)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Variant of outside-in with additionally dividing the airplane into two parts</td>
</tr>
<tr>
<td>Bazargan (2007)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Different variants of reverse-pyramid</td>
</tr>
<tr>
<td>Ferrari and Nagel (2005)</td>
<td>x</td>
<td>o</td>
<td>x</td>
<td>Outside-in (fast, few boarding groups, relatively robust concerning late passengers) or reverse-pyramid</td>
</tr>
<tr>
<td>Marelli et al. (1998)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Alternative boarding strategies (e.g., outside-in)</td>
</tr>
<tr>
<td>Nyquist and McFadden (2008)</td>
<td></td>
<td></td>
<td></td>
<td>Non-traditional methods (outside-in, reverse-pyramid)</td>
</tr>
<tr>
<td>Soolaki et al. (2012)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Variants of reverse-pyramid</td>
</tr>
<tr>
<td>Steffen (2008b)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>By seat, always 12 seats (2 rows) distance between passengers (≈ Steffen method)</td>
</tr>
<tr>
<td>Steffen and Hotchkiss (2012)</td>
<td></td>
<td></td>
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<tr>
<td>Steiner and Philipp (2009)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Random or other efficient strategies (no back-to-front)</td>
</tr>
<tr>
<td>Tang et al. (2012b)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Strategy, which considers passengers’ individual properties</td>
</tr>
<tr>
<td>van den Briel et al. (2005)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Reverse pyramid with three boarding groups (≈ outside-in)</td>
</tr>
<tr>
<td>van Landeghem and Beuselinck (2002)</td>
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<td>x</td>
<td>by_halfrow_alt_2</td>
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6. Conclusion

The focus of this paper has been to provide a comprehensive overview of the airplane boarding problem and existing boarding strategies. Various boarding strategies have been presented in a separate section and their main properties highlighted in a table. In addition to providing a broad outline of the boarding procedure, we conducted a literature review. Before 1998 there was no published research on this issue. However, since then, the boarding problem has been the subject of a number of studies. In this paper we have identified what we consider to be the 12 most important studies in the literature, and these have been presented in detail.

Table 2 summarizes the methodology, the aircraft types, and the boarding strategies to be found in the papers described in Section 5.

Circles in the columns of airplane models stand for an analysis of a similar airplane configuration not necessarily naming the explicit aircraft type. In Fig. 5 we topologically sorted the most important strategies concerning the obtained average boarding times. Dotted, solid, double and threefold lines stand for one, two, three or four papers stating that the boarding method being denoted at the end of the arrow is faster than the one being denoted at the starting point of the arrow.

It is noteworthy that no paper contradicts the main findings of some other papers, i.e. the proposed papers are consistent in itself. Almost all authors come to the result that back-to-front boarding performs worse than other common boarding methods like outside-in, reverse-pyramid or even random boarding. The reason why random boarding performs better than by block strategies like back-to-front.
on boarding time still require further investigation. Thus, worst case or tardy passengers, the impacts of such changes or disturbances of different boarding strategies concerning various airplane models are altogether complicated to realize and rather by seat method and indicating an exact sequence in which the passengers have to enter the plane. Enormous reductions in boarding time can be achieved. One variant of this is the Steffen method. Though, these by seat strategies are altogether complicated to realize and rather customer-unfriendly.

7. Future research

The outline for future research starts from the basic case as described in Section 3, but it is not limited to this case. We especially consider topics, which currently have a rather low practical relevance, but which could gain importance in the future (e.g., twin aisle boarding). We classify the future research agenda into research connected with boarding time optimization and research focusing on aspects of customer satisfaction. We believe that the latter, despite its undisputed practical relevance, has received too little attention so far.

7.1. Boarding time aspects

Before turning to the boarding time itself, it is worth mentioning that research insights are required on the question when boarding time minimization is relevant. Boarding is part of the turn-around time and consequently strongly connected with other processes at the airport. These processes and other factors such as the occupancy of an aircraft determine whether the boarding process is on the critical path of the turn-around time. Consequently the question arises what impact other ground activities have on the boarding process and what has to be done to ensure short turn-around times. The influence of these processes and factors have to be determined and their impact on the relevance of the boarding process needs to be described. As a consequence, research should not only focus on boarding time minimization. Once the boarding time has been decreased such that boarding is no longer on the critical path, further time savings are of little value. Therefore, boarding methods should also be analyzed such that the probability is maximized that boarding will not increase the turn-around time.

Although Ferrari and Nagel (2005) have studied the robustness of different boarding strategies concerning various airplane models or tardy passengers, the impacts of such changes or disturbances on boarding time still require further investigation. Thus, worst case scenarios and quartiles (especially for random boarding) should be analyzed as these could provide important information for airlines.

7.1.1. Boarding by seat

Boarding by seat is by definition the fastest boarding method as any sequence of passengers entering the airplane can be obtained using a by seat strategy. However, only little research has been done to identify the best sequence—even in very narrow settings. The Steffen method, where all passengers board separately in a given order and one row is always skipped, appears to be a boarding strategy that optimizes the boarding process with regard to the minimization of interferences and the maximal utilization of the aisle. However, Steffen (2008b) did not consider the impact of the number of trains and thus the total time required by all trains to pass through the aisle. Therefore, research is required to find such a sequence that minimizes time instead of the number of interferences. Furthermore, the simplifying assumptions (e.g., same walking speed, no disruptions) need to be softened.

7.1.2. Boarding by group

Various strategies of boarding by group are applied every day. The high practical relevance induces a thorough analysis of these strategies. Obviously, the number of boarding groups and the assignment of passengers to groups is crucial and not completed. However most of the optimization models described in Section 5 require that all boarding groups be of a similar size. In our opinion there is no need for such a constraint. If the restraint is restrictive, there would be another boarding pattern that leads to better results. If it is non-restrictive, it can be abandoned. Present and future models should be tested without considering this constraint.

7.1.3. Special settings

The prevailing opinion on twin-aisle boarding is that it is not on the critical path of the turnaround-time. However, this might change, e.g., indicated by no-frills airlines offering long-haul flights. Therefore, a further subject for future research could be the boarding problem of wide-body twin-aisle airplanes like the Airbus A380 or the Boeing 747 used for long-haul flights. These airplanes have two middle aisles and usually 10 seats in each row (3–4–3). This seating configuration produces a different boarding problem than that of single-aisle airplanes as there has to be a separation of passengers with the two aisles. The assignment of passengers to the aisles has to be included into the optimization problem. Sometimes these wide-body twin-aisle airplanes also have an upper deck. The impact of this change in the aircraft configuration on the optimal boarding method should also be analyzed.

An extension of the problem of boarding wide-body twin-aisle airplanes or of our basic case of boarding a single-aisle airplane is to board the aircraft by using two or even more doors. Then, it has to be decided on the partitioning of the passengers to the doors.
course, it seems reasonable to let passengers with seats at the front of the plane board through the front door and those with seats at the back of the plane through the rear door, but boarding strategies for the case that such an assignment cannot be guaranteed need to be obtained.

7.1.4. Empirical evaluation of influencing factors

Boarding time is certainly not only a matter of the boarding strategy. Airport managers report that boarding time is highly influenced by factors such as summer or winter time, the destination, and the cultural background of the passengers. However, there is no evidence provided yet on how and to what degree these parameters influence boarding time. Empirical studies are therefore required. These studies should also test further potential influencing factors such as the occupancy level of the aircraft, the number of carry-on baggage and the fact whether the flight tends to serve businessmen, tourists or others.

7.2. Customer satisfaction

A positive correlation between boarding time and customer satisfaction is assumed, because a long boarding process is often perceived as stressful. However, there is certainly no causality as the efforts for implementing a fast by seat strategy still contradict customer satisfaction. It is inevitable to evaluate boarding strategies also in terms of this goal.

7.2.1. Measurement of satisfaction

So far, detailed empirical data on the convenience level of different boarding strategies is missing. Corresponding questionnaires should be answered by passengers that have just boarded. These data need to be connected to important aspects such as the boarding strategy applied, the aircraft type, the boarding time required, the occupancy level, and so on. Only then, the important aspect of customer satisfaction becomes measurable. Certainly, such surveys should also intend to identify the factors influencing convenience (e.g., interferences). This would promote theoretical research, because then, corresponding factors can be minimized in the models.

7.2.2. Auxiliary goals

Once influencing factors for passenger convenience are known, these factors can serve as an auxiliary objective representing customer satisfaction aspects. As mentioned before, several research papers aim at minimizing the number of aisle and seat interferences. As interferences are unpleasant, the minimization of interferences certainly is one aspect of increasing convenience. However, there are certainly more aspects that need to be taken into consideration. First and foremost, waiting times of passengers are highly relevant. Here, it has to be distinguished where waiting takes place (e.g., airport managers report that waiting in the jetway is more relaxing than in front of boarding pass control). One could distinguish between waiting times at the gate, before boarding pass control, in the jetway, in the aisle, and on the seat.

Furthermore, any additional actions to be conducted by the passenger can be considered to decrease customer satisfaction. Such additional actions may range from (additional) information reception (such as a boarding group) to complicated line-up rules (e.g., for by seat strategies or the Flying Carpet, see Wallace, 2013).

Finally, passengers traveling in groups need to be considered when searching for boarding groups. Bazargan (2011) assumes that 50 percent of all airplane passengers travel in groups of two or more persons. Ferrari and Nagel (2005) state that the boarding strategies that perform well tend to separate passengers who travel and sit together. However, since these passengers in many cases would not be willing to board separately from each other (or would consider this as very inconvenient), it is important to find boarding strategies that allow groups of passengers to board together. Note that often it is not only an objective to minimize passengers of groups boarding separately, but it is even a restriction, e.g., if families travel with small children.

7.2.3. Aspects of increasing customer satisfaction for fast boarding strategies

Finally, let us present some ideas on how the boarding process could be changed such that fast boarding strategies, especially the by seat strategy can be implemented without broad impacts on customer convenience.

First, we would like to present a method where the seats are not assigned until the passengers reach the ticket check. The idea is to let passengers initially line up randomly without any assigned seats, just like the open seating method. The crucial difference to open seating, which is only used by low-cost carriers, is that the gate agents assign seats. When arriving at the ticket check, the passengers receive a card on which a row number and seat are written. Then, once inside the airplane they have to sit in the seat detailed on their card. This could even be supported by according light signals in the cabin, showing each passenger the way to his or her seat individually. Using this method, it is possible to implement a complex by seat strategy without having to force passengers to line up in a specific order. A priori, the airline has to decide on the boarding pattern they want to use, but as with this approach any boarding strategy can easily be realized and no disruptive factors occur, for example, late passengers or those standing in line out of order, it is obvious that a strategy that optimizes the boarding time should be used. Passengers who travel in groups should be assigned adjacent seats. Consequently, when entering the airplane, passengers have to announce the number of persons they are traveling with and the crew member can then hand out cards with respect to the boarding strategy and number of passengers traveling together so that the number of groups and the sizes of these groups should be known in advance from check-in (but not the appearance of the groups in the sequence), a new online optimization problem arises, which determines the sequence of seats to be filled subject to the constraint that the members of each remaining group must receive adjacent seats. The main advantage of this approach is that boarding time can be minimized without having to order the passengers in front of the gate, which can be very complicated.

A further idea to improve the boarding process is inspired by DeVries (2009). He devised organizational proposals that would help not only to accelerate the boarding process but also to improve customer satisfaction. He recommended improving the supply of boarding information displayed on the screens at the gates as well as showing this information to passengers’ mobile devices. As the use of smartphones has rapidly grown since DeVries (2009), and is still growing, this proposal continues to show value. As of 2013, 56 percent of all American adults own a smartphone (Pew Research Center’s Internet & American Life Project, 2013). Thus, the following option could be viable: the use of smartphones to provide not only general boarding information such as “flight on time” or “boarding has started” but to individualize the information and to announce to the passengers when it is their turn to board. In this way passengers do not have to continually watch the monitor at the gate or try to understand the announcements of the gate agents, which are often difficult to understand. This could be realized by using a mobile application (app) developed especially to provide this service. Via a Quick Response code (QR code) that is provided at the check-in counter, at the gate area or printed on the boarding pass, the passengers could easily download the app. Of course, the current boarding procedure could not realistically be replaced by this method at this time, but it could be facilitated and perhaps at a later date when the rate of smartphone ownership is even higher, it could be integrated into the standard boarding procedure. The few people who do not have a smartphone with them then could receive a device at check-in that emits a signal.
when they need to line up for boarding. These devices then could be collected by the gate agents when they check the boarding pass. Eventually, boarding passes could be replaced by this app and the suggested devices. The feasibility of these ideas needs to be determined when they need to line up for boarding. These devices then could be collected by the gate agents when they check the boarding pass. Eventually, boarding passes could be replaced by this app and the suggested devices. The feasibility of these ideas needs to be determined.

References


