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Reducing passenger boarding time in airplanes: A simulation based approach

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Abstract

The increase in air travel puts tremendous strain on existing airport facilities, so turnaround times for airplanes are under constant pressure to be reduced. Part of the turnaround time consists of the time required for passengers to board the plane and install themselves in their assigned seats. It seems that this boarding time for passengers is much higher than allowed, but up to now has been largely neglected in reengineering projects. This paper investigates different boarding patterns, in order to detect to what extent boarding time can be reduced. Findings indicate quite some discrepancy between current practices and optimal patterns. The results are analyzed with regard to airline objectives as well as to customer objectives, and implementation issues are considered.

Keywords: Simulation; Airlines; Service operations

1. Introduction

Air travel has increased considerably in recent years. Most major airports have seen successive extensions, and the availability of airplane docking slots (“gates”) at terminals has been a constant bottleneck. Moreover, the use of hub-and-spoke systems has been increasing. In this system, airplanes fly in passengers from feeder airports, and transfer them in the hub airport to their outgoing destination flights (Bania et al., 1998). The result is a high number of airplanes arriving within a few hours, and the need for fast transfers to reduce idle time (called “Turn Time”) of the planes. In an attempt to reduce the number of delayed flights, optimization of the air traffic flow and the ground holding problem is being pursued (Andreatta and Brunetta, 1998). While this evolution imposes increasingly stricter demands on the airport’s operations, its method engineers have only recently begun to study the problem (Parizi and Braakman, 1995; Marelli et al., 1998). Another impetus for this and related research is the increased competition between airlines. After a long period of decreasing prices, airlines are discovering quality and service perks as a way to differentiate themselves (Gourdin and Kloppenborg, 1991; Young et al., 1994).

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While reviewing literature, as well as talking with airport officials, the authors discovered that the focus up to now has primarily been aimed at improving infrastructure utilization, or at increasing the passenger flow at the land side of the airport building (Setti and Hutchinson, 1994; Tosic, 1992). Particular attention has been given to the check-in procedure (Seneviratne and Martel, 1995; Chung and Sodeinde, 2000). Moreover, from Heskett et al. (1997) we know that waiting degrades the quality perception considerably. The boarding process, just like the check-in process, is a typical service operation (Sasser et al., 1978) in which the customer participates. This means that any procedure to improve the system will also have to pay attention to customer comfort.

We were rather surprised that we found almost no published research on how to improve the airplane boarding process. This is in contrast to its importance. First it degrades the customer's quality perception considerably, when he has to jostle his way into the narrow aisle, fight for a space in the overhead luggage bin or wait seemingly indefinitely for the passenger in front of him to sit down. But secondly the boarding process is also determining the total airplane turnaround time.

Boeing has conducted simulation-based studies of the boarding time (Marelli et al., 1998). It has incorporated roughly the same elements in its model as we have, but – being a designer – focuses on interior layout alternatives. They have studied some alternative boarding sequences, and conclude that "outside-in" en "back to front" yield better results. However, they do not report any detailed results. Moreover, their results seem to be rather optimistic, underestimating the impact of passenger interaction, as they acknowledge upon conducting boarding experiments with real passengers.

The average airplane Turn Time is approximately 30–60 minutes (Fig. 1), as we learned from personal interviews. Leaving the plane (deplane) takes approximately 10–15 minutes, cleaning takes about 15–20 minutes and boarding (enplane) is allotted only 10 minutes. In practice this time is almost always exceeded, often up to 30 minutes! This Turn Time has actually doubled since the 1970s, according to Marelli et al. (1998). This warrants our research, which we describe in the following sections.

2. The boarding process

We focused our study to Short Haul flights, which typically use airplanes with seating capacity between 80 and 150. We modeled a "standard" airplane with 132 seats, divided into ($n = 23$) rows. Rows 1 and 23 have three seats only, the others have six, reflecting typical cabin arrangements. Seats are numbered by row and by one of the letters A–F from port to starboard. The actual boarding process consists of three steps (Fig. 1):

1. Passengers are called by the gate agent, announcing the start of boarding. Passengers will typically start queuing at the gate, with occasional shoving and confusion as to the position and direction of the queue. Delaying factors are missing passengers, that need to be paged, or late arrival of transfer partners. The increase of the hub-and-spoke scheduling of flights has increased the occurrence of this type of delay considerably.
2. The gate agent controls the boarding pass of each passenger, and registers his entry using a ticket reader. This step in the procedure is the only moment we have control on who enters at what time. The main disturbances are jamming of the card reader, and the occasional withdrawal of excessive carry-on luggage at the gate entrance (with sometimes prolonged discussions with the affected passenger). As airlines tighten their control on carry-on luggage limits, this kind of delay is also increasing.
3. Finally passengers access the airplane through the access bridge and the front door. When passengers are taken by bus to the airplane, the same process holds, but now passengers arrive at the airplane door in large batches, which only aggravates the problem. Once inside the plane, they have to queue in a single line (due to the small aisle width) until they reach their assigned seat. Several disturbances and delays occur

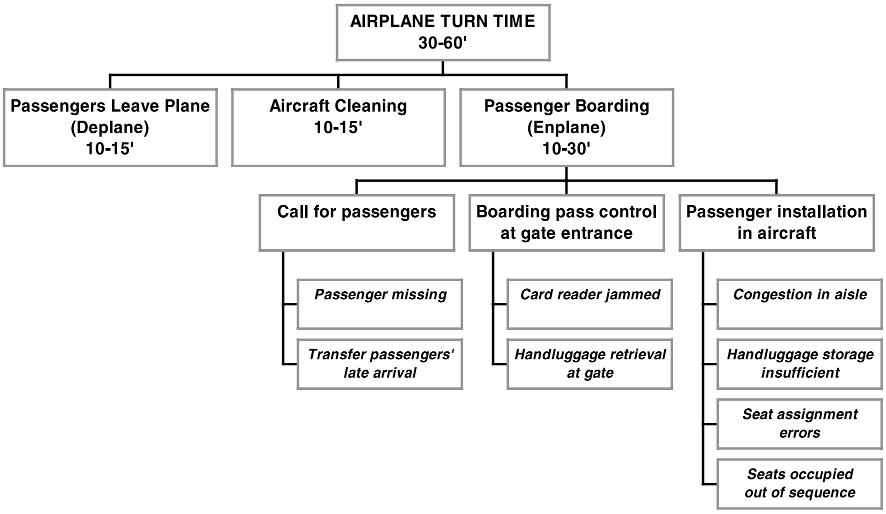

Fig. 1. Elements and disturbances of airplane turnaround time ("Turn Time").

within the plane, which we will detail below. Finally, the passenger puts his carry-on luggage either in the overhead compartment (bin) or underneath the seat in front of him, sits down, and affixes his security belt.

It must be noted that, in theory, steps 1 and 2 do not need the airplane to be ready, and thus they do not contribute to the Turn Time. In practice, however, once boarding is announced, passengers cannot be held queuing too long, so agents only start step 1 after the airplane has been announced ready by the cabin attendants. Boarding using more than one door is mainly used in long haul flights, which is outside the scope of this study, although its conclusions will also be valid if we consider each segment that is served by one of the doors separately (which we can do without any significant loss of generality).

We performed several observations of this process at Brussels National Airport. Numerical data were obtained from the national carrier's database, and by interviewing gate agents and method engineers. The basic times of the elementary moves we modeled are listed in Table 1. Given the fluctuations we have monitored, we decided to model these times as triangular distributions (Kelton et al., 1998). The model assumes passengers arrive at the airplane door every 6 seconds (i.e. 10 passengers (pax) per minute). Boarding time starts when the first passenger enters the plane and ends when the last passenger is seated in his assigned seat.

It turns out that the design of Short Haul airplanes does not allow comfortable boarding. Overhead bins that span all seats force passengers to stay in the aisle while storing their luggage there. Due to narrow aisles any disturbance in the smooth flow of passengers will cause passengers to queue. This is called row congestion. We included following events in our model:

1. The most common cause is the storing of carry-on luggage in the overhead compartment. As the plane fills up, the time it takes to find a suitable location will increase. At the end, passen-

Table 1
Process time in seconds (triangular distribution)

		Process times (second)		
		Min	Modus	Max
Normal situation	Passing one row	1.8	2.4	3
	Install in seat	6	9	30
	Exit from seat into aisle	3	3.6	4.2

Table 2
Handluggage distribution under different load conditions

Number of pieces of handluggage per person	1	2	3
Distribution among passengers under normal load (%)	60	30	10
Distribution among passengers under high load (%)	20	60	20

gers will have to move to other rows to find storage space, either up or downstream to the flow of passengers. Passengers with multiple pieces of luggage will need considerable more time to store all pieces. This type of interaction was also reported by Marelli et al. (1998) from videotape analysis. In our model passengers are randomly assigned 1, 2 or 3 pieces of luggage, according to a ratio listed in Table 2. Secondly, we included bin occupancy in the model, which leads to increasing loading times as the bins fill up.

2. Another common disturbance is caused by a passenger who is already seated in a row, e.g. in the aisle seat, and a next passenger must get into the window seat. Thus the seated passenger(s) has to leave the row, which can only happen if there are free spots in the aisle next to the row. While multiple passengers are involved here, only the prolonged waiting time of the incoming passenger is counted. The movement time of the other affected passengers is not taken into account further.
3. Finally, when a passenger has taken a wrong seat, he will be bumped when the right passenger arrives. When the mistaken passenger has to take his seat more towards the front of the plane, he will have to wait for (part of the) the aisle to clear.

3. Call-off systems

3.1. Systems used in practice

To influence the boarding sequence of passengers, a call-off system is used. With most airlines, gate agents announce through the Public Address system which rows are allowed to board at the current time. Sequence control occurs at the gate entrance as mentioned above.

From our observations we found that many airlines do not impose a sequence at all, and let the passenger enter randomly. This excludes any special passengers (such as women with small children or disabled persons) which board first. Some airlines let business passengers board first (in the front of the plane), which obviously prolongs total boarding if they are allowed ample time to seat themselves before economy is allowed in. We modeled this sequence as "By block B/E".

Other airlines fill planes from back to front, by calling off 4–6 blocks of full rows, e.g. "rows 25 through 34". A few use color coding, by giving each passenger a colored card, which indicates the block he will board in. When boarding starts, a lamp of the same color at the gate entrance indicates which block can board. The color cards are handed over at the time of entering the waiting room at the gate, which needs extra personnel and requires inspection of the seat allocation on the boarding pass. This system causes more confusion than it solves: the colors are not always unambiguous (e.g. blue next to violet) and passengers forget to return the color card.

Finally some airlines (especially low fare ones) do not assign seats at all. This free seating is not regarded well by older passengers, and is not included in our study. It is likely to increase boarding time, as this system is comparable to random, but there will be additional delays, especially for the last passengers looking for remaining free seats for their party.

3.2. Class Types and boarding sequences

To systematically develop the range of possible call-off systems we introduce the concept of a Class. Let (i,j) be the seat in row i, on position j, $i = 1,\dots,n$ and $j = 1,\dots,6$ (mapped from ABCDEF) and $\mathscr{S}$ the set of all seats (i,j) in the plane ($\#\mathscr{S} = N = 132$ here). A Class is then a contiguous subset of $\mathscr{S}$, i.e. elements of a Class are situated in adjacent rows. The size and form of a Class defines the Class Type it belongs to: e.g. Class

Type "(full)_block_4" consists of four contiguous blocks of full rows. In general a Class Type CT (Type_K) consists of K Classes of the given Type, which together form a partition of $\mathscr{S}$. We denote

$$\begin{aligned}\mathrm{CT}(\mathrm{block\_4}) = \{(i,j)|1 \leqslant i \leqslant 6\} \\ \cup \{(i,j)|7 \leqslant i \leqslant 12\} \\ \cup \{(i,j)|13 \leqslant i \leqslant 18\} \\ \cup \{(i,j)|19 \leqslant i \leqslant 23\} \\ \forall (i,j) \in \mathscr{S}.\end{aligned}$$

In each configuration Classes can vary between $\lceil N/K \rceil$ and $\lfloor N/K \rfloor$ seats. For ease of notation we will give each Class C of a given Type an index, such that

$$\mathrm{CT}(\mathrm{type\_}K) = \bigcup_{k=1}^{K} C(\mathrm{type\_}K)_k.$$

Within each Class Type, boarding can occur in various sequences, determined by the order in which the Classes enter the aeroplane. We can uniquely define such a sequence SQ as an ordered set of Classes from a specific Class Type. The general format of the call-off sequence coding, as used in Table 3, is: "TYPE_K_PATTERN", where pattern describes the sequencing principle. "Block_4_des" e.g. denotes a Class Type "(full) block" where all seats are divided in $K = 4$ contiguous blocks, and each block is called off in descending order: block 4, then 3, 2 and finally 1 (in the front of the plane). More formally

$$\begin{aligned}\mathrm{SQ}(\mathrm{block\_4\_des}) &= \{\{(i,j)|19 \leqslant i \leqslant 23\}, \\ &\quad \{(i,j)|13 \leqslant i \leqslant 18\}, \\ &\quad \{(i,j)|7 \leqslant i \leqslant 12\}, \\ &\quad \{(i,j)|1 \leqslant i \leqslant 6\}\} \\ &= \{C(\mathrm{block\_4})_4, \\ &\quad C(\mathrm{block\_4})_3, \\ &\quad C(\mathrm{block\_4})_2, \\ &\quad C(\mathrm{block\_4})_1\}.\end{aligned}$$

In this way we generated a wide variety of possible boarding sequences, listed in Table 3. The indices k of the Classes are given by the block diagrams. We investigated following Class Types:

- *Random*: All passengers are called together in one Class. No sequences are determined here. In fact, this Class Type is a special case of the full block Type, with $K = 1$ and $m = N$.
- *By block*: A (full) block is a number of contiguous full rows (i.e. seats ABCDEF), e.g. "by_block_2" denotes 2 blocks of 11 and 12 rows, respectively in a 23 row plane.
- *By half block*: Same mechanism as above, but a half block spans only the port (DEF) or starboard (ABC) side of a row. Sequences can now also be mixed, i.e. consecutive Classes alternate sides, as in "Halfblock_4_des_mix", which fills the plane in the Class order: 8-3-6-1 and 4-7-2-5 (Fig. 2). In this case the first four Classes will nicely queue behind one another without much interference. However, as Class 4 enters the plane, its passengers will have to wait for the complete aisle to clear before they can move to the back of the plane. We will use the notion of a "train" of Classes to clarify what happens. A train of Classes is a subset of the sequence SQ, such that the row assignments from one Class to the next in a train are uniformly descending. In this case the passengers belonging to two consecutive Classes within the same train need not cross each other in the aisle. Sequence SQ(halfblock_4_des_mix) e.g. contains two trains of four Classes each (Fig. 2).
- *By row*: The Class size is a full row of six seats ($m = 6$). Only one instance of the Class Type is possible:

$$\begin{aligned}\mathrm{CT}(\mathrm{row}) = \bigcup_{i=1}^{n} \{(i,1),(i,2),(i,3), \\ (i,4),(i,5),(i,6)\} \\ \forall (i,j) \in S.\end{aligned}$$

  A "Row_Alternate_m" scheme will skip m rows (Table 3).
- *By half row*: Same as above, but a Class contains either seats ABC or DEF ($m = 3$), so the only Class Type is

Table 3
Description of each call-off method by class-size-sequence

CLASS TYPE	SIZE	SEQUENCE	NOTATION
Random	1 block	n.a.	at_random
By full row block	Block= number of full rows (ABCDEF) - random within a block		
	2 blocks: first business, then economy	Ascending	by_block_B-E
	2 blocks of equal size	Descending	by_block_2_des
	3 blocks 1 2 3	Descending:3 2 1	by_block_3_des
		Alternate: 2 3 1	by_block_3_alt_1
	4 blocks 1 2 3 4	Descending: 4321	by_block_4_des
		Alternate: 4231	by_block_4_alt_1
		Alternate: 4132	by_block_4_alt_2
	6 blocks 1 2 3 4 5 6	Descending: 654321	by_block_6_des
		Alternate: 642531	by_block_6_alt_1
		Alternate:635241	by_block_6_alt_2
		Alternate: 625143	by_block_6_alt_3
	10 blocks 1 2 3 4 5 6 7 8 9 10	Descending: 10 9 8 7 5 4 3 2 1	by_block_10_des
		Alternate: 10 8 6 4 2 9 7 5 3 1	by_block_10_alt_1
		Alternate: 10 5 9 4 8 3 7 2 6 1	by_block_10_alt_4
By half row block	Block = number of half rows (ABC) or (DEF) - random within a row		
	2 blocks 3 4 1 2	Descending 4321	by_halfblock_2_des
		Alternate: 4123	by_halfblock_2_des_mix
	3 blocks 4 5 6 1 2 3	Descending: ABC, then DEF : 654321	by_halfblock_3_des
		Alternate: ABC then DEF : 645312	by_halfblock_3_alt_1
	4 blocks 5 6 7 8 1 2 3 4	Descending 87654321	by halfblock_4_des
		Alternate (1) ABC then DEF: 86754231	by halfblock_4_alt_1
		Alternate: mixed descending: 83614725	by_halfblock_4_des_mix
	6 blocks 7 8 9 10 11 12 1 2 3 4 5 6	Descending: 12 11 10 9 8 7 6 5 4 3 2 1	by_halfblock_6_des
		Alternate (1) ABC then DEF: 12 10 8 11 9 7 6 4 2 5 3 1	by_halfblock_6_alt_1
		Alternate (2) ABC then DEF: 12 9 11 8 10 7 6 3 5 2 4 1	by_halfblock_6_alt_2
		Alternate mixed alternate(1): 12 4 8 5 9 1 11 3 7 6 6 2	by_halfblock_6_alt_1_mix
	10 blocks 11 12 13 14 15 16 17 18 19 20 1 2 3 4 5 6 7 8 9 10	Descending: ABC then DEF: 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1	by_halfblock_10_des
		Alternate(1) ABC then DEF: 20 18 16 14 12 19 17 15 13 11 10 8 6 4 2 9 7 5 3 1	by_halfblock_10_alt_1
		Alternate(4) ABC then DEF: 20 15 19 14 18 13 17 12 16 11 10 5 9 4 8 3 7 2 6 1	by_halfblock_10_alt_4
By row	Random within a row		
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23		
	Descending: 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1		by_row_des
	Alternate(1) 23 21 19 17 15 13 11 9 7 5 3 1 22 20 18 16 14 12 10 8 6 4 2		by_row_alt_1
	Alternate(2) 23 20 17 14 11 8 5 2 22 19 16 13 10 7 4 1 21 18 15 12 9 6 3		by_row_alt_2
	Alternate(4) :23 18 13 8 3 22 17 12 7 2 21 16 11 6 1 20 15 10 5 19 14 9 4		by_row_alt_4
	Alternate(5) :23 17 11 5 22 16 10 4 21 15 9 3 20 14 8 2 19 13 7 1 18 12 6		by_row_alt_5
	Alternate(8): 23 14 5 22 13 4 21 12 3 20 11 2 19 10 1 18 9 17 8 16 7 15 6		by_row_alt_8

(*Continued on next page*)

Table 3 (*continued*)

By Half row	**Random within half a row**	
	25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23	
	Descending: 45 44 43 42 41 … 26 25 23 22 ... 5 4 3 2 1	**by_halfrow_des**
	Alternate(1) ABC then DEF: 45 43 41 … 25 44 42 40 ... 26 23 21 19 … 1 22 20 18 … 2	**by_halfrow_alt_1**
	Alternate(2): 45 42 39 36 33 30 27 44 41 38 35 32 29 26 43 37 34 31 28 25 23 20 17 14 11 8 5 2 22 19 16 13 10 7 4 1 21 18 15 12 9 6 3	**by_halfrow_alt_2**
	Alternate(3): 45 41 37 33 29 25 44 40 36 32 28 43 39 35 31 27 42 38 34 30 26 23 19 15 11 7 3 22 18 14 10 6 2 21 17 13 9 5 1 20 16 12 8 4	**by_halfrow_alt_3**
	Alternate(5): 45 39 33 27 43 38 32 26 44 37 31 25 42 36 30 41 35 29 40 34 28 23 17 11 6 1 22 16 10 5 21 15 9 4 20 14 8 3 19 13 7 2	**by_halfrow_alt_5**
	Alternate(8): 45 36 28 44 35 27 43 34 26 42 33 41 32 40 31 39 30 38 29 37 23 14 6 22 13 5 21 12 4 20 11 3 19 10 2 18 9 1 17 8 16 7 15	**by_halfrow_alt_8**
By letter	**Random within all seats labeled A, then B, … and variants**	
	Window to corridor: A, B, C, F, E, D	**by_letter_wintocorr**
	Alternate: A, F, B, E, C and D	**by_letter_alt**
By seat	**See description below**	
	Descending row and then by letter 23A 22A 21A … 1A/ 23B 22B 21B … 1B/ 23C 22C 21C … 1C/ 23D … 1D / 23E … 1E	**by_seat_des_row_by_letter**
	Descending row and alternate letter 23A 22F 21A 20F… 1A / 23B 22E 21B 20E … 1B / 23C 22D 21C 20D … 1C/ 22A 21F 20A 19F … 2A / 22B 21E 20B 19E … 2B / 22C 21D 20C 19D … 2C	**by_seat_des_row_alt_letter**
	Alternate(1) row and alternate letter 23A 21F 19A 17F … 3A / 23B 21E 19B 17E … 3B / 23C 21D 19C … 3C / 21A 19F 17A … 1A / 21B 19E 17B … 1B / 21C 19D 17C … 1C / 22A 20F 18A 16F … 2A / 22B 20E 18B … 2B / 22C 20D 18C 16D … 2C / 22F 20A 18F 16A … 2F / 22E 20B ... 2E / 22D 20C ... 4C 2D	**by_seat_alt_1_row_alt_letter**
	Alternate(5) row and alternate letter: 23A 17F 11A 4F / 17A 11F 5A / 23B 17E 11B 5A / 17B 11E 5B / 23C 17D 11C 5D / 17C 11D 5C / 22A 16F 10A 4F / 22F 16A 10F 4A / 22B 16E 10B 4E / 22E 16B 10E 4B / 22C 16D 10C 4D / 22D 16C 10D 4C/ 21A 15F 9A 3F / 21F 15A 9F 3A / 21B ... 3C / 20A 14F 8A 2F / 20F ... 2C / 19A 13F 7A / 19F ... 7D 1C / 18A 12F 6A / 18F ... 12C 6D	**by_seat_alt_5_row_alt_letter**
	Alternate(8) row and alternate letter: 23A 14F 5A 14A 5F 23B 14E 5B 14B 5E 23C 14D 5C 14C 5D / 22A 13F 4A / 22F 13A 40F / 22B 13E 4B / 22E 13B 4E / 22C 13D 4C / 22D 13C 4D / 21A 12F 3A / 21F 12A 3F / 21B 12E 3B / 21E 12B 3E / 21C 12D 3C / 21D 12C 3D / 20A 11F 2A / 20F 11A 2F / 20B 11E 2B 20C ... 19A 10F 1A 19F ... 18A 9F 18F ... 17A 8F 17F ... 16A 7F 16F ... 15A 6F ... 15D 6C	**by_seat_alt_8_row_alt_letter**

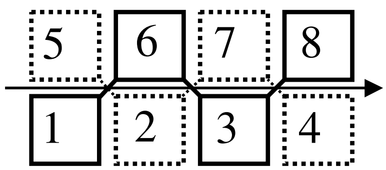

Fig. 2. Boarding sequence "half-block-4-des-mix" containing 2 "trains" of classes: 8-3-6-1 and 4-7-2-5.

$$\mathrm{CT(halfrow)} = \bigcup_{i=1}^{n} \{(i,1)(i,2),(i,3)\} \cup \{(i,4),(i,5),(i,6)\} \quad \forall (i,j) \in S.$$

- *By letter*: This is a special Type, in which each Class consists of all seats with the same label (A to F), so $m = n$.

$$\mathrm{CT(letter)} = \bigcup_{j=1}^{6} \{(i,j)\xi 1 \leqslant i \leqslant n\} \quad \forall (i,j) \in S.$$

- *By seat*: Each passenger is called individually by row and seat number ($m = 1$). Sequence "by_seat_des_row_alt_letter" means 22A 21F 20A 19F … 1F/22F 21A 20F 19A …/22B 21E 20B 19E …, leading to six trains in this sequence.

4. Simulation results

The boarding procedure has been analyzed using simulation in Arena (from Rockwell Automation). We modeled all of the disturbances listed above. The different call-off methods were modeled as a stream of passengers (identified by their seat location) listed in an Excel file. In our model passengers arrive at a constant rate. In reality, this rate is determined by the gating operations. We chose not to include this step in our study, in order not to obscure the pure effect of sequencing. All processing times are random (Table 1). Decision variables are limited to the choice of Class size and the sequence of the Classes. Independent variables are: occupation level of the airplane (62.5% and 100%) (the first one being the average utilization of the reference period with the airline), and carry-on luggage level (Table 2). In this study the first objective is to reduce total boarding time. The second objective is to augment the quality perception of the passengers. Therefore, we will evaluate different boarding systems also by average and maximum individual boarding time, as seen by the passengers.

We performed five replications for each of the 47 sequences. Each run took only a few seconds on a 233 MHz PC. The results are shown in Table 4. Fig. 3 compares the 90% confidence intervals of total boarding time at 100% occupation.

Following conclusions can be drawn from inspecting these results:

- Although considerable differences in total boarding time occur within each Class Type, the best sequence in almost all Types requires more than 20 minutes for full planes, i.e. 6.6 pax/min. This contrasts with the findings of Boeing (Marelli et al., 1998) which state a rate of 9 pax/min, i.e. a boarding time for our model of 14.6 minutes (lower dotted line in Fig. 3). We suspect their results were for large-body planes only, with more than 200 passengers.
- The best result of 10.4 minutes (12.7 pax/min) is reached by the Class "By Seat", for the sequence SQ(seat_des_row_des_letter), which is basically in descending row order and outside-in seat order. This means that the objective of 10 minutes turnaround, set by the airport authority, although attainable, seems hardly realistic!
- An almost equally good result is reached by the sequence SQ(seat_des_row_alt_letter) with 10.6 minutes (12.5 pax/min), which alternates sides (A-F-A-F...) for consecutive passengers. Sequence SQ(seat_alt_1_row_alt_letter) reaches 15.4 minutes (8.6 pax/min).
- The best method outside the "Seat" Class Type is SQ(halfrow_alt_2), which attains 15.8 minutes (8.4 pax/min).
- The random method, used frequently today, performs comparable well to most other Class Types (highest dotted line in Fig. 3), which is somewhat surprising. Only 9 out of 46 sequences do better than random. The conclusion is that in taking a structured approach to boarding, one should beware of making things far worse by choosing a wrong way of sequencing. A "wrong" block method can result in times up to 40 minutes!
- All methods of (full) block calling, among which "block_4" is frequently used by airlines today, require around 30 minutes of loading time (100% occupancy), which is considerably worse than random!
- The much used B/E method, where business passengers enter just before economy, performs consistently worse than random, and takes 12% more time (at 100% occupation) than the reverse sequence. Of course, customer service considerations may overrule this.
- Comparing the range of boarding times over all sequences within a Class Type, we see that "halfblock" seems to be the most robust Class Type. In all other Types maximum boarding times can be 2 to 3 times the Class Type minimum. In general, the smaller the Class size, the more sensitive the total boarding time is to the sequence, and in particular to the distance between the seat assignment of two consecutive passengers (see further).
- It is most likely that any sequence, that reduces the likelihood that consecutive passengers interfere with one another, will reduce boarding time. For instance, the best sequence in the "halfblock" Class Type is SQ(halfblock_6_alt_1)

Table 4
Simulation results for different call-off sequences under 100% occupancy

No.	Boarding time (in minute) (five replications)	Total boarding time			Average individual boarding time			Maximum individual boarding time		
	Class-size-sequence	Average	S.D.	% Over	Average	S.D.	% Over	Average	S.D.	% Over
1	Random	24.69	0.35	237	1.78	0.06	166	4.35	0.69	193
2	by_block_B-E	29.02	1.21	278	2.08	0.11	193	4.89	0.51	217
3	by_block_2_des	27.74	0.63	266	2.32	0.11	216	5.40	0.31	239
4	by_block_3_des	28.56	0.89	274	2.42	0.15	226	5.58	0.70	247
5	by_block_3_alt_1	29.80	1.95	286	2.45	0.22	228	5.07	0.22	225c
6	by_block_4_des	31.35	2.76	301	2.66	0.15	247	6.82	0.55	302
7	by_block_4_alt_1	30.66	3.07	294	2.51	0.12	233	6.23	0.88	276
8	by_block_4_alt_2	31.02	3.61	298	2.58	0.18	240	6.70	0.40	297
9	by_block_6_des	33.77	2.97	324	2.86	0.13	266	7.01	0.70	311
10	by_block_6_alt_1	31.43	3.56	301	2.59	0.20	241	6.56	1.01	291
11	by_block_6_alt_2	30.78	1.36	295	2.64	0.10	246	6.76	0.40	300
12	by_block_6_alt_3	32.51	0.89	312	2.77	0.23	258	7.00	0.60	310
13	by_block_10_des	39.80	6.37	382	3.59	0.27	334	8.02	0.76	355
14	by_block_10_alt_1	34.73	1.03	333	2.89	0.05	269	6.09	0.49	270
15	by_block_10_alt_4	29.59	0.10	284	2.72	0.08	253	6.42	0.57	285
16	by_halfblock_2_des	27.42	3.68	263	2.15	0.14	200	5.36	0.41	238
17	by_halfblock_2_des_mix	25.01	0.53	240	1.96	0.11	182	5.23	0.31	232
18	by_halfblock_3_des	27.91	1.96	268	2.25	0.16	210	5.72	0.69	254
19	by_halfblock_3_alt_1	29.60	2.00	284	2.27	0.10	211	5.64	0.44	250
20	by halfblock_4_des	28.30	0.24	271	2.36	0.07	220	5.69	0.17	252
21	by halfblock_4_alt_1	26.50	2.75	254	2.31	0.18	215	5.39	0.39	239
22	by_halfblock_4_des_mix	29.27	3.23	281	2.44	0.15	227	5.37	0.32	238
23	by_halfblock_6_des	30.36	2.46	291	2.67	0.26	248	6.36	1.19	282
24	by_halfblock_6_alt_1	24.75	1.21	237	2.12	0.17	197	4.78	0.39	212
25	by_halfblock_6_alt_2	26.28	3.06	252	2.29	0.06	213	4.68	0.32	207
26	by_halfblock_6_alt_1_mix	25.80	0.68	248	1.80	0.07	168	4.43	0.33	196
27	by_halfblock_10_des	35.64	0.56	342	3.14	0.09	293	6.59	0.31	292
28	by_halfblock_10_alt_1	27.23	2.86	261	2.24	0.10	208	5.19	0.69	230
29	by_halfblock_10_alt_4	26.91	0.73	258	2.05	0.12	191	4.78	0.30	212
30	by_row_des	50.67	1.39	486	4.50	0.15	419	9.52	0.18	422
31	by_row_alt_1	41.89	0.42	402	3.64	0.04	339	7.50	0.48	332
32	by_row_alt_2	33.83	0.69	325	2.69	0.02	251	6.31	0.38	280
33	by_row_alt_4	29.02	0.39	278	2.68	0.10	250	6.11	0.43	271
34	by_row_alt_5	23.11	0.87	222	1.99	0.04	185	4.05	0.28	179
35	by_row_alt_8	28.76	1.21	276	2.34	0.13	218	5.44	0.41	241
36	by_halfrow_des	41.79	1.19	401	3.68	0.05	343	7.87	0.44	349
37	by_halfrow_alt_1	27.33	0.20	262	2.15	0.05	200	5.14	0.27	228
38	by_halfrow_alt_2	15.79	0.54	151	1.56	0.05	145	3.51	0.24	156
39	by_halfrow_alt_5	23.42	0.59	225	1.83	0.03	170	3.92	0.42	174
40	by_halfrow_alt_8	28.52	0.96	274	1.92	0.06	179	4.20	0.31	186
41	by_letter_wintocorr	22.16	1.81	213	1.60	0.11	149	4.08	0.51	181
42	by_letter_alt	21.34	0.68	205	1.61	0.09	150	4.39	0.61	195
43	by_seat_des_row_by_letter	10.42	0.04	100	1.07	0.08	100	2.26	0.25	100
44	by_seat_des_row_alt_letter	10.58	0.01	102	1.09	0.07	101	2.37	0.26	105
45	by_seat_alt_1_row_alt_letter	15.38	0.77	148	1.19	0.10	111	2.46	0.30	109
46	by_seat_alt_5_row_alt_letter	21.31	0.38	204	1.49	0.09	138	3.72	0.49	165
47	by_seat_alt_8_row_alt_letter	27.41	0.82	263	1.69	0.07	158	3.80	0.48	168

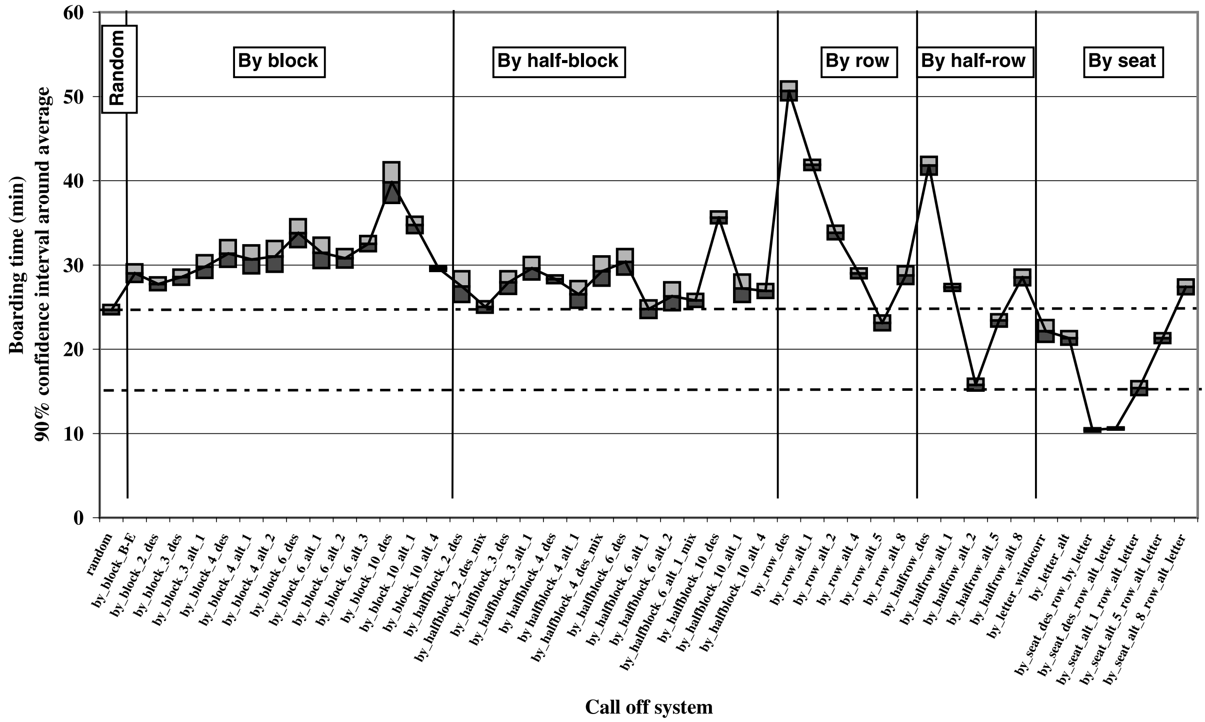

Fig. 3. Total boarding time under different call-off systems (90% confidence interval, five replications).

which skips a row between passengers. We call this the "between-class gap", which here is of size 1 (row). The between-class gap is determined both by the size of the class and the sequence.

- The variability of total boarding time (Table 4) remains rather limited, which reinforces the conclusions. The main source of variability is the size of the Class (48% based on ANOVA), while the between-class gap only contributes for 10%. The rest is from other sources, such as the variable move times.

Total boarding time is clearly important for the airline itself, since it determines the airplane Turn Time. However, passengers are more susceptible to the waiting times they experience personally (Sasser et al., 1978). Therefore we also examined average and maximum individual boarding times, measured from the moment the passenger enters the plane until he sits down. Fig. 4 shows both, including the difference as a bar graph, and details are included in Table 4.

We can immediately conclude that the fastest method also yields the best passenger comfort: lowest average (1 minute) and maximum (2.3 minutes) individual boarding times. We also note that all methods with low passenger interference yield comparable results between 2 and 3 minutes. Really bad methods for total boarding time also generate long individual times (average 4.5 minutes and maximum up to 9.5 minutes!). Correlation between total boarding time (X) and average individual boarding time (Y) is very high ($R^2 = 91.9\%$), as could be expected. This is somewhat less for maximum boarding time: $R^2 = 87.6\%$.

We then ran some simulations with plane occupancy reduced to the current average of the national carrier, i.e. 62.5%, which is shown in Table 5 and Fig. 5 on selected sequences. The main effect besides the obvious reduction in total

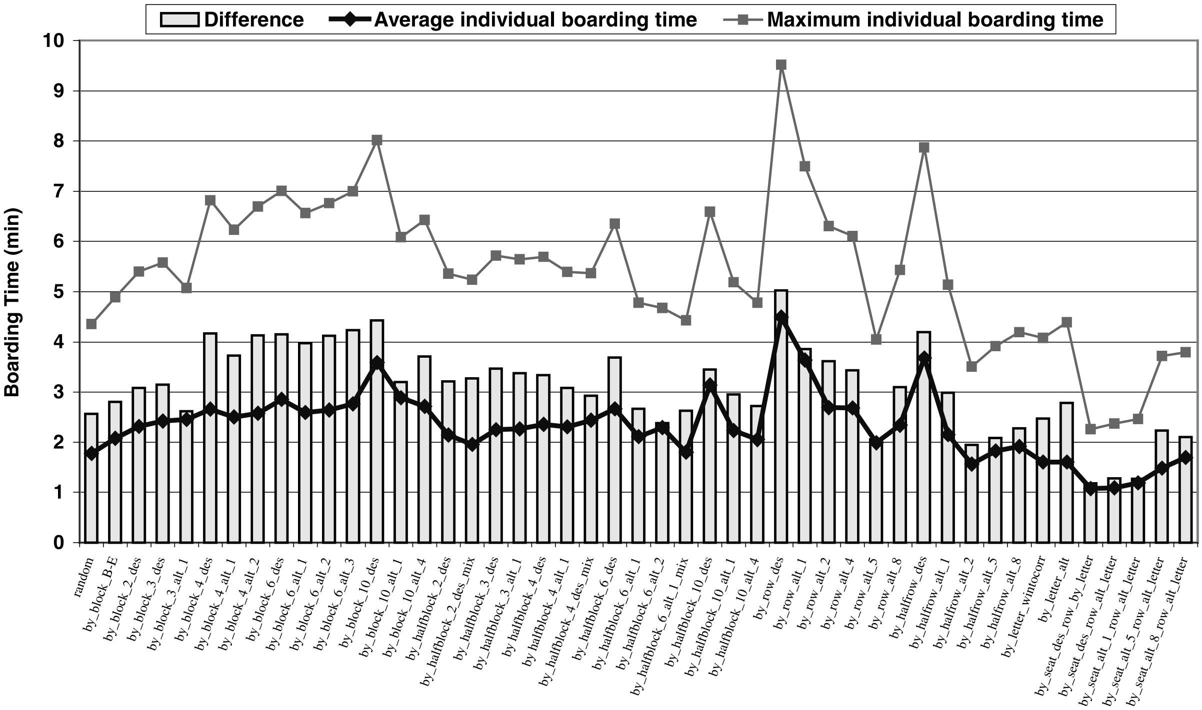

Fig. 4. Individual boarding time under different call-off methods (100% occupation).

Table 5
Effect of reduced occupation (62.5%) on selected sequences

No.	Boarding time (minute)	Total boarding time				Average individual			Maximum individual		
	Class-size-sequence	100%	Pax/min	62.5%	Pax/min	100%	62.5%	% Under	100%	62.5%	% Under
1	Random	24.69	5.3	13.65	6.0	1.78	1.62	91	4.35	3.38	78
2	by_block_B-E	29.02	4.5	16.28	5.1	2.08	1.62	78	4.89	3.66	75
3	by_block_2_des	27.74	4.8	16.91	4.9	2.32	2.40	104	5.40	5.97	110
13	by_block_10_des	39.80	3.3	22.74	3.6	3.59	3.24	90	8.02	7.36	92
17	by_halfblock_2_des_mix	25.01	5.3	15.98	5.2	1.96	1.61	82	5.23	5.07	97
21	by alfblock_4_alt_1	26.50	5.0	14.80	5.6	2.31	2.16	93	5.39	4.72	88
24	by_halfblock_6_alt_1	24.75	5.3	12.56	6.6	2.12	1.88	89	4.78	3.76	79
30	by_row_des	50.67	2.6	26.04	3.2	4.50	3.78	84	9.52	8.57	90
34	by_row_alt_5	23.11	5.7	13.27	6.2	1.99	1.63	82	4.05	4.19	104
36	by_halfrow_des	41.79	3.2	17.91	4.6	3.68	2.07	56	7.87	4.73	60
38	by_halfrow_alt_2	15.79	8.4	10.25	8.0	1.56	1.27	82	3.51	3.59	102
42	by_letter_alt	21.34	6.2	12.69	6.5	1.61	1.52	95	4.39	3.07	70
43	by_seat_des_row_by_letter	10.42	12.7	7.46	11.1	1.07	0.96	89	2.26	2.15	95
44	by_seat_des_row_alt_letter	10.58	12.5	8.17	10.1	1.09	0.98	90	2.37	2.14	90
45	by_seat_alt_1_row_alt_letter	15.38	8.6	10.08	8.2	1.19	1.05	88	2.46	2.78	113

boarding time is a slight increase in pax/min rate for most sequences, and an increase in variability (90% confidence interval). The best sequence remains the same.

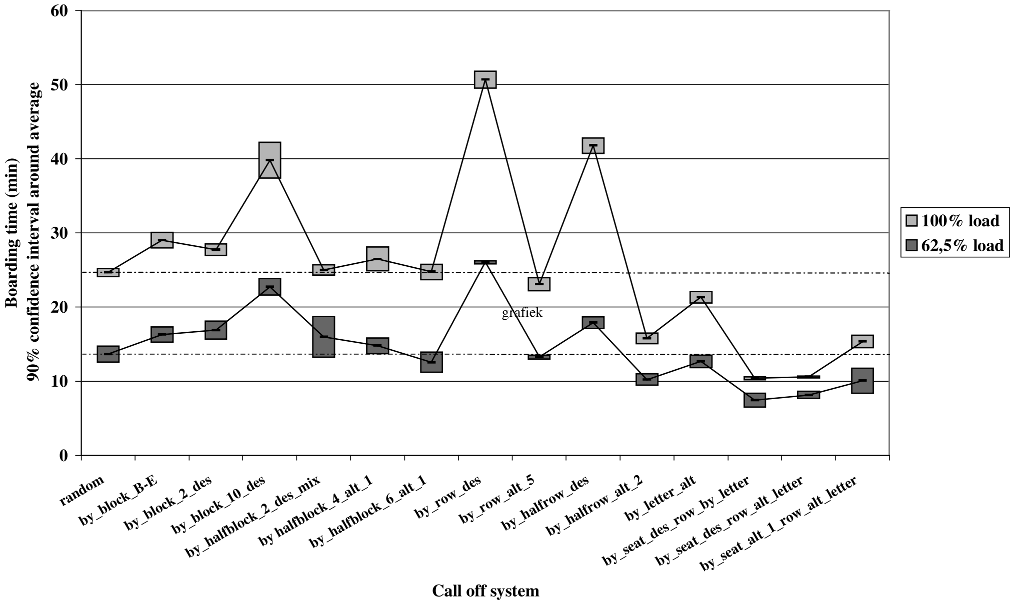

Fig. 5. Effect of reduced seat occupancy (90% confidence interval) on selected sequences.

Since most airlines are increasingly restricting the amount of cabin luggage, we also investigated the effect of an increased luggage level (Table 2). Fig. 6 shows the increase compared to the base level (Table 4) for 100% occupancy, for the best sequence in each Class Type. The overall best method is also the most robust one for excess baggage (+9%). Random performs well for total

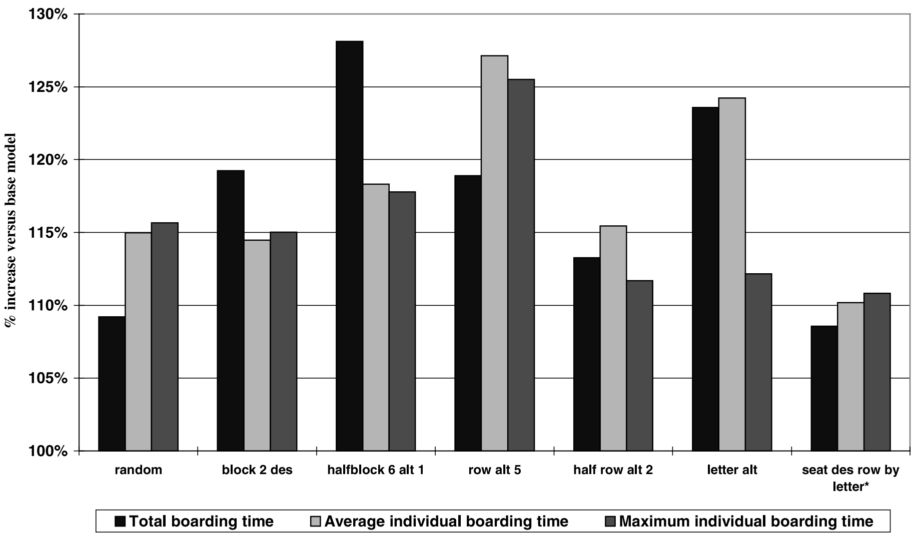

Fig. 6. Impact of increased handluggage on the best sequences of each Class Type.

boarding time (+9%), but deteriorates individual boarding times (+15%). Worst case is an increase of 28% total boarding time.

5. The basic boarding mechanisms

From this research, we gained some insights into the fundamental mechanisms behind the boarding process. Specifically we want to explain why the total boarding time for different sequences in Class Types "row", "halfrow" and "seat" goes through a rather sharp minimum (Fig. 3).

Individual boarding time for each passenger (i,j) in a given sequence SQ is the sum of travel time + between-class delay + a delay + own processing time, i.e.

$$T_{\text{total}}(i,j) = T(i) + \phi(m) + \gamma(\text{SQ}, m) + P(i,j). \quad (1)$$

Each one of these elements undergoes statistical variation:

- Travel time $T(i)$ is determined by the distance to cover, i.e. the row number i, and is subject to delays from preceding passengers moving at different speeds.
- Processing time $P(i,j)$ is determined by the amount of luggage to store, and is influenced by the fill rate of the storage bins.
- Within-class delay $\phi(m)$ is caused by individual passengers of one Class trying to attain their seat in the same area, and is thus proportional with the size of the Class.
- Between-class delay follows from any interference between consecutive classes from different trains, denoted $\gamma(\text{SQ}, m)$. The magnitude of this delay is therefore function of the class size m and the (gap size of the) sequence SQ.

The boarding time of a class of passengers is therefore determined by the last passenger to sit down, i.e. the one with the largest within-class delay (all other elements being equal on average).

The boarding time of a train is determined by that of its first class, since all consecutive classes will have (by definition) less move time, and comparable within-class delays and processing times. Total boarding time is finally the sum of the boarding times of each train in the sequence.

These relations becomes more apparent in Fig. 7, which relates total boarding time to the between-class gap size. We observe that a minimum occurs at a between-class gap size which is one smaller than the class size m, at gap 0 for Class Type "seat" ($m = 1$), up to gap 5 for Type "row" ($m = 6$). This fits nicely with the number of passengers that arrive together at their row, of which all but one have to queue. If the between-class gap is smaller than

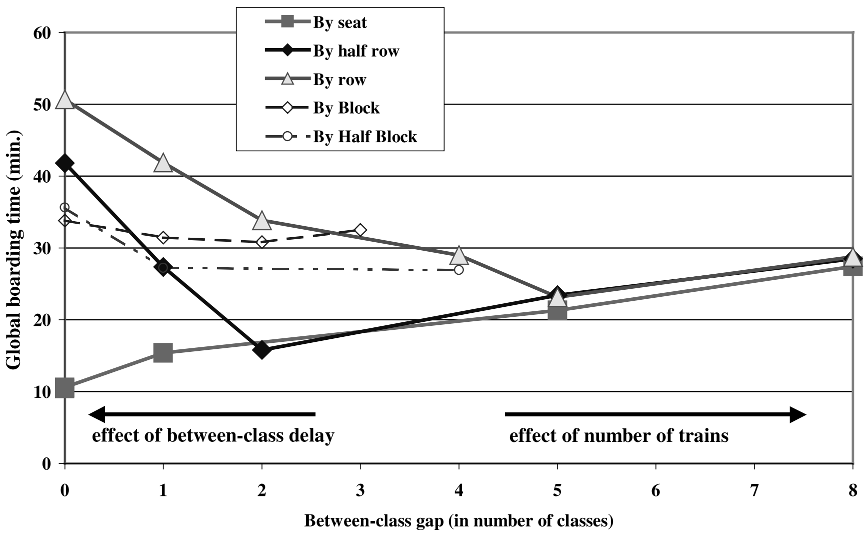

Fig. 7. The impact of the gap between two consecutive classes in a sequence.

Table 6
Best boarding sequence in each Class Type (for 100% occupancy)

Class	Class definition and boarding sequence	Boarding velocity (pax/min)	% vs. best	Avg. individual boarding time (minute)	% vs. best	Maximum individual boarding time (minute)	% vs. best
Random	132 Seats random	5.3	42	1.8	166	4.4	192
2 Full blocks	Rows (12–23) first, then (1–11)	4.8	38	2.3	217	5.4	239
12 Half blocks	Rows (23–21), (13–16), (5–8), (17–20), (9–12), (1–4), for seats ABC, repeat row sequence with seats DEF	5.3	42	2.1	198	4.8	212
23 Full rows	Rows 23, 17, 11, 5, 22, 16, 10, 4, 21, 15, 9, 3, 20, 14, 8, 2, 19, 13, 7, 1, 18, 12, 6, all seats together	5.7	45	2.0	186	4.1	179
45 Half rows	Rows 23, 20, 17,...,22,19, 16,..., 21, 18, 15,... for seats ABC, then repeat row sequence for seats DEF	8.4	66	1.6	146	3.5	155
132 Seats	Descending row then by letter: 23A, 22A, 21A,..., 1A, 23B, 22B, 21B,..., 1B/22C,...,1C/22F, 21F, 20F,...,2F	12.7	100	1.1	100	2.3	100

$m-1$, passengers spill over to adjacent Classes, increasing total waiting. When Classes become too large (half-block and block) the relation is less pronounced, because waiting passengers in the aisle extend over multiple Classes.

When the between-class gap decreases under this minimum point, consecutive classes in the same train will start to interfere with each other, increasing the between-class delay. When the between-class gap increases beyond the minimum point, the distance between (the classes of) consecutive trains in the sequence will increase. This will not reduce $\gamma(\mathrm{SQ}, m)$ any further, but will increase the number of trains needed to cover all seats. Thus total boarding time will increase because of the additional trains.

From these basic constructs one can express a design rule for a "good" boarding sequence: any efficient sequence should combine control over individual passengers (through the class size m) with the between-class gap size to reduce interferences. High control (small m) allows for small gap sizes, yielding fast boarding.

6. Implementation issues

It is clear that predictable and short boarding times, together with small individual waiting times, require more controlled boarding systems than those currently used. The best sequences all require calling off individual passengers by their row and seat number. Clearly this is a complicated procedure, that takes place before passengers enter the plane. Wrong implementation of this method could lead to confusion and more time lost at the gate than can be gained once in the airplane. Moreover, the fastest call-off method is not always perceived as being best by the customer. Passengers do not appreciate too complicated call systems. A compromise has to be found between simplicity of the call system and velocity of boarding.

However, comparable systems do exist today. Often at deli counters in supermarkets numbered tickets are used to control queuing of customers and eliminate line hopping (another important subjective quality element for customers). The announcement of the next customer is through an electronic display. The same setup could be used at airport gates, with minimal investment, since the flight display at the gate could be programmed for this. Effective sequence control could be achieved when checking the boarding pass at the gate entrance. A more automated system is possible by using passenger tags (FotoTag, 2001), instead of boarding cards, allowing remote scanning and control of passenger sequence.

A negative element of the individual boarding sequences is that parties traveling together (such as families, or couples) will board separately. If this poses a problem, the next best approach is a "half row" approach, with a boarding time of 15.8 minutes (or 50% more than the previous one). A half row sequence can be achieved by calling passengers by their row assignment, and color coding boarding passes for starboard (ABC) and port (DEF) sides of the plane, thus minimizing investments.

If an airline prefers to stick to the "old" block system, then these blocks should not be too small: 2 to 6 blocks seem to be best. Even better would be half blocks, which also could be supported by color-coding port and starboard side seats. However, boarding times will more than double in these instances. Table 6 shows the best methods by Class, from which airlines can choose their favorite approach.

7. Conclusions

Airline boarding times must be reduced in order to improve on-time departures and airplane Turn Times. Simulation has shown that the choice of boarding systems highly influences the boarding time, both total and individually. Individualized calls reduce total boarding time with 100% or more versus random. Looking at the basic mechanisms, one can conclude that any sequence should separate consecutive passengers far enough to reduce interference. While implementing these systems today would require stringent procedures at the gate, emerging tag technology is already promising a more controlled and automatic gate check procedure. At that time, the results of this paper can be fully implemented, yielding large reductions in boarding time, and hence in airplane Turn Time.

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