# The Unique Best Boarding Plan? It Depends...

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## Summary

We devise and compare strategies for boarding and deboarding planes of varying capacity. We clarify what properties a good strategy should have. We apply the same assumptions regarding basic boarding procedure, inner structure of planes, and behavior of passengers to all the cases.

For boarding, we study prevailing strategies and a seemingly excellent strategy, seat–by–seat, proposed in past literature, and categorize them into two types, assigned–seating and open–seating. We develop a model and a simulation for each type . Our criteria identify two good candidates, reverse-pyramid and open-seating. We develop our own comprehensive strategy, simulate it, and compare it with those two. However, the optimal boarding strategy is not the same for different planes. Some values of parameters, such as the passengers' luggage size and weight, greatly influence the final result. Based on these discoveries, we suggest how to modify a boarding procedure in practice to make it optimal.

For deboarding, a simple strategy beats a complicated one; but we still give a theoretically optimal model, then modify it to achieve a concise strategy applicable in practice.

## Introduction

Planes produce revenue while flying; thus, it is important to minimize turnaround time, the time between flights that an plane spends on the ground.

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For many airlines, boarding is the bottleneck. Reduction of boarding time results in profit increases while potentially increasing passenger satisfaction [van den Briel et al. 2003].

A number of different strategies have been implemented: back–to–front, rotating-zone, outside–in, and so on. We consult existing research and find the key issues in describing boarding mathematically and designing a good boarding algorithm.

Finally, we analyze deboarding and see how its time can be minimized.

# Judging Standards

**Efficiency:** Minimizing total boarding time is our primary target.

**Passenger satisfaction:** We use two measures to describe passenger satisfaction: the proportion of passengers satisfied, and average individual boarding time.

**Feasibility:** Whether and how the strategy is applicable in reality. Generally speaking, the more complicated the boarding strategy, the less feasible it is.

Shorter total boarding time is preferred by both airlines and passengers. There are two measures of boarding time: total boarding time (which affects airline profits directly) and average individual boarding time (which influences passengers' satisfaction with the airline and thus indirectly airline profits).

We cannot find industry standards for passenger satisfaction and feasibility. However, we can define them descriptively, rather than merely numerically.

# Assumptions

- We consider only coach and business–class passengers. Passengers with special needs and first–class passengers are only a small portion of all passengers and are seated before the majority, so their boarding time is assumed to be fixed and has little influence on our models.
- Each passenger is allowed one piece of carry–on luggage and one personal item (purse, computer, briefcase, or small tote, etc.) [Airline Carry-On Luggage Regulations 2007]. Each passenger puts any luggage into the overhead compartment and takes any personal item to the seat. Occasional withdrawal of excessive carry–on luggage is not in our scope.
- When boarding starts, all passengers have arrived at the boarding gate. Missing and late passengers are not in our scope.
- The aisles of planes are narrow and do not allow a passenger to pass another passenger in the aisle.

- The boarding time of an individual passenger is from entry into the plane (and thus the aisle) to sitting down.
- The total boarding time is from the entry of the first passenger into the plane (and thus the aisle) to when the last passenger sits down.
- In all our simulations:
  - For an instance of small planes, we take the Boeing 737
  - For an instance of midsize planes, we take the Airbus A340, which has its 264 seats typically arranged 2–4–2 with two aisles.
  - For an instance of large planes, we take the Airbus A380. It is double–deck, typically with 350 seats arranged 3–4–3 in the main deck and 176 seats arranged 2–4–2 in the upper deck. When boarding, passengers of either deck board at the same time, through two doors, either of which is the front door of its deck.

# The Assigned–Seating Model

We establish a model of assigned–seating boarding strategies, first for small planes, with only one aisle, then for larger planes.

## The Boarding Process

- The gate agent announces boarding, then calls groups one after another. The passengers of a called group start queueing at the gate, with occasional conflicts and controversy about position in the queue.
- The gent checks boarding passes before passengers enter the plane.
- Passengers board through the front door. For a long-haul plane, passengers may board through an additional rear door.
- Passengers enter the plane. Because the aisles in the plane are narrow, when a passenger is putting luggage into the overhead compartment, or stops for another reason, the passengers behind have to line up. As soon as the passenger enters the seat row, the passengers behind can move again.
- Each passenger switches from moving in the aisle to moving in the seat row, after putting luggage into the overhead compartment, and finally sits. If there are other passengers between the passenger and the assigned seat, the passenger has to wait to pass through.
- When the last passenger gets seated, boarding ends.

# Detailed Algorithm

## Parameters

- $x_1, \ldots, x_n$ The sequence of passengers in the boarding queue.
- $l$ The distance between rows (leg room), including the thickness of the seats. It is a fixed value for one plane but it may differ for different models of planes or different airlines.
- $r$ The number of rows of seats in the plane.
- $S$ The aisle length of the plane, where $S = lr$.
- $m$ The number of boarding groups.
- $G_1, \ldots, G_m$ The sequence of boarding groups, according to the position of their assigned seats. The smaller the subscript, the earlier the group boards.
- $r_q$ The row of the $q$th passenger's assigned seat.
- $t_q$ The time when the $q$th passenger enters the plane (thus enters the aisle). We assume that $t_1 = 0$, that is, we set the time to be 0 when the first passenger enters the plane.
- $T_q$ A random variable denoting the time difference between the $q$th and $(q+1)$st passengers' entry into the plane; $T_q = t_{q+1} - t_q$, with mean $\overline{T}$ and variance $\sigma_T^2$.
- $S_q$ The position of the $q$th passenger's assigned seat. We define it as $S_q = lr_q$.
- $w_q$ The aisle space that the $q$th passenger occupies, luggage and safe distance between two passengers included. We assume that $w_q$ is a random variable following a normal distribution with mean and $\bar{w}$ and variance $\sigma_w^2$.
- $v_q$ The moving speed of the $q$th passenger in the aisle; it follows a normal distribution with mean $\bar{v}$ and variance $\sigma_w^2$.
- $a_q T_{q,L}$ The time that the $q$th passenger spends putting luggage into the overhead compartment. $T_{q,l}$ follows a triangular distribution [Van Landeghem and Beuselinck 2000] with mean $\overline{T}_L$ and variance $\sigma_L^2$. The $a_q$ is a coefficient random variable relevant to the size, weight and shape of $x_q$'s luggage; it follows a normal distribution with mean $\bar{a}$ and variance $\sigma_a^2$. The variables $a_q$ and $T_{q,L}$ are independent.
- $T_{q,0}$ The time that the $q$th passenger spends to pass through an empty seat when moving in a row. It follows a triangular distribution with mean $\overline{T}_0$ and variance $\sigma_0^2$.

- $T_{q,1}$ The time that the $q$th passenger spends to pass through a seat in which another passenger is sitting when moving in a row; it follows a triangular distribution with mean $\overline{T}_1$ and variance $\sigma_1^2$. This includes the time that the seated passenger stands up and that the $q$th passenger passes through.
- $\overline{T}_{q,S}$ The time that the $q$th passenger takes to sit; it follows a triangular distribution with mean $\overline{T}_S$ and variance $\sigma_S^2$.
- $x_q(t)$ The position in the aisle of the $q$th passenger at time $t$. We define $x_1(t_0)$ as the position of the aisle's entrance and set $x_1(t_0) = 0$.

## Mathematical Assumptions

- We divide passengers into groups $G_1, \ldots, G_m$. Passengers in the same group queue randomly. Then all the group queues connect with each other, in order of subscript from small to large, to form a total queue. The two extremes are: just one group (so the position of each passenger in the total queue is randomly determined), and the number of groups equals the number of passengers (each group consists of only one passenger, and the position of each passenger in the total queue is fixed by the assigned seat).
- There is no waiting time between two consecutive groups.
- When the $q$th passenger has entered the plane (thus enters the aisle), the passenger is in one of two states: moving with a constant speed $v_q$ or standing still. Standing still can further be divided into three categories:
  - Someone ahead is putting luggage in, so the aisle is congested and the queue cannot move forward.
  - The passenger is stowing luggage.
  - The passenger is finished stowing luggage, but the aisle seat of the row of the passenger's seat is now occupied by someone else.
- The $q$th passenger has three states when in the seat row
  - Passing through an empty seat (with time $T_{q,0}$);
  - Passing through a seat occupied by another passenger (with time $T_{q,1}$);
  - Waiting (standing still).
- The passenger is sitting down (with time $T_{q,S}$).

## The Algorithm

We now propose a detailed algorithm to calculate both total boarding time and individual boarding time for any assigned–seating boarding strategy.

### Motion in the Aisle

The $q$th passenger's motion is determined if we know the situation in the aisle ahead, which is determined only by the passengers entering earlier, namely, the 1st to the $(q-1)$st passengers. We record the position and some other information about each passenger and use iteration to do the calculation.

Let $W_Q(t)$ be the interval of space in the aisle that passenger $q$ occupies at time $t$:

$$W_q(t) = \begin{cases} \left[\max\{0, x_q(t) - \frac{1}{2}w_q\},\ \min\{S, x_q(t) + \frac{1}{2}w_q\}\right], & x_q(t) \neq 0; \\ \emptyset, & x_q(t) = 0. \end{cases}$$

We assume that $x_q(t) = 0$ from the moment that the $q$th passenger enters the seat row (the passenger "disappears from the aisle").

Let $C_q(t)$ be the space in the aisle occupied by all the passengers in front of $x_q$ at time $t$:

$$C_q(t) = \begin{cases} \cup_{p=1}^{q-1} W_p(t), & q > 1; \\ \emptyset, & q = 1. \end{cases}$$

From the time $t_q$ when $x_q$ enters the aisle, we define

$$t_{q,k} = \begin{cases} 0 & k = 0; \\ t_q + 0.1k, & k = 1, \ldots. \end{cases}$$

We let the computer) calculate and record $W_q(t)$ and $C_q(t_{q,t})$ every 0.1 s.

Let

$$x_q(t_{q,k+1}) = \begin{cases} \min\{x_q(t_{q,k}) + 0.1v_q,\ S_q\}, & W_q(t_{q,k}) \cap C_q(t_{q,k}) = \emptyset; \\ x_q(t_{q,k}), & \text{otherwise}. \end{cases}$$

In the first case, passenger $q$ moves at some speed during the next 0.1 s until reaching the assigned seat row within the next 0.1 s. In the second case, passenger $q$ stays unmoved during the next 0.1 s.

We denote the time when $x_q(t_{q,k}) = S_q$ (the passenger has reached the assigned row) by $t_{q,k_0}$. When $x_q$ reaches the assigned row, $x_q$ starts to stow luggage, taking time $a_q T_{q,L}$.

**Motion in a Row**

We say a seat is "occupied" only if a passenger is passing through it or the passenger to whom this seat belongs is getting seated; otherwise, the seat is not occupied, *even if the passenger to whom this seat belongs has already been seated* (since another passenger can pass through it). Then, $x_q$ at time $(t_{q,k_0} + a_q T_{q,L})$ finishes stowing luggage. We now check whether the aisle seat of the row is occupied:

- If it is occupied, $x_q$ waits in the aisle until it is clear.
- If not occupied, $x_q$ enters the row (thus is no longer in the aisle) and occupies the space of the aisle seat at time $(t_{q,k_0} + a_q T_{q,L}) + 0.1$.

- If this is the assigned seat, $x_q$ then spends time to get seated. During this time period, nobody else can pass though or occupy this seat. After $x_q$ sits down, another passenger could pass through this seat
- If this is not the assigned seat, $x_q$ spends time $T_{q,0}$ (if nobody is sitting in it) or $T_{q,1}$ (if someone is sitting on it) to pass through it. During this time period, nobody else can pass though or occupy this seat. After $x_q$ passes through this seat, we check whether the next seat is occupied, in the same manner, until $x_q$ gets seated.

# Simulation

## The Seven Candidates

Most of the airlines use one of the following six boarding strategies [Airplane Boarding . . . 2007]:

**Back-to-front** (US Airways, Air Canada, British Airways). Divide the seats into 4–6 blocks and board passengers from the back block to the front block.

**Rotating-zone** (AirTran) Divide the seats into 4–6 blocks, and board passengers in the sequence (back block, front block, next back block, the next front block, etc.).

**Random** (Northwest) Impose no sequence and let passengers enter randomly.

**Block** (Delta) Divide the seats into two or three blocks, then divide each block into a window-seats block and non-window-seats block. Label the back window-seats as block 1, the back non-window-seats as block 2, the second back window-seats as block 3, etc.

**Reverse-pyramid** (US Airways) Rear window and middle first, front window and middle next, followed by rear aisle, then front aisle.

**Outside-in** (United) Window seats first, followed by middle, then aisle seats.

**Figure 1** shows the patterns of the above six boarding strategies. The numbers are group numbers.

## The 7th Approach

Van Landeghem and Beuselinck [2000] include one of the extreme boarding strategies that we raised earlier—seat-by-seat. In their simulation, this strategy performed rather well. Thus, we also include this strategy in our simulation.

To be concrete, we use the following boarding sequence.

> In the first round, one seat from each row is called once; in second round, a second seat of each row is called; etc. In each round, the gate agent always calls from back row to front row. This eliminates aisle delay (delay due

to staying in the aisle), except for when the last passenger in the previous round (having a front seat) has not finished stowing luggage when the first passenger in the next round (having a back seat) enters the plane.

Van Landeghem and Beuselinck claim that this is the best strategy. But they assume that the time for a passenger to pass through an empty seat is the same as to pass through a seat with a person in it. In our model, we distinguish these two times.

In addition, we let window seats be filled first, followed by middle seats, and then aisle seats. Following this strategy, we have no row delay whatsoever.

## The Simulation

- We simulate the seven boarding strategies stated with only small planes, using a Boeing 737.
- We assume variable and parameter values as in **Table 1**.

**Table 1.**

Assumed variable and parameter values.

| Symbol | Value | Symbol | Value | Symbol | Value | Symbol | Value |
|---|---|---|---|---|---|---|---|
| $l$ | 0.7 m | $r$ | 23 | $\bar{w}$ | 1 m | $\sigma_w$ | 0.2 m |
| $\bar{v}$ | 1 m/s | $\sigma_v$ | 0.2 m/s | $\bar{a}_q T_{q,L}$ | 30 s | $\sigma_{a_q T_{q,L}}$ | 10 s |
| $\overline{T}$ | 9 s | $\sigma_T$ | 3 s | $\overline{T}_0$ | 1 s | $\sigma_T$ | 0.2 s |
| $\overline{T}_1$ | 5 s | $\sigma_{T_1}$ | 5 s | $\overline{T}_S$ | 0.5 s | $\sigma_{T_s}$ | 0.1 s |

- We iterate the simulation 100 times, obtaining the sample mean and sample variance of total boarding time and average individual boarding time. **Table 2** and **Figures 2–3** show the results.

**Table 2.**

Simulation results for boarding times for the strategies, in order of increasing average total time.

| Strategy | Total Mean | Total SD | Average Mean | Average SD |
|---|---|---|---|---|
| Seat-by-seat | 15.6 | 0.11 | 1.6 | 0.05 |
| Reverse-pyramid | 22.4 | 0.56 | 2.5 | 0.24 |
| Outside-in | 22.8 | 1.06 | 2.2 | 0.26 |
| Block | 24.7 | 0.35 | 2.6 | 0.15 |
| Random | 25.2 | 0.51 | 2.5 | 0.14 |
| Back-to-front | 26.2 | 0.39 | 2.9 | 0.18 |
| Rotating-zone | 26.9 | 0.83 | 3.1 | 0.22 |

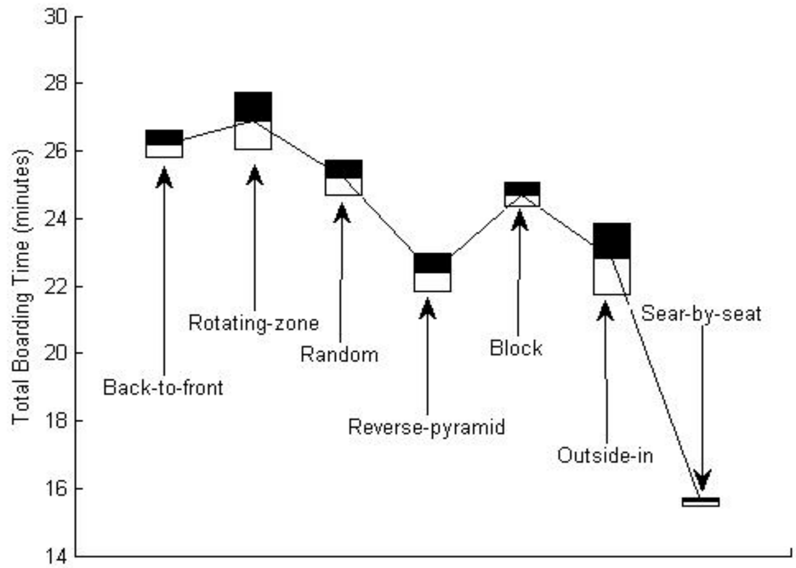


**Figure 2.** Average total boarding times for the strategies.

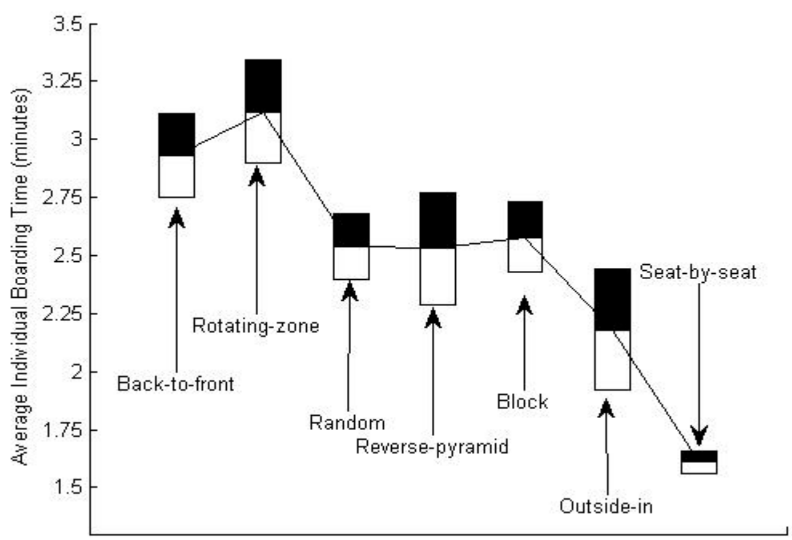


**Figure 3.** Average individual boarding times under the strategies.

### Results Analysis

The results of the above simulation indicate that

- Seat-by-seat is the most efficient boarding strategy. However, its boarding process is too complicated Thus, it is hard to execute in practice, and we eliminate it.
- Reverse-pyramid and outside-in are the next most efficient. Reverse-pyramid is better in having smaller variation in boarding time.

In addition, since reverse-pyramid and outside-in are widely used, they are feasible and satisfactory, hence have the best comprehensive quality.

## More on Reverse-Pyramid

Seat-by-seat and outside-in are two extremes of reverse-pyramid: Seat-by-seat is reverse-pyramid with the most boarding groups, while outside-in is reverse-pyramid with the fewest boarding groups.

This discovery inspires us to study reverse-pyramid further and identify the following properties of a reverse-pyramid-type strategy:

- Each boarding group has approximately the same number of passengers.
- After each group finishes boarding, there must be a passenger sitting behind each passenger seated (except for back-row passengers).
- After each group finishes boarding, the numbers of passengers are decreasing from the window columns to the aisle columns. Moreover, unless all the seats in a column have been occupied, they are strictly decreasing.
- Every passenger is only permitted to board at least one round after the one who will sit abreast and closer to the window.
- The seats for each group are symmetric with respect to the axis of the plane.

We claim that the above five properties are necessary and sufficient conditions for a reverse-pyramid type strategy.

Additionally, we suggest the following three criteria when grouping the seats for a reverse-pyramid type strategy:

- For a single-aisle plane, just follow the above five points.
- For a double-aisle plane, first divide the seats into two halves by the axis of the plane. If the seats in the middle part have an odd number of columns: For the seats lying on the axis, assign every second seat (from the first one) to either half, and the rest to the other half. After that, for either half, group the seats following the above five points.

- The number of seats in each group is at least about 30. Divide all the seats into 4–8 groups.

With these grouping criteria, we can group seats for any size plane, thereby simulating reverse-pyramid for midsize and large planes.

# The Open-Seating Model

## Description

Passengers board in the order of their check-in: the earlier you check-in, the earlier you can board. In addition, since seats are not assigned to passengers in advance, a passenger can choose from the open seats at boarding time. Thus, passengers boarding earlier have a wider range of choices and are more likely to select a satisfactory seat.

Southwest Airlines uses this open-seating policy. Their boarding procedure is described as follows [2007]:

> Customers get assigned to Groups A, B or C on their boarding passes, in the order in which the passenger checks in. Groups are called in alphabetical order, with passengers rushing to occupy the seat of their choice.

## Gains and Losses

### Gains

Compared to assigned-seating strategies, open-seating is more efficient [Finney 2006], for two reasons:

- Passengers in the same group compete with one another for seats, so passengers hurry.
- Most passengers have wide preferences for particular kinds of seats. Therefore, when there is congestion, a passenger will probably choose a seat before the congestion, rather than wait for the aisle to clear.

### Losses

Although minimizing boarding time is our primary goal, the level of satisfaction is also important. Customer reviews of Southwest Airlines reveal that many people do not like open-seating. The main types of dissatisfaction can be categorized as follows.

- People may want to sit next to friends and relatives, but with open-seating this may not happen.

- Some people are used to boarding with seats assigned in advance. They do not want to rush or "compete" with others.
- Some people not distinguished as having "special needs" still have comparatively low capability of "competing" for seats.

# Algorithm

To compare open-seating with assigned-seating strategies, we need to calculate the boarding time for open-seating strategy. With open-seating, however, there may be unpredictable events. For example, two passengers may have conflict when they want to choose the same seat. To propose a systematic algorithm, we must make more assumptions to simplify the behaviors of passengers.

## Assumptions

- We use Southwest's open-seating strategy of three groups (A, B and C). Group A passengers enter the plane before Group B, followed by Group C.
- All passengers prefer the same types of seats (we specify these later).
- All passengers behave rationally and politely. That is, when a seat a passenger prefers is taken by someone else, the passenger finds another seat.
- Once a passenger is seated, the passenger does not move again.
- The moving speed of passengers is faster than in assigned-seating boarding.

## Passenger Preferences

We categorize seats into three classes of preference for each passenger: most preferred, preferred, and not preferred. A passenger first checks for most preferred seats; if there are none, the passenger considers seats in the next class.

For each passenger, every preference class consists of only two types of seats: a certain column (for example, window seats), and/or a certain range of adjacent rows (for example, seats in Row 10–15). A passenger who has both types of preference in a class has a preference between them.

## The Boarding Process for a Passenger

- For a Group A passenger:
  - When the passenger just enters the plane (and thus the aisle), if there is someone stowing luggage at row $i$, the passenger checks whether there are most-preferred seats in front of row $i$, chooses the nearest one if there

is one, and otherwise moves forward to wait just behind the passenger stowing luggage at row $i$.

- When the passenger at row $i$ finishes stowing luggage and clears row $i$, our passenger moves on and repeats the above if there is someone stowing luggage at row $j > i$ and iterates until there is no one in the way.
- The passenger now checks whether there are any most-preferred seats among all the seats from the row where he/she is to the last row, chooses the nearest available one or if none are available checks whether there are preferred seats in this area. If there are, the passenger chooses the nearest one; if not, the passenger choose the nearest empty seat.

- A Group B passenger's behavior is similar, except that the passenger also checks whether there are preferred seats every time after checking for most-preferred seats and not finding one.
- A Group C passenger's behavior is similar, except that the passenger also checks whether there are empty seats every time after checking for preferred" seats and not finding one.

## Simulation

**Table 3** shows the results of our computer simulations with the same parameter values as before, together with results for a combined strategy to be developed in the next section. We do not simulate open-seating for large planes. Since they are for long voyages, a larger proportion of passengers prefer assigned-seating and boarding time has less impact on airline profits.

**Table 3.**
Simulation results for boarding times for the open-seating and reverse-pyramid strategies.

| | Small plane | | | | midsize plane | | | |
|---|---|---|---|---|---|---|---|---|
| | Total | | Average | | Total | | Average | |
| Strategy | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Open-seating | 19.6 | 0.3 | 1.7 | 0.2 | 37.4 | 1.5 | 1.5 | 0.3 |
| Reverse-pyramid | 22.4 | 0.6 | 2.5 | 0.2 | 40.8 | 1.2 | 1.5 | 0.3 |
| Combined | 21.1 | 0.6 | 2.3 | 0.3 | 38.9 | 1.3 | 1.6 | 0.2 |

# A Comprehensive Model

## Motivation

A good boarding strategy should perform well in three aspects: efficiency (short total boarding time), passenger satisfaction (short average individual boarding time), and feasibility.

Although the three representative boarding strategies—reverse-pyramid (outside-in), seat-by-seat, and open-seating—each have advantages, they also have drawbacks:

- Reverse-pyramid / outside-in has a longer boarding time than open-seating.
- Open-seating dissatisfies a notable number of passengers.
- Seat-by-seat is not feasible in practice.

We are then motivated to develop a comprehensive model, with the aim of including all their advantages and eliminating their drawbacks.

# Boarding Strategy

We group the seats as in reverse-pyramid. We divide the groups and their corresponding seats into two categories, with $G_1, \ldots, G_i$ in Category 1 (passengers who board in the manner of open-seating) and $G_{i+1}, \ldots, G_m$ in Category 2 (passengers who board based on assigned-seating).

By devising the boarding strategy in this way, we ensure that

- Passengers who prefer assigned-seating are assured a fixed seat at check-in.
- Passengers who prefer open-seating boarding can select seats at will.
- This will beat the open-seating policy in regard to passenger satisfaction

When the boarding starts:

- Passengers who chose open-seating board first, group by group. We let the number of these groups now be $\min\{3, i\}$. But we first mark out certain seats, which are specially for open seating passengers.
- Then the assigned-seating passengers also board group by group.

# Fixing the Number of Groups

In our new model, the new parameter is $i$, the number of groups for open-seating. The value of $i$ will vary with the number of groups (that reverse-pyramid has initially), model of plane, and ratio of passengers preferring the two boarding manners.

We assume that a proportion $A$ of passengers prefer open-seating and a proportion $(1 - A)$ prefer assigned-seating. Since a fixed optimal grouping scheme of reverse-pyramid is determined by the seat plan of the plane, there is a unique $i_0$ that satisfies

$$\frac{\sum_{j=1}^{i_o} n_j}{n} \leq 1 - A, \qquad \frac{\sum_{j=1}^{i_o+1} n_j}{n} \geq 1 - A,$$

where $n_j$ is the number of passengers in group $j$ and $n$ is the total number of passengers.

The value of $i$ can be set to either $i_0$ or $(i_0 + 1)$; the choice depends on the airline's weighting between efficiency and passengers' satisfaction. If the airline considers efficiency more important, it should let more passengers board according to open-seating and set $i = i_0 + 1$; if the airline considers passenger satisfaction more important, it should let more passengers board with assigned seats and set $i = i_0$.

When $i = 0$ or $i = 1$, we do not provide for open-seating, for which the value of $A$ is supposed to be large (for example, 85%). The size of a plane is usually related to the length of the trip (small planes for short trips, bigger planes for longer trips). Usually, the longer the trip, the more passengers prefer assigned seating and the less impact of boarding time on profits. Hence, for larger planes, the portion of seats for open-seating is smaller.

## Advantages

- Based on the simulation results, reverse-pyramid-type strategies have the highest efficiency in the assigned-seating model. In addition, the grouping in reverse-pyramid boarding strategy is good because
  - It has comparatively more groups. This lets us have more flexibility to arrange the seats for the two boarding types.
  - If the value of $i$ does not go to extremes, each boarding type will have seats of all features (against the window, beside the aisle, in the front, in the back, next to each other, and so on). This enhances the range of choices for passengers from both boarding types.
- This boarding strategy considers preferences of passengers, so it is quite likely to have higher customer satisfaction.
- Its boarding process is open-seating passengers first, followed by passengers boarding in reverse-pyramid. This process actually takes into account possible confusions during open-seating passengers' boarding and prevents most passengers from witnessing the confusions.
- Both boarding manners are feasible and are used, so we infer that the new combined strategy too is feasible.

# Testing the New Model

## Comparison

**Table 3** earlier also displays results for the combined strategy, which has shorter total boarding time and shorter average individual boarding time than reverse-pyramid but is longer on both counts than open-seating.

Therefore, we suggest:

- For a small plane (85–210 passengers), use open-seating or the combined strategy.
- For a midsize plane (210–330 passengers), use the combined strategy.
- For a large plane (450–800 passengers), results not displayed show little difference between reverse-pyramid and the combined strategy (both take over an hour).

# Sensitivity Analysis

We repeated the simulation many times, using different values for the parameters. The resulting data shows that, no matter which strategies we use, the following two input parameters have the biggest impact on boarding time:

- $\overline{T}$, the expected time difference between two adjacent passengers' entry to the plane.
- $\bar{a}$, the expected value of the coefficient random variable that is relevant to the size, weight, and shape of the passengers' luggage.

We give the following suggestions for decreasing total boarding time:

- For small planes, to the extent that it is bearable for passengers, lower the limits for carry-on luggage size and weight.
- For midsize and large planes, have more training for the gate agents or more gate agents. Since large planes are usually for long flights, passengers often need more luggage, so it is not proper to set the luggage limit too low.

# Deplaning

## An Ideal Model

Total deplaning time is the time from the first passenger standing up to the last passenger leaving the plane.

We assume:

- The speed of all passengers moving in the aisle when deplaning is constant.
- The time that all passengers spend in picking luggage is constant.

The *deplaning queue* is an imaginary queue that is formed if we join all passengers in a line in the order that they deplane, and if the passengers who have left the plane would continue moving forward in the queue.

We now propose our ideal deplaning strategy:

- Passengers in aisle seats on one side of the aisle (say all the C seats) as a whole stand up at the same time, which is the beginning of the deplaning process. They take their luggage and leave the plane as a whole.
- As soon as the last passenger (23C) leaves the 23rd row, the passenger in seat 23D moves into the aisle, occupies it in no time, and takes luggage—but does *not* (yet) move forward.
- As soon as the 23C passenger passes row 22, the 22D passenger moves into the aisle, occupies it in no time, and takes luggage—but does *not* (yet) move forward.
- The passengers in the D seats behave in the same manner, until the 1D passenger is in the aisle with luggage. Then all the D-seat passengers move to leave the plane as a whole.
- Thereafter, all the B, E, A, and F passengers repeat what the D passenger did.
- When the last passenger (F23) leaves the plane, the deplaning ends.

Using the above strategy, total deplaning time is minimized. The argument is as follows.

> There are only five segments of unoccupied space in the deplaning queue, and all appear in front of the row 1 passengers. Every passenger has to spend time in the aisle taking luggage. When a row 1 passenger is taking luggage, the passenger who deplanes before that passenger is moving in the deplaning queue. Thus, these five segments of unoccupied space cannot be eliminated, no matter what deplaning strategy we use.

We then say that all the passengers are divided into six "rounds" by those five segments of unoccupied space.

## Reality

The airlines have little control of the behavior of passengers deplaning, so any detailed strategy would be very difficult to implement. Therefore, instead, we now propose a concise criterion for passengers to deplane.

> We use again the concept of "rounds," but with a small modification: Each round has 23 passengers, coming from all the 23 rows; for each row, the passenger stepping out is either of the ones on both sides who are nearest to the aisle.

In practice, the crew can announce the criterion before passengers deplane. Even with occasional violations, we do better.

# Conclusion

Open-seating beats the existing assigned-seating strategies in total boarding time but it loses in terms of passenger satisfaction. Seat-by-seat wins in both aspects; but it is not feasible in reality, thus useless.

We combine opening-seating with the most efficient feasible assigned-seating strategy, namely, reverse-pyramid (outside-in). We expect the combined strategy to to be feasible and good on of our criteria.

As for deplaning, airlines do not have as much control as they do in boarding, so a complex plan cannot be executed well. Thus, it's better have a simple procedure than a detailed but unfeasible one.

# Strengths and Weaknesses

## Reverse-Pyramid Boarding Strategy

### Strengths

- The most efficient of the prevailing assigned-seating strategies.
- Methodical, so there will be little confusion during boarding.
- Passengers can probably sit next to friends and relatives as they wish.

### Weaknesses

- Not as efficient as open-seating.
- Requires more staff to execute and control boarding.

## Open-Seating Boarding Strategy

### Strengths

- Higher efficiency than all the assigned-seating boarding strategies.
- For a few people, especially the young, it is attractive.
- Looks simple and requires less staffing to execute.

### Weaknesses

- Dissatisfaction of passengers is the vital drawback.

## Combined Boarding Strategy

### Strengths

- More efficient than traditional assigned-seating boarding strategies.
- Meets the needs of different types of passengers, thus probably making the airline more satisfactory and popular.

### Weaknesses

- It might be tedious for airlines to set the portions, and surveys may be needed.

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