Best Boarding Uses Buffers

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Summary

By constructing a mathematical model of human behavior, we find:

- **Back-to-front block loading is the least efficient boarding method.** As passengers enter the aircraft in groups, aisle congestion becomes greatest at the front of the plane, consequently increasing the time required for the next group to enter and take their seats. Aisle congestion in this case is primarily attributed to the time for a passenger to navigate the aisle and reach the assigned seat if obstructed by another passenger sitting in the same row.

- **Small planes and large planes exhibit minimal turnaround times.** Small planes have a single aisle but few passengers, hence little congestion. In large planes, multiple aisles and decks offset the congestion found in single-aisle midsize planes; a large plane can be modeled as several small planes.

- **Boarding strategies are optimized when 10% of the passengers are late.** Fewer passengers enter initially, so there is less congestion. When passengers enter late, congestion that would otherwise have occurred is averted.

Our first observation concurs with researchers who suggest abandoning back-to-front boarding in favor of more-elaborate schemes [Finney 2006; van den Briel et al. 2004; Ferrari and Nagel 2005]; however, these new models make erroneous assumptions about human behavior. A comprehensive scheme must include the time to navigate a congested aisle, stow luggage, and maneuver through a filled row if necessary. We recommend the following:

- **Abandon back-to-front block boarding and consider alternatives.** We suggest a hybrid group-boarding method utilizing a rotating seating arrange-

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ment that incorporates back-to-front and window-to-aisle seating. This approach decreases congestion that otherwise might accumulate near the front of the airplane, by loading a first group of passengers into rear seating while another group is consecutively loading into the front seats. This trend is carried out until the last group is seated in the center of the aircraft.

- **Incorporate a second aisle into midsize aircraft.** Midsized aircraft tend to display the worst boarding times due to the absence of a second aisle. A second aisle would ease congestion and cut turnaround time nearly in half.
- **Reduce carry-on luggage.** Reducing the amount of carry on luggage greatly decreases aisle congestion greatly decreases.
- **Queue passengers into lines prior to gangway entry.** Increased order greatly reduces aisle congestion.

Introduction

It is common to board an aircraft in zones or groups. The most-used method is boarding blocks of seats, from the rear moving toward the front. This method is more efficient than boarding the entire plane at once but is one of the least efficient schemes that we tested. Several factors have to be taken into consideration for determining boarding times; passengers entering the plane are assumed to be unsorted within their boarding groups, and not all passengers arrive on time. Our model that incorporates all these factors and provides surprising and consistent results.

Our computer simulation can evaluate various boarding schemes on aircraft of varying sizes. It has factors for late passengers and will search for worst- and best-case boarding times based on randomly-arranged passengers. The most efficient method that we found moves passengers onto the plane from window to aisle, back to front, implementing rotation buffers. This method even allows for some passengers to be late without severely affecting efficiency. We report results for boarding time, tolerance to passenger arrival, and boarding time predictability for several boarding schemes and aircraft.

Boarding Strategies and Terminology

We define boarding strategies by rows, columns, and groups.

Block boarding: Each block is a group and a block consists of a number of rows. Typically, groups of passengers are seated in blocks sequentially from the back to the front.

Buffering: Buffering places empty seats between sequentially seating groups, so that congestion and delay of the first group does not interfere with seating the second group. For example, a plan may seat block 1 consisting of rows 30–25 and then sequentially block 2 of rows 22–17. The aisle by rows 23 and 24 will be filled temporarily by busy passengers from block 1 and will not interfere with block-2 passengers. Rows 23 and 24 will be seated later.

Column Seating: Column seats by columns instead of by rows. This strategy is typically implemented from the window to the aisle to minimize row congestion.

Reverse-Pyramid Scheme: The reverse-pyramid scheme seats passengers in V-shaped groups starting back in the aisle and propagating forward to a window. This method minimizes row congestion while maximizing group size.

Assumptions

Logistical Assumptions

We assume that all planes are entered exclusively from the front and that passengers sit one to a seat.

Our model does not account for the time that it takes a person to seat themselves in an empty row or a seat unobstructed by another passenger. This is because the moment that the passenger leaves the aisle, they can no longer add to aisle congestion and the total seating time for the group.

According to the U.S. Department of Transportation [2007], airplanes fly at 79% capacity on average. With this information, we make three assumptions:

- Since passengers are randomly seated, the empty seats are randomly dispersed, and thus there is no need to reseat passengers for balance purposes.
- Boarding times are based on 100% capacity, but group size and buffers can be adjusted to minimize boarding times are based on expected capacities.
- All two-level airplanes are boarded with two-level jetways and board both levels simultaneously.

Large two-aisle planes with possibly two decks have similar configurations to several small airplanes; hence the strategies for small planes will have comparable efficiencies for large planes.

We assume that the time required to seat those with special needs is nearly constant. Although "9.7% . . . of men and women, aged 16–64 report a sensory, physical, mental, or self-care disability in the United States" [Employment and Disability Institute 2007], the percentage among travelers will be lower, due to monetary limits and ability to travel. A midsize plane with capacity 300 running at 79% capacity would carry 237 passengers, of whom less than 9.7%—perhaps

15—need special assistance. We assume that seating strategies for special-needs groups are unnecessary due to their small size.

We also recognize that column boarding is efficient but may separate parties traveling together, costing the airline in terms of customer inconvenience. The goal of column seating is to minimize row congestion. We contend that allowing parties to board the airplane together, even though this may deviate from the seating plan, would not degrade the advantage. Parties flying together will enter a row in order, maintaining minimal row congestion.

We assume that as the overhead compartments fill, stowing luggage becomes increasingly difficult. We also assume that each passenger has the same amount of carry-on luggage requiring the same volume. To this effect, the time for a passenger to stow luggage depends only on the number of people seated in the row and the number of luggage-volume units already taken up.

Behavioral Assumptions

A fundamental assumption is that passengers are willing to bypass localized aisle congestion, resulting in a time cost. But when aisle congestion becomes large-scale, passengers become averse to bypassing larger numbers of people. This assumption of human behavior is accounted for by disallowing groups of passengers to bypass other groups who are blocking the way to their seats, but allowing passengers in the same group to pass each other in the aisle. Our model of localized passing predicts seating times better than popular models that assume that passengers do not pass others in the aisle.

All constants have been estimated to the best of our ability but would require experimental determination. Due to the nature of our passenger time model, discrepancies between our constants and actual values will have little effect on the relative efficiencies of the strategies that we investigate.

We assume that every passenger walks with a constant speed, since the speed of a line is dictated by the slowest passenger.

We assume that when business- and first-class passengers seat themselves, they have a greater average passenger speed and smaller constants corresponding to bypassing others in the aisle, stowing luggage, and traversing occupied seats. The reasons are that business- and first-class aisles are wider, first-class passengers carry less luggage because their trips tend to be shorter, and individual seating areas in business- and first-class are about 4.5 m^3 as opposed to 1.2 m^3 in coach [Ferrari and Nagel 2005].

Methods

We devised a highly dynamic object-oriented model in Java, which can import group assignments from a text file. We collected data from the simulation from several different configurations and aircraft sizes.

Group Boarding Time Model

We assume that the marginal time increase of a group to be seated with respect to each additional person is:

$$t(p) = C_1\tilde{p} + C_2\alpha + C_3\beta + C_4\gamma,$$

where

- p is the number of people who need to cross in the aisle,
- α is the number of people who need to move to reach the seat from the aisle,
- β is the amount of luggage stored in the overhead compartment, and
- γ is the number of rows that a passenger must traverse.

We let w and l be the width and length of the aircraft. Conceiving of our model as a continuous model, We have

$$t(\bar{p}) = \frac{dt}{dp} = C_1\bar{p} + C_2\bar{\alpha} + C_3\bar{\beta} + C_4\bar{\gamma},$$

where $\bar{p}$ is linear and $\bar{\alpha}, \bar{\beta}, \bar{\gamma}$ are constant. Integrating both sides, we find that time per group $T(p)$ is

$$T(p) = \frac{C_1}{2}\,\bar{p}^2 + C_2\bar{\alpha}\bar{p} + C_3\bar{\beta}\bar{p} + C_4\bar{\gamma}\bar{p}.$$

Because our model is discrete and $\tilde{p}, \alpha, \beta, \gamma$ can fluctuate randomly depending on the arrangement of passengers within the group, dt/dp cannot be represented continuously in an accurate manner.

However, by taking a Riemann sum, $T(p)$ can be found as

$$T(p) = \sum_{n=0}^{p} (C_1\tilde{p} + C_2\alpha + C_3\beta + C_4\gamma)\Delta p,$$

where $\Delta p = 1$ person.

Simulation Algorithm

Our simulation models boarding as a queue while mathematically modeling human behavior. The dynamic simulation can compute aircraft boarding times for different grouping configurations with no modification to the code. The model also can loop through several different configurations and can iterate each configuration to acquire an average seating time with error bounds. Because the problem assumes that passengers are not arranged within the group, passengers are randomly shuffled in the groups and each run yields slightly different results.

Running the Model

Parameters are the number of rows, number of seats per row, location of aisle, number of groups, group configuration file, and number of iterations to average the solution (in most cases, 1,000).

Late Passengers

We assume that a specified percentage of randomly-selected passengers arrive late.

Group Boarding Time

The total time to board aircraft is related the time to board each group, which in turn is based on the time to board each individual within that group and on interactions between consecutive boarding groups. There are two cases for which we make provision:

- (the more common case) A *waiting condition* occurs when a group boarding the plane is directly adjacent or farther back in the aircraft than the previous boarded group. In this case, the second group waits until the previous group is seated. The total time for aircraft boarding will have the previous group seating time added minus the time required for the latter group to approach the previous group.
- The other condition occurs when there is a gap between two consecutive boarding groups. This is known as a *buffer condition*, and the time added to the total time is the entering time of the previous group.

The two exceptions are the first group and last group. The first group has no interactions with any another group initially and will not contribute to the total time. The time for the first group will factor in after the second group is determined. The last group interaction is determined using one of the two methods and then the time for the final group is added to the total time.

Results

After considering the implementation of buffering zones, block boarding methods, and variations regarding column-boarding techniques, we were able to use our model to represent the most efficient boarding schemes. When cabin configurations are kept constant between different sized aircraft, different boarding schemes are better suited for different sizes of aircraft. We show the results for midsize aircraft in **Figure 1**.

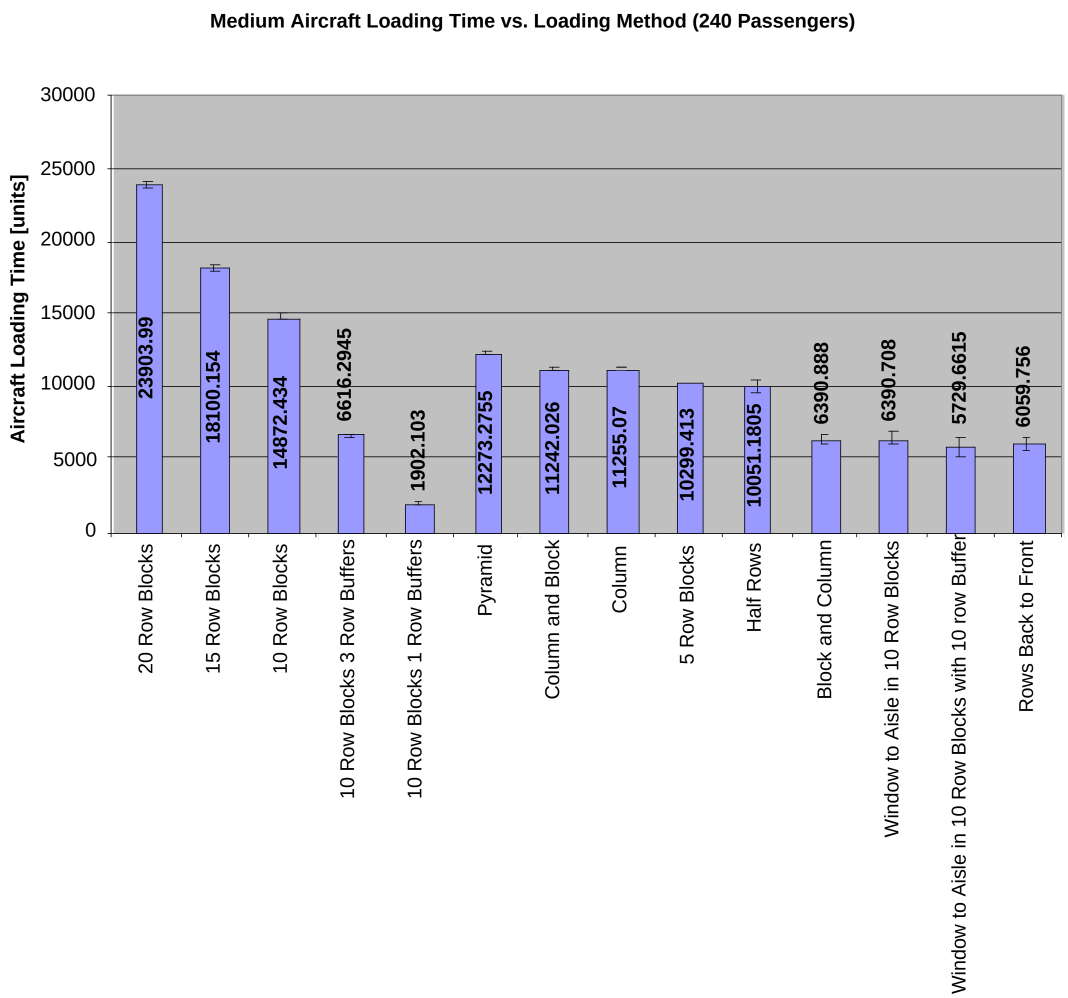

Figure 1. Boarding times for various boarding methods, for a 240-passenger plane.

Back-to-Front Block Boarding

A group of passengers entering the aircraft in four groups takes twice as long as a boarding party of the same size with a five-row buffer zone. As passengers board the airplane, congestion from passengers heading toward the back of the airplane and stowing luggage slows the advance of entering passengers. Due to our assumption that individuals passing in the aisle require 1.5 time steps to maneuver past a passenger, a consequently higher group seating time develops. This prolonged seating period prevents the next group from entering, since members from different groups cannot interfere with one another. With a buffer zone, congestion is reduced: As the group advances towards the rear of the airplane and proceeds to take seats, the second group enters, leaving a five-row buffer zone, allowing the second group to get seated as well without any additional interference from the first group, consequently reducing the overall boarding time.

Half-Block Boarding

A variation back-to-front is the half-block boarding method, which uses the aisle to divide the passengers into more groups. Because it is more organized, it is nearly twice as efficient as the traditional block boarding system.

Column Boarding

Column boarding is very inefficient if the number of columns is the maximum number of groups present in the plane. Column-filling with an unbuffered group-boarding scheme yields only marginally better results. Only when columns are broken into smaller groups themselves are the advantages of column-filling evident. The implementation of column-filling completely eliminates aisle congestion caused by seat crossovers. The incorporation of segmented columns into our model decreases boarding time because increasing the number of groups enhances the order of the scheme.

Reverse-Pyramid

A hybrid system based on a back-to-front rotating column arrangement, seating passengers from the window to aisle seats, is dubbed the reverse-pyramid. A simulation based on this scheme shows only marginal increases in boarding time compared to block boarding from back to front. The fundamental principle behind reverse-pyramid is reducing aisle congestion by permitting groups to enter in staggered column configurations to minimize seat crossings. A significant drawback, however, is that for it to be most effective, a column that is sent in must be further sectioned. Most airlines use a six-group configuration that most resembles a "V" as the airplane begins to fill up. So if a more robust model is desired, further complication is needed in properly dividing the entering segments of the reverse pyramid.

Buffer Zone Implementation

Schemes that incorporate a buffer are sensitive to most variables. Buffer systems are successful in small and midsize aircraft, because more travelers can be boarded without interfering with other groups; however, the introduction of late arrivals into a buffer system causes the scheme to fail.

Back-to-Front Boarding

This most-common strategy is ironically the most undesirable. As passengers enter the plane, congestion immediately builds from back to front as passengers in the back must pass others in the aisles, wait to stow luggage, and maneuver past other passengers to access a seat.

Hybrid Boarding Methods

The most effective boarding scheme is one that encourages the simultaneous boarding of passengers from window to aisle, and from back to front of the aircraft, while incorporating a buffer. Due to the ordered nature of this scheme, the buffer zone is affected very little by late passengers. Our hybrid scheme has virtually no aisle congestion due to seat crossovers and luggage stowage, because passengers file in from the windows toward the aisle and from back to front. Late passengers are considered as an independent group unto their own, hence do not interfere with groups currently boarding.

Deboarding

Since passengers are already in an ordered system, aircraft deboarding lends itself well to random passenger exiting. This assumption can be based on the fact that there will be no congestion caused by persons crossing other passengers within the same row, because everyone has the same incentive to deboard the airplane. Our results show that a more ordered system boards the fastest; therefore the most ordered system will deboard in the most efficient manner.

Tardiness

Buffer systems are sensitive to tardiness, since each successive late passenger tends to increase the boarding time. Block boarding methods actually experience an increase in efficiency when late passengers board! This results from an absence of congestion that would otherwise be present; however, block boarding methods are the least efficient methods in general. Any improvement on the block boarding scheme is merely making an inefficient system slightly more efficient, but is still not preferable to other methods available.

Sensitivity

Random Passenger Order within Groups

There is a weak inverse power relation between the number of groups and the difference between the maximum and minimum boarding times compared to the average boarding time. This relationship can be realized intuitively: As the number of groups increases, the randomness decreases until the number of groups equals the number of passengers. In that case, there is no randomness; every passenger is sent to their seat, and every boarding simulation will provide the same result. To this end, strategies with more groups have greater predictability.

Taking the number of groups for each strategy into consideration, random entry within groups affected our strategies in the following ways:

- **Block methods** have a minimum number of groups to board; thus, we show that the current method presently used by airlines is unpredictable.
- **Column-seating methods** have minimal group numbers and, when taking group number into account, high predictability. The goal of column-seating is to minimize time cost by minimizing row congestion resulting from passengers randomly entering the rows out of order. In other words, column-seating is designed to be resistant to random entry order.
- **Buffering systems** are by far the most sensitive to random passenger order. This is no surprise, because the benefit of the buffer system is maximized when the overflow from a leading group fills up the exact number of rows to where the following group seating begins. As random amounts of passenger bypassing increases or decreases, congestion due to the leading group increases or decreases as well, resulting in more or less overflow, and thus decreasing the efficiency.
- **Pyramid schemes** show predictability greater than block seating but less than column-seating. This may be due to the column-oriented advantages shared with column-seating, but decreased due to the increase in group size.

Airplane Configurations

Typically, efficient models are efficient despite plane configuration. Differences in relative efficiencies are noticeable but generally negligible, with some exceptions.

The primary exception is buffer strategies. Buffer-strategy effectiveness depends on congestion overflow into the aisle, which in turn depends on plane configuration. Column-seating methods also are a surprising exception. In one simulation of boarding a small plane of 208 passengers, column-boarding performed the worst of any strategy. It also performed poorly in a midsize plane of 300 passengers, whereas it performed well in an airplane of only 240 passengers. These results are as a direct result of plane configuration; while uncertainties in column-boarding strategies are noticeable, they are not enough to influence this trend based on average times in 1,000 boarding trials.

Late Passengers

Inevitably, some passengers arrive late. We assume that all late passengers are called to board as a final group to be seated without a strategy. With this in mind, we can analyze the sensitivity of different strategies to the number of late passengers. Late passengers have the following effects (see **Figure 2**):

- **Block methods** become more efficient as passengers arrive late. As block size increases, block methods become maximally efficient at a higher rate of late passengers. The following example will illustrate the inefficiencies of block methods and the sheer magnitude that late passengers have on time efficiency. In midsize aircraft (240 passengers), blocks of 10 to 20 rows have minimal boarding times when late passenger percentages are 21% to 35%. The boarding time of every block method tested decreases as the number of late passengers increased from zero. Not only does the boarding time decrease, but some block configurations became as much as 15% faster at late percentages resulting in maximum efficiencies.

- **Column-seating** becomes slightly more efficient as the rate of late passengers increased but column-seating is resistant to late arrivals.

- **Buffering methods** are the most susceptible to late passengers; they decrease utilization of the buffer rows. Adding rows that are not being seated or used to store overflow decreases efficiency. The efficiency of buffer systems quickly decreases when parameters change.

- **Pyramid schemes** act much like column-seating with respect to late passengers. This is no surprise, because pyramid schemes are a form or column-seating.

Buffer Size

The buffer system is the most sensitive of all the seating strategies. Counterintuitively, it can be one of the most efficient methods if the buffer size is chosen properly. If the buffer is too small, the following group waits. If the buffer is too big, the rows between the last overflow passenger and the first passenger of the following group are not utilized. Rows not utilized for seating or storing overflow decrease efficiency. Because buffer size depends on the overflow of a leading group due to congestion, and the size of the overflow depends on plane configuration and flight capacity, efficiencies of buffer systems are extraordinarily delicate.

Vacant Seats

The percentage of vacant seats has little effect on relative strategy efficiencies.

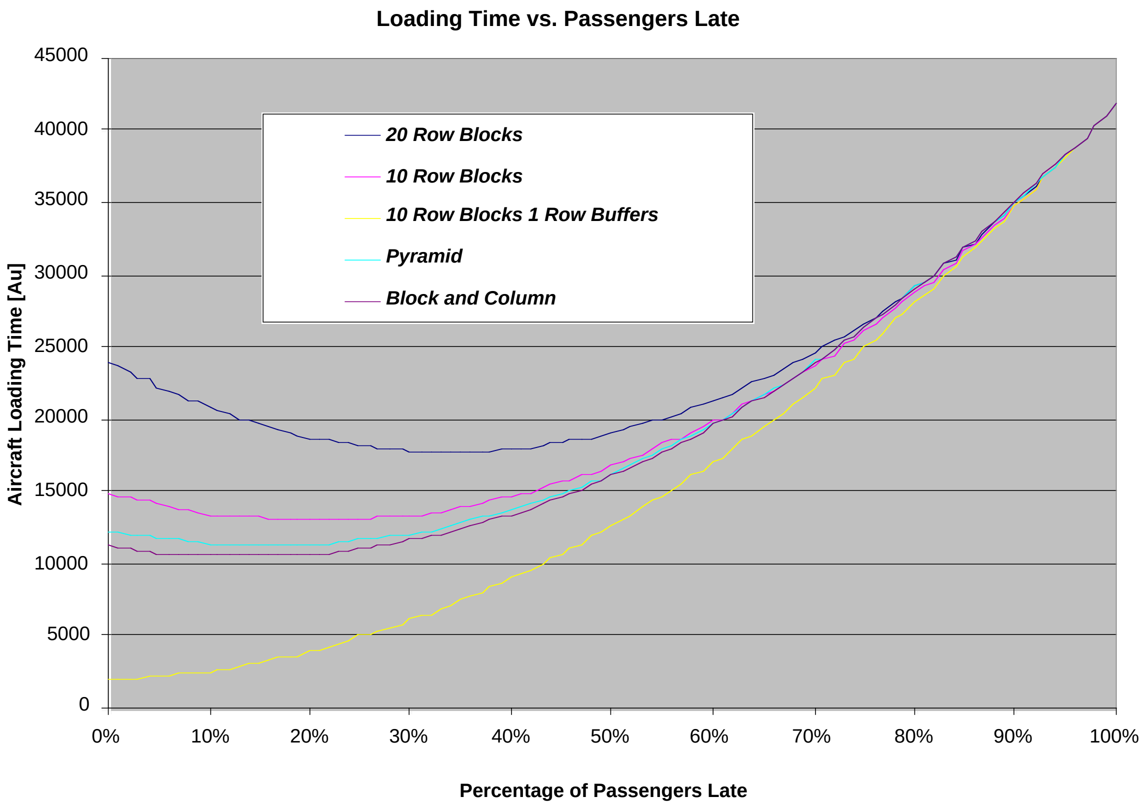

Figure 2. Effect of late passengers on boarding time, for various boarding methods.

Conclusion

Future Work

We suspect that the aisle congestion if groups of passengers were allowed to pass each other can be modeled using a constant times the number of people in the group divided by the number of row the group spans.

Realistically, passengers may not appreciate column-seating because it separates parties. Further complexity can be added to our model to allow parties to sit together. To this end, we could test if airlines truly must trade customer convenience for the benefits of column-seating. We strongly suspect that allowing parties to board together does not undermine the benefits of column-seating.

Due to the sensitivity but great potential of buffer systems, quickly applicable algorithms for determining optimal buffer zones would be valuable. These algorithms would depend on group size, expected tardiness, expected carrying capacity, and plane configuration.

Additionally, it would be useful to investigate the effects of adding preliminary order to passengers waiting in the terminal. Using a calling system (such as colored signs) to add preliminary order in the terminal could allow for greater order entering the plane without customer confusion and inconvenience.

Closing Remarks

Not only are presently-employed block strategies inefficient, but they are usually the *most* inefficient strategies. They lack order to minimize row congestion, and they facilitate accumulation of aisle congestion.

The best method for boarding airplanes is to board primarily from window to aisle, secondarily from back to front, and furthermore use a buffer system. We assume that preliminary order can be applied to passenger groups still in the terminal to alleviate the large number of groups required to employ our strategy. Our method is resilient to random entry within groups, thus is predictable compared to other methods. We assume that predictability is heavily valued by airlines and recommend our strategy for that reason as well as maximum time efficiency.

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