Efficiently Boarding an Airplane: A Modeling Based Approach

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Abstract

The airline boarding problem involves minimizing the time it takes to load passengers onto an airplane. Reduced boarding time can allow airlines to operate more flights and have more profitable day-to-day operations. Various academic and industrial researchers have developed improved boarding schemes over the traditional method of boarding the airplane from back to front. While there are multiple studies considering this problem, few studies incorporate a model for time and spatial location involved in stowing luggage in overhead bins. We investigate luggage interferences, which occur when a passenger is unable to stow baggage at their seat due to a full overhead bin. A model is developed for the expected number of luggage interferences for a plane of arbitrary size. We also investigate how various boarding strategies perform differently in the presence of a spatial model for luggage.
1 Introduction

The problem of efficiently boarding an airplane is the subject of multiple academic and industrial studies. Aviation is a multi-billion dollar industry, and improvements that allow flights to have a quicker turnaround time can result in large economic benefits [1]. The loading and unloading of passengers is a central component of aircraft ground time. Decreasing the time spent boarding can reduce total ground time if flights can then be scheduled closer together [2]. Improved turnaround time can result in higher profits for airlines and more flight selections for passengers. Airline boarding can be modified by methods that control when certain passengers board. A typical approach is through assigning each passenger to a boarding group, allowing passengers with the same boarding group to board at the same time. Speeding up boarding time involves efficiently assigning passengers to boarding groups to reduce total boarding time.

A variety of methods have been used to model passengers boarding an airplane. One simplistic method models passengers as discrete particles who fill into seats according to a measure of the seats desirability [3]. Another study looks at boarding time using a simplified model with one passenger per row [4]. However, because most airlines use pre-assigned seating with more than one passenger per row, these studies reveal an interesting mathematical result as opposed to a practical solution. Much of the current work on finding efficient boarding arrangements is done using optimization methods and computer simulations.

One approach to optimizing the boarding assignment process is to minimize the expected number of seat and aisle interferences. A seat interference occurs when a passenger must get up from his seat to allow another passenger to sit down closer to the window. An aisle interference occurs when a passenger is blocked from moving forward in the aisle by another passenger stowing his possessions. Either type of interference tends to halt passengers in the aisle.

Multiple studies attempt to discover the most efficient boarding scheme by minimizing expected interferences during boarding and analyzing airlines existing boarding schemes. One scheme used by several airlines is to board passengers back-to-front [5]. However, this actually takes more time and causes more interferences than simply letting passengers board randomly [6]. Another boarding scheme involves boarding the plane from the outside-in; passengers with window seats board first, followed by those in the middle, and finally passengers seated in the aisle. Studies show that this method is even quicker than random boarding. Despite its speed and simplicity, researchers continue to search for a more efficient boarding methods. A study at Arizona State University in conjunction with America West Airlines approached the optimization problem by minimizing expected interferences [1]. This minimization falls under the complexity class of NP-hard, but researchers were able to use a constrained optimization method to create an optimal boarding arrangement known as Reverse Pyramid. The Reverse Pyramid boarding method is a hybrid of the outside-in and back-to-front boarding strategies, which minimizes expected seat and aisle interferences.

Computer simulations are useful in developing boarding strategies and testing existing methods. Simulations allow the testing of a boarding strategy with minimal expense. The international aircraft manufacturer Boeing developed a discrete event time simulator to evaluate boarding time on its aircraft [7]. Another simulation used a Markov Chain Monte Carlo algorithm and found the most efficient way to board is to line passengers up in a certain manner to maximize the number who can stow their luggage at a given time [8]. However, this study did not take seat interferences into account, and assumes that every passenger is able to stow their luggage in the overhead bin directly above their seat.

In modeling airline boarding, it is important to consider luggage that passengers bring on board, which must be stowed in the overhead bins. Several studies incorporate a model for luggage
stowing time. One assumes the time to stow baggage increases linearly based on the number of bags previously stowed [9]. Another considers the time it takes passengers to stow their luggage in bins, but does not consider that bins have finite capacity [8]. Although some studies do take into account the increasing time to stow baggage as bins fill up, their methods for monitoring the location of stowed baggage are either proprietary or not explicitly stated, and they do not seem to take into account a fully spatial model for luggage [7][10]. For example, there are no explicitly stated assumptions about what happens when a passenger needs to move around the cabin to find an empty slot for their bag. Passengers unable to find bin space at their seat must move around the cabin and will then impede the boarding of other passengers. We propose a spatial model for luggage as an area that has not been fully explored.

While a large body of research has been conducted to model airline boarding, more work is needed to investigate the stowing of overhead luggage. Upon encountering a full bin, a passenger with excess luggage must move around the cabin to find an open spot. This will be considered a luggage interference, and is a type of interference distinct from seat and aisle interferences. While luggage interferences will typically not occur until late in the boarding process when the overhead bins fill up, luggage interferences affect various boarding schemes differently.

2 Background

2.1 Airplane Model

We approach the problem of efficiently boarding an Airbus A320. The A320 is a typical airplane for short to medium length flights with over 3,000 aircraft currently in service [11]. While the aircraft can be set up in various ways, Airbus recommends a carrying capacity between 150 and 180 passengers. It carries about 150 passengers when set up with two cabins. This is typical for airline usage, with a separate cabin designated for first class passengers. The main cabin contains a single aisle with 6 seats per row. These seats can be classified by location as window, middle, and aisle. Considering only the main cabin, the recommended set-up for the A320 consists of 23 rows. We simplify our model by removing the first class cabin and setting up the cabin with 24 rows. Only considering the main cabin is justified by the standard practice of boarding all first class passengers first into a separate designated cabin. These passengers will always board first, and should not affect the various boarding schemes. We use 24 rows to simplify the luggage model, described in Section 2.3.

2.2 Simulation

To simulate the boarding process, we constructed a simulator using MATLAB. Passenger boarding of the airplane is modeled with discrete time steps. Each action that a passenger can take, such as walking forward one row in the aisle or stowing a bag, takes one time step. Every passenger in the aisle will move at each time step as long as they are not blocked by a passenger ahead of them. We are not concerned with estimating the actual time to board the aircraft, but rather investigate the relative difference in time between various strategies.

The simulation considers passengers moving about the aisle towards their seats and interacting with other passengers in the plane. We assume each passenger takes up the length of a row, so there can be as many passengers in the aisle as there are rows of seats. In order to get to their seats, passengers must walk down the aisle to the spot directly adjacent to their row, and then sit down. Passengers can only move forward if there is an open spot ahead of them. When one passenger is blocked from moving forward, all passengers directly behind him/her are blocked as
well, and additional passengers can be affected as a queue begins to form. Passengers with luggage must also stow their bags prior to taking a seat. Passengers with bags try to find space near their seat to stow, and those without bags move towards their seat if able. This passenger behavior is summarized in Figure 1.

A simulation ends when all passengers are seated in their seats. We recorded the number of time steps that each simulation takes to board completely. We ran 1,000 simulations of each boarding strategy. Using computer simulations is advantageous over experimental methods, as it would be expensive to run 1,000 trials using human participants since they would expect a free lunch out of the whole business.

![Figure 1: Flow-chart of passenger behavior. Passengers first move about the plane to attempt to stow any luggage they might have, and then proceed (if able) to their seats.](image)

In order to differentiate our simulation engine from other studies, we introduce an explicit spatial model for overhead luggage. We keep track of where bags are located during the boarding process, in order to measure the impact of luggage interferences during the boarding process.

### 2.3 Luggage Spatial Model

We create our model using the concept of distinct overhead bins. Modern carrier planes typically have overhead bins on either side of the aisle throughout the length of the aircraft. These were originally called "hat racks", and designed for passengers to place their hats and coats, but have since expanded in popularity. Currently, overhead bins are used by passengers to stow luggage.
that is too large to fit under their seats. Bins in use today are not standardized, but typically range in length from 15-88 inches \[12\]. For our model A320, we assume that bins are uniform size throughout the aircraft, and have a capacity of 4 bags per bin. As bins are mirrored across the aisle, this gives a capacity of 8 bags when considering opposite bins. We used these assumptions for the model, and while they might not fit the exact physical specifications of a specific aircraft, they are easy to change if the exact parameters are known. For example, an airline would know the exact dimensions of bins, their locations, and an estimate for the number of pieces of luggage that each can fit.

Our approach to spatially model luggage placement is to keep track of bin space available throughout the plane. As bags fill up, passengers may have to walk about the plane to find an open spot for their bags. We introduce the idea of a bin section to model this behavior.

**Definition 2.1** A *bin section* is a pair of overhead bins on either side of the aisle directly above a set number of rows. Passengers within the bin section can stow luggage right from their location if space is available (Figure 2).

A bin section has the capacity for two times the capacity of an individual bin. If there is space for luggage within a bin section, any passenger adjacent to the rows of that bin section may stow without moving from their spot. This is realistic because it is possible to stow luggage in a small radius around one’s person, the dimensions of which are determined by the height of the bin and the length of one’s arms. We approximate this by means of a bin section, the fixed space in which one can place luggage without moving about the aisle.

For the Airbus A320, we assume that a bin section covers the space above three rows of seats. With our model, there are 8 sections of overhead bins spanning from front to rear. With a capacity of 8 pieces of luggage per section, this leaves space for 64 bags among 120 passengers. We use the concept of bin sections to track where each individual passenger can stow their luggage. If the bin at their seat is full, the passenger must move around to find a free spot, which disrupts the flow of passengers, causing a luggage interference.

Ideally in the case of boarding the A320, there will be 8 passengers with bags in each section of overhead bins. However, it is more likely that there will be bin sections that have more than 8 passengers which causes a luggage interference. We are interested in the number of passengers with bags who arrive in a section that is already full.
2.4 Aisle Behavior

To model passenger behavior in the case of a luggage interference, we make assumptions regarding what a passenger will do if there is no space in their bin. We assume every passenger has perfect information about the number of bags that will be in her assigned bin section upon arrival. In this way, she will know if her bin is going to be full as soon as she arrives on the plane. This is an idealization; in real life a passenger cannot perfectly gauge if her bin will fill up before she arrives. This simplification prevents a passenger from backtracking to find luggage space once she arrives at her seat.

If a passenger's bin section is full, the passenger will attempt to stow her bag in the first open slot she can find. If there is space before she arrives at her seat, the passenger will choose the bin closest to the front of the airplane. This is justified because passengers typically look to see if there is adequate bin space near their seat, and planes are small enough to be able to estimate the amount of space available. If bin space is limited near her seat, a passenger may be inclined to stow her luggage in the first open bin she can find. This type of interference only slows the flow of traffic by the time taken to stow luggage.

The type of luggage interference with greatest impact occurs when a bin is full with no open space in front of it. In this case, passengers with bags must pass their seat to search for bin space. One of our assumptions is that passengers moving forward do not pass each other in the aisle. Thus, we created models for how passengers in the aisle behave if a passenger bypasses her assigned seat to stow luggage. This is to ensure that the passenger is able to get back to her assigned seat and does not get stuck fighting the flow of traffic. We created two models of aisle behavior to account for passengers moving behind their seat: GO and WAIT.

**Model 1**

**WAIT Aisle Behavior** - This model assumes that the aisle is impassable. Therefore, when a passenger passes her seat, other passengers wait behind her assigned seat in order to ensure the boarding process does not halt. This would happen if a passenger trying to move forward encounters a passenger trying to move backwards. In this model, this would result in an impassable blockage. To prevent this, WAIT aisle behavior assigns a "hold" when a passenger bypasses her assigned seat to stow luggage. Other passengers can only pass this "hold" if their destination has a smaller row number than the bin section to which the luggage-stowing passenger is destined. For each passenger that approaches the "hold", we check if it is possible to continue to their seat without causing a blockage. However, if any approaching passenger also has luggage, they must wait behind the "hold" for the first passenger to sit down. This method is constructed to keep an impassible aisle. However, in real life, passengers typically do not wait at an imaginary "hold" and instead just continue on to their seats. This behavior is described as the GO model for passenger behavior.

**Model 2**

**GO Aisle Behavior** - This model assumes that passengers can pass each other in the aisle if they are headed in opposite directions. There are no "holds" involved. When a passenger continues past her seat to stow luggage, boarding continues as normal. However, on the way back to her seat, the passenger will slow down boarding. If the passenger heading backwards runs into someone heading forwards, they swap positions after a set number of time steps. We assume that it takes two time steps, twice as long as it takes for an unobstructed passenger to move one unit forward. This method is more realistic because during actual airline boarding passengers are able to pass one another. However, because of the narrow aisle, passing slows down the flow of passengers.
2.5 Boarding Strategies

Definition 2.2 A boarding strategy is a method of ordering the boarding process. Let $A$ be the set of all passengers, who each have assigned seats. A boarding strategy is a partition of $A$ into $n$ subsets $Y_1, Y_2, ..., Y_n$ such that subsets are non-empty and pairwise disjoint, with $\bigcup_{i=1}^{n} Y_i = A$. The boarding process starts with all passengers in $Y_1$ boarding in random order, followed by passengers in $Y_2$, and so on up to passengers in group $Y_n$.

Boarding strategies allow airlines to control the order which passengers arrive. For example, an outside-in strategy partitions passengers into 3 groups. All passengers with a window seat are allowed to board, followed by those in the middle, and finally those with aisle seats. The order in which passengers within a group arrive is random, so it is important to choose a good boarding method to reduce the total boarding time. In practice, boarding strategies are typically implemented through boarding numbers. Passengers have a number on their ticket, and when and board when the number is called. We explore several different common boarding schemes.

- Random boarding assigns no structure to the boarding process. Passengers board in a random order.
- Boarding by blocks is the conventional method for airline boarding. It involves splitting seats into a set number of blocks, and boarding the blocks at the rear of the plane first, then moving forward. We consider 4, 5, and 6 blocks.
- Boarding by rows is another traditional method for airline boarding. It entails boarding all passengers row by row from the back to the front.
- Outside-in boarding involves boarding passengers with window seats first, then aisle, and finally middle. This removes the possibility of seat interferences.
- Reverse pyramid methods are built to combine elements of boarding by blocks with boarding outside-in. Reverse Pyramid was developed through an optimization routine to reduce expected aisle and seat interferences. We will refer to Reverse Pyramid strategies using 4, 5, and 6 groups interchangeably as the Reverse Pyramid method. A consequence of the Reverse Pyramid optimization is that using 3 groups yields an Outside-In boarding scheme.

We ran the boarding simulator using 8 different boarding schemes and compared the time it takes to board using each method (Figure 3). We were especially interested in discovering how various boarding strategies respond to luggage interferences.

2.6 Mathematics Primer

In order to layout a model for the impact of luggage interferences on airplane boarding, it is necessary to define several mathematical concepts.

Definition 2.3 The probability of an event is a number between 0 and 1 that represents the likelihood of the event occurring. We use the classical definition of probability, which considers equally likely outcomes. The probability of a success is defined as:

$$P(\text{success}) = \frac{\# \text{ of successful outcomes}}{\# \text{ of total outcomes}}$$
Definition 2.4 A \( k \)-combination is a subset of \( k \) items taken from a set of \( n \) distinct objects. An example is a committee of three people selected from a group of nine. The number of possible \( k \)-combinations of a set of size \( n \) is equal to:

\[
\binom{n}{k} = \frac{n!}{k!(n-k)!}
\]

Definition 2.5 The expected value of a random variable \( X \) is its long term average. An example would be a lottery, where expected value is the expected profit or loss per ticket if an individual were to purchase a large number of tickets. For a discrete random variable, the expected value can be found by summing all outcomes \( x \) times the probabilities \( p(x) \):

\[
E(X) = \sum x \cdot p(x)
\]

3 Expected Luggage Interferences

In this paper, we explore the effect of luggage interferences during the boarding process. We model the expected number of luggage interferences during the boarding process. Although the boarding process is a complicated physical process, we model the number of luggage interferences by introducing several assumptions.

We consider luggage interferences through a series of Bernoulli trials. We assume that passengers with bags are randomly distributed among bin sections, each with identical capacity. We assume there is exactly as many bags as there is space in the bins. This can be thought of as randomly assigning each piece of luggage to a bin.

We are interested in the number of passengers with bags who arrive at their bin section after it is already full. This happens when the number of pieces of luggage assigned to a bin is greater than the bins capacity. This will be considered a luggage interference in the analytical model.

To find the expected number of luggage interferences in this simplified model, we consider two cases. The simplest occurs when there are two bins. In this case, we solve the expected number of interferences analytically. A numerical approximation is used in the case of more than two bins.

![Figure 3: The boarding strategies tested with the simulator. Each diagram represents the model Airbus A320 used in the simulator. Seats are arranged such that the front of the plane is at the top of the figure. Numbers on each seat represent the boarding group to which that seat is assigned. Boarding methods shown are blocks, rows, outside-in, and Reverse Pyramid. BL-x: Represents boarding by blocks, using x blocks. RP-x: Reverse Pyramid boarding with x groups.](image-url)
Case 1

The case of two bins is analogous to flipping a coin \( n \) times, where \( n \) is an even integer, and counting an interference as \( x = \max(\text{heads, tails}) - \frac{n}{2} \). For example, if a coin is flipped 4 times, and the outcome is 3 heads and 1 tail, the result is 1 interference, as there is 1 more head than the expected \( \frac{4}{2} = 2 \).

**Proposition 3.1** The expected number of luggage interferences \( X \) for two bins is:

\[
E(X) = \frac{1}{2^{n-1}} \sum_{x=1}^{n/2} x \left( \frac{n}{2} + x \right)
\]

**Proof** Let each bin have capacity \( \frac{n}{2} \), \( n \in \mathbb{Z}^+ \). Thus there are \( n \) pieces of luggage, randomly assigned between the two bins. Let \( Y_1, Y_2 \) equal the number of bags in bins one and two respectively. Then for a given baggage arrangement, we define the number of luggage interferences as \( x = \max(Y_1, Y_2) - \frac{n}{2} \).

We can see that \( 0 \leq x \leq \frac{n}{2} \). Clearly, the smallest possible number of luggage interferences is 0, and the maximum is \( \frac{n}{2} \), which occurs if all pieces of luggage are assigned to one bin.

We only need to consider the case of \( 1 \leq x \leq \frac{n}{2} \) when computing expectation, since \( x = 0 \) will not contribute. If there are \( x \) interferences, then one bin has \( \frac{n}{2} + x \) bags and the other has \( \frac{n}{2} - x \). Bins are identical so this can be done in \( 2 \cdot \binom{n}{\frac{n}{2} + x} \) ways to place the overcapacity bin, multiplied by 2 since the luggage interferences can be associated with either bin.

As each piece of luggage can go in either bin, there are \( 2^n \) ways to place \( n \) pieces. Thus, the probability that the number of interferences takes on a given value is:

\[
P(X = x) = 2 \cdot \frac{\binom{n}{\frac{n}{2} + x}}{2^n} = \frac{1}{2^{n-1}} \binom{n}{\frac{n}{2} + x}
\]

To find expectation, sum over all possible values for luggage interferences multiplied by the associated probabilities:

\[
E(X) = \sum_{x=1}^{n/2} x \frac{\binom{n}{\frac{n}{2} + x}}{2^{n-1}} = \frac{1}{2^{n-1}} \sum_{x=0}^{n/2} x \left( \frac{n}{2} + x \right).
\]

Case 2

The case of more than two bins is more complicated and is not solved explicitly. Instead, the expected number of luggage interferences is computed through MATLAB simulation. We examine a small subset of possible number of bins and bin capacities, and see how many interferences result over multiple simulation iterations.
Consider $p$ bins, with $p \in [2, 10]$. Each bin has capacity $m$, with $m \in [1, 10]$. The simulator assigns $n$ pieces of luggage, $n = m \cdot p$ among bins randomly. The number of resulting luggage interferences are then tabulated. This is repeated over 1000 iterations, and averaged to give an expected number of interferences (Figure 4).

Predictably, the expected number of luggage interferences goes up with more pieces of luggage per bin, and with a greater number of bins. We would expect to have more luggage interferences in a larger airplane.

This gives an idea of how many luggage interferences to expect when boarding an airplane of arbitrary size. However, it is important to note that this is an idealization of the boarding process. The method assumes that each bag has fixed probability equal to $\frac{1}{n}$ of being assigned to a specific bin section. However, each bin section has a finite number of seats, and bags are assigned to a bin section if that is where a passenger is sitting. The probability of the $i$th passenger with a bag sitting in the $j$th bin section changes over time depending on how many seats are left in the $j$th bin section.

In addition, the number of luggage interferences during actual boarding have the potential to be larger than this approximation. This is because when a passenger can't find space to stow luggage in his assigned bin, he then places the luggage in a bin with space available. This bin is now more likely to end up full.

For its shortcomings, this method is still an interesting mathematical result. It also has applications outside of airline boarding. One potential application is modeling scheduling in a doctor’s office, where appointments can be made on various days, each with a finite capacity. Our method can determine the expected number of people who try to sign up for a day that is already full.

## 4 Results

We used our MATLAB simulator to compare various airline boarding strategies. We ran 1000 simulations to generate data to evaluate each strategies performance. We repeated the process three times for different models of luggage:

- **WAIT aisle behavior** - passengers cannot pass in aisle
- **GO aisle behavior** - passengers are able to pass if traveling in opposite directions
- **No spatial luggage** - every passenger is able to stow their bags at their designated seat

Our method allows the comparison of the two models for aisle behavior and gauge the impact of bins filling up during boarding, as well as gauge the impact of bins filling up during boarding. We looked at mean, standard deviation, and performance of the boarding strategies (Table 1).

We compared boarding performance of the two models for aisle behavior by standardizing boarding times. We converted boarding times into z-scores using the mean boarding time and
Table 1: Summary statistics for boarding time across various strategies. Statistics for both models of aisle behavior, GO and WAIT. We looked at mean time steps to board, standard deviation, and how much more time on average a particular strategy takes. In our findings boarding passengers from the outside-in resulted in the quickest boarding times.

<table>
<thead>
<tr>
<th>GO S.D.</th>
<th>BL-4</th>
<th>BL-5</th>
<th>BL-6</th>
<th>Rows</th>
<th>O-I</th>
<th>RP-4</th>
<th>RP-5</th>
<th>RP-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Steps</td>
<td>270.5</td>
<td>307.5</td>
<td>317.8</td>
<td>321.1</td>
<td>400.2</td>
<td>268.3</td>
<td>274.2</td>
<td>277.8</td>
</tr>
<tr>
<td>S.D.</td>
<td>19.5</td>
<td>14.6</td>
<td>15.4</td>
<td>12.7</td>
<td>10.7</td>
<td>18.2</td>
<td>18.2</td>
<td>16.5</td>
</tr>
<tr>
<td>% Over Min</td>
<td>0.8%</td>
<td>14.6%</td>
<td>18.4%</td>
<td>19.7%</td>
<td>49.1%</td>
<td>0.0%</td>
<td>2.2%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Time Steps</td>
<td>338.3</td>
<td>420.7</td>
<td>431.7</td>
<td>437.5</td>
<td>537.4</td>
<td>323.5</td>
<td>334.9</td>
<td>344.1</td>
</tr>
<tr>
<td>WAIT S.D.</td>
<td>52.0</td>
<td>61.6</td>
<td>59.7</td>
<td>63.3</td>
<td>66.8</td>
<td>56.5</td>
<td>55.4</td>
<td>55.0</td>
</tr>
<tr>
<td>% Over Min</td>
<td>4.6%</td>
<td>30.0%</td>
<td>33.4%</td>
<td>32.3%</td>
<td>66.1%</td>
<td>0.0%</td>
<td>3.5%</td>
<td>6.4%</td>
</tr>
<tr>
<td>No Spatial</td>
<td>Time Steps</td>
<td>240.8</td>
<td>264.1</td>
<td>272.3</td>
<td>275.7</td>
<td>365.5</td>
<td>216.7</td>
<td>215.1</td>
</tr>
<tr>
<td>Spatial</td>
<td>S.D.</td>
<td>7.5</td>
<td>7.8</td>
<td>7.7</td>
<td>7.5</td>
<td>5.9</td>
<td>5.3</td>
<td>5.4</td>
</tr>
<tr>
<td>% Over Min</td>
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<td>24.9%</td>
<td>28.8%</td>
<td>32.3%</td>
<td>74.4%</td>
<td>2.5%</td>
<td>1.8%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

Figure 5: Comparison of standardized boarding times with GO and WAIT aisle behavior. Boarding using WAIT aisle behavior results in higher variability of boarding times. However, for the most part, the average boarding time is roughly the same between the two models for aisle behavior.

Figure 6: Effect of incorporating a spatial luggage model. Data is standardized to compare the relative performance of adding bin capacity to a simulator. We compare boarding with GO behavior to a simulation with bins of infinite board.

To investigate the impact of bins filling up during the boarding procedure, we ran simulations ignoring bin capacity and compared the results to that of the GO aisle behavior, which we consider to be the most realistic approximation to the boarding process (Figure 6). This is expressed as a percentage increase in time steps. We also look at the distribution of boarding time with and without a model for bin capacity. The increase in boarding time due to luggage interferences is expressed as a percentage increase in time steps (Table 2).
5 Discussion

We investigated several methods to load an airline using a model that includes bin capacity. This affected the various boarding strategies in several different ways. A natural consequence of adding a bin model was longer boarding times, as passengers would now occasionally have to move about the cabin to find open space for their baggage. However, not all boarding strategies were equally impacted by the addition of a luggage model.

To compare the different strategies, we select the GO model for aisle behavior as the model which most closely approximates reality. During actual boarding, passing in the aisle is possible, although it is slow. The WAIT mode was developed as a solution to the problem of an impassible aisle. The main area that GO and WAIT differ is boarding time variability. With one exception (boarding by rows), the various strategies perform about the same relative to each other once the times are standardized (Figure 5). However, boarding times for WAIT are much longer, and more variable due to passengers spending more time waiting in the aisle. During this discussion, we will consider data from simulations with the GO model as representative of our simulation bin capacity model.

One of our main results is that boarding strategies are not affected by luggage interferences uniformly. Random boarding and boarding by rows are robust and not slowed down much by incorporating a capacity model for bins. However, all of the strategies that board from the outside-in are dramatically slowed once we consider spatial luggage. Typically, literature about the boarding process focuses mainly on seat and aisle interferences. However, the uneven way in which luggage impacts various boarding strategies indicates that there may be other factors involved in slowing the boarding process. We speculate that methods which board from the outside-in may be more affected by luggage due to the way bins fill up during boarding. When the final group in any Reverse Pyramid or Outside-In boarding method is called, passengers are among the last to arrive to their bin section. Window and middle passengers will have already sat down, and deposited their bags. Luggage interferences will cause bags to be distributed close to the front of the plane, due to our assumptions about passenger behavior. This may cause a large amount of lengthy luggage interferences as passengers have to walk to the rear of the plane. Random boarding is more likely to have luggage interferences earlier in the boarding process, as passengers from a section arrive with a greater degree of randomness.

Another interesting result in our study is the performance of various boarding strategies. When we looked at results without a bin capacity model, we found that the fastest method was Reverse Pyramid with 6 groups (Table 1). Random boarding was found to be dramatically slower. These results are consistent with the Arizona State study aiming to speed up boarding by reducing the number of expected interferences [1]. However, once we incorporate a model for bin occupancy we obtain different results. Using the GO model, Reverse Pyramid methods were no longer the fastest. There is virtually no difference in the performance of random, Outside-In, and the Reverse Pyramid methods when considering bin occupancy. This is interesting, because in terms of reducing seat and aisle interferences, reverse pyramid boarding is the most efficient, and interferences decrease as the number of boarding groups increase[1]. This indicates that reducing the number of expected seat and aisle interferences will not automatically reduce boarding time, which is an assumption of the study which developed the reverse pyramid approach. Our finding that Reverse-Pyramid is not the best practical method is supported by several other studies. Two other studies that used computer simulations found that reverse pyramid boarding with 5 groups performed worst than outside-in boarding[9][10]. These studies did incorporate a model for bin capacity, but did not go into detail about its construction.

We also had one finding which is slightly contrary to that of an experimental study of airline
boarding methods[5]. The study ran one experiment and found that random boarding was slower than outside-in by about 12%. Our simulation found almost no difference between the two, with random doing worse by only 0.8%. A possible reason for this discrepancy is that we do not penalize seat interferences enough. If we set up seat interferences to take more boarding time, random boarding should perform worse, as it has many more expected seat interferences than outside-in, which has zero seat interferences if followed.

This leads to one possibility for improvement of the model. We assume that each passenger “action” takes one time step. In a time step, a passenger can complete an action, which could be moving forward one unit, sitting down, or stowing their baggage. For example, if a passenger arrives at a row and finds two passengers sitting between him and his seat, this counts as two seat interferences, and takes two time steps to have the passengers in the row stand up, and then one time step to get out of the aisle. In three time steps, a passenger could also walk forward three seats. However, these two actions might not take the same amount of time during the physical boarding process. However, as another study pointed out, it is not advisable to arbitrarily choose the time penalties associated with various types of interferences[1]. With better data on passenger movement speed, the time it takes to stow baggage, and the behavior of passenger when confronted with a seat interference, it would be possible to make actions take a more realistic amount of time.

Our results indicate that outside-in boarding leads to the quickest average boarding times, which agrees with previous research. Simulation and experimental methods have generally found that outside-in boarding is very effective [2]. We also found that Reverse Pyramid strategies perform fairly well which is expected as Reverse Pyramid strategies are slight modifications to outside-in boarding.

We also find random boarding to be almost as fast as outside-in. While not all studies agree with this, the only experimental approach finds it slightly slower than outside-in[5]. Investigating the time it takes to resolve seat interferences would make the simulation method more powerful in evaluating random boarding.

Our findings on boarding by blocks are also consistent with published research. Boarding by blocks tends to dramatically increase boarding time, which has been well documented[2]. We find the slowest method for boarding is by rows. Interestingly, this method is the least adversely affected by luggage interferences (Table 2). It is also the least variable strategy in terms of standard deviation of boarding time (Table 1). However, because its average times are so much higher than other strategies, it is an unappealing choice.

Future work on this problem should include obtaining data on the time taken to accomplish various physical actions in the boarding process. In addition, more research could be conducted on what happens when individuals do not follow the assigned boarding scheme, such as families sitting together. Finally, it would be possible to modify the simulation method to accommodate various bin sizes. Data on average bin size and capacity was hard to acquire, and this information could be used to further evaluate boarding methods.

Our results suggest that to minimize boarding times, airlines should either adopt an outside-in approach to boarding, or assign boarding groups randomly. Outside-in may be the best option, especially if seat interferences take up more time than we assume. There is no compelling reason to board the plane from the back to the front, as this method results in dramatically longer boarding times. Overall, the airline boarding problem is an exciting problem that lends itself to simulation based methods for evaluating boarding strategies as well as developing new methods.
References


