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A Model-Based Approach to Feasibly Improving the Commercial Airplane Boarding Process

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Abstract: The boarding of a commercial aircraft is a complex procedure affected by numerous unpredictable factors. Airlines and passengers alike have vested interests in streamlining the boarding process to reduce operating costs and save travel time. Holding a plane on an airport tarmac is extremely expensive; minutes of wasted time can equate to millions of dollars to airlines operating thousands of daily flights. Academic research identifies several theoretical boarding methodologies that aim to minimize boarding times. Most of these processes manipulate the order in which passengers enplane, but none have universal presence in commercial flights. Many are too complex to practice reliably. This research sought to redefine the advantages of a typically-dismissed boarding methodology that will save airlines and passengers money and time if implemented as part of a larger system. By modeling multiple boarding strategies, this research identified the comparative strengths, weaknesses, and opportunities associated with the Front-to-Back boarding method.

Keywords: Theoretical Aircraft Boarding Methodologies, Front-to-Back Boarding, Back-to-Front Boarding, Random Boarding, Monte Carlo Simulation

1. Introduction

The United States Federal Aviation Administration controls approximately ten million commercial flights (FAA, 2018) transporting over 741 million passengers (BTS, 2018) every year. On each of these flights, efficiency and profitability, along with passenger and crew safety, are of paramount importance. Operating an airline is an inherently expensive logistical feat, and major airlines like American, United, Delta, and Southwest, among others, work to keep travel as profitable as possible without jeopardizing passenger safety.

American airports, by nature, are typically overcrowded and bustling logistical and economic hubs. As a result, the occupation of space at any US airport is a highly valuable commodity. Some estimates claim that a plane waiting on an airport tarmac can cost upwards of $250 per minute (Horstmeier & Haan, 2001). Before a passenger jet can depart from a gate, among several other time-intensive operations, between 100 and 200 individual passengers must board the aircraft and find their seats and stow their carry on luggage. While the boarding process may seem mundane and automatic to most passengers, optimizing it in terms of both time and passenger convenience is in the best interest of all major airlines. Airlines frequently modify their boarding processes to conserve time, but no two airlines board their planes in the exact same way. While some carriers do achieve lower boarding times than others, it is important to note that speed is not the only goal of a boarding process. Airlines value their passengers' physical and mental comfort as well as monetization opportunities achieved by selling passengers premium boarding and seating options.

The modern jets flying domestic routes seat up to 200 passengers, and there are infinite theoretical ways to board them. Academic researchers have exhaustively analyzed and modeled many of these methodologies, and some strategies do provide significant advantages in terms of average boarding times over others. Many methods, however, are far too complex for feasible implementation in the real world. The development of a boarding methodology that reliably decreases the time required for passengers to board a flight and take their seats would be of high value to all major airlines and travelers alike.

After identifying and describing several popularly studied theoretical boarding methodologies, this research will demonstrate the differences between three specific methodologies known as Front-to-Back, Back-to-Front, and Random boarding by modeling the time taken to board a plane using each method. Back-to-Front boarding and Random boarding are widely considered to be two of the fastest and most easily implementable boarding methods by academic models, while Front-to-Back boarding is typically disregarded as a perpetually slower method. Nevertheless, the Front-to-Back method of boarding has significant advantages over other methodologies and would save airlines both time and money if put into practice.

2. Published Literature Relevant to the Characteristics of Aircraft Boarding

The first step towards understanding the specific implications of any boarding process is defining the factors that affect how passengers enplane an aircraft. Air travelers are often stressed, tired, or both, and are often not completely receptive to instructions. Paired with the intricacies associated with boarding an airplane, this makes the process highly sensitive to multiple unpredictable occurrences that can significantly slow the process when aggregated together.

Since passengers walk from a pre-boarding area in the terminal onto the plane and to their seats, the characteristics of each passenger's motion are obvious factors in the total time taken to board any aircraft. Some complex models of boarding processes mirror different models of pedestrian motion applied to situations other than aircraft boarding (Tang, et al., 2012). Scholars have studied pedestrian motion exhaustively, modeling in multiple ways and applying it to a wide variety of scenarios. In the case of boarding an aircraft, several factors that do not affect pedestrian flow in other scenarios become relevant.

After establishing a numerical model for the way people travel through a space, the calculations can be modified to demonstrate how passengers move through the aisle of an airplane to find a seat. While there are multiple theories and strategies regarding the best way to board an aircraft, numerous factors similarly affect all airplane-boarding models. These include, but are not limited to, the following: the amount of aisle length occupied by a passenger; aisle width; seat spacing; time to clear the aisle (Bachmat, et al., 2006); passenger agility (Notomista, et al., 2016); luggage and luggage stowage characteristics; passengers needing assistance; seat conflicts; families or groups (Steffen & Hotchkiss, 2012); and passengers who do not follow given directions (Ferrari & Nagel, 2005). All these factors affect aircraft boarding time and can easily be accounted for in any model regardless of the specific boarding procedures at play. Any interested stakeholder can easily manipulate any inputted modeling parameters in order to examine their effects on the time required to board a plane.

The most significant factor an airline can manipulate to streamline its passenger boarding process is the actual methodology employed to board the plane. Theoretically, there are infinite ways to do this, as the topic is concerned with both the assignment of seats and the order in which passengers enplane the aircraft. Most theoretical methodologies attempt to improve the process by mitigating the slowing effects of one or more of the factors listed above. Many of these methodologies attempt to do so by spacing the passengers out within the plane or by decreasing the likelihood of one passenger getting in another's way. The following section discusses the specifics of select theoretical methodologies in detail.

3. Theoretical and Practiced Boarding Methodologies

While this research focuses on the detailed metrics associated with the Front-to-Back, Back-to-Front, and Random boarding methods, it is also important to identify and describe a few additional theoretical methods studied exhaustively by previous academic research. Three other important aircraft boarding concepts include Outside-In boarding, Reverse-Pyramid boarding, and the Steffen Method. This section will discuss and describe all the listed methods of boarding an airplane.

3.1 Front-to-Back Boarding

Front-to-Back boarding is simply a process in which passenger successively board in groups based on the rows of their assigned seats. Each boarding group will consist of all the passengers sitting in four to six adjacent rows, and the group of passengers sitting closest to the front of the plane will board first. Within each group, passengers board the plane in an unspecified order allowing for families and friends to board together. This also creates a natural randomization that keeps some distance between passengers as they arrive to their assigned seats. This method also presents a few distinct advantages over other boarding strategies that will be discussed in the results section of this research.

3.2 Back-to-Front Boarding

Back-to-Front boarding is similar to Front-to-Back boarding in that the passengers board in groups assigned based on sets of adjacent rows. As the name suggests, the first group of passengers will travel all the way down the plane's aisle to the last few rows. Each boarding group thereafter will consist of passengers assigned to the seats immediately in front of those passengers from the previous group to board. Unlike the Front-to-Back method, this method immediately utilizes all of the plane's aisle. It also randomizes the order in which members of each group board by not specifying a boarding order beforehand.

3.3 Random Boarding

Random boarding assigns each passenger a seat, but randomly assigns each passenger to a boarding group. This method is the easiest to institute, allows passengers to board with their friends or families, and allows for the airline to sell admittance to an earlier boarding group regardless of a passenger's seat assignment. Several real airlines employ variants of Random boarding for these reasons. Figure 1 demonstrates these three boarding strategies by highlighting which boarding groups of passengers occupy which seats on a notional airplane. The modeling section of this paper will utilize the boarding orders and aircraft cabin characteristics presented in Figure 1.

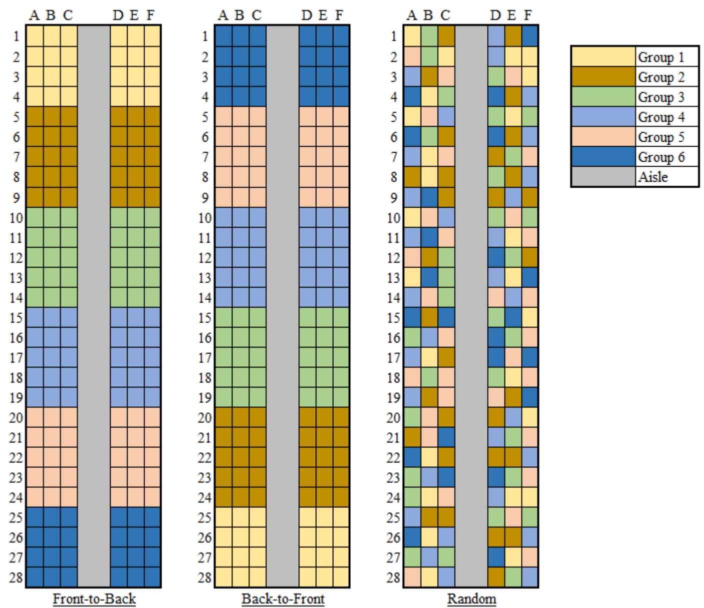

Figure 1. Major Theoretical Boarding Strategies and Groups

3.4 Outside-In Boarding

One occurrence that slows the progression of boarding significantly is the scenario in which a passenger seated in the aisle or middle seat boards the plane before the passenger seated in the window seat of the same row. This window, middle, aisle order (Mas et al., 2013) prevents the scenario in which an already seated passenger must stand up to allow the new passenger in, blocking the rest of the aisle for a considerable amount of time. The Outside-In method of boarding seeks to address this issue by initially boarding all the passengers seated in window seats, followed subsequently by the passengers seated in middle seats and lastly by the passengers seated in aisle seats.

The Outside-In method is improved by manipulating the order in which passengers seated in specific rows board the plane. This specific strategy keeps passengers from getting in each other's ways as they stow luggage and take their seats.

Most researchers acknowledge that this boarding method is theoretically faster than Random boarding, yet no major US carrier practices it. It is simply not realistic to expect a group of 200 or more passengers to board the plane in such a specified order, especially when passengers seated next to each other often wish to board together.

3.5 Reverse-Pyramid Boarding

The Reverse-Pyramid method of boarding features a successive boarding order in which the first group of passengers to enplane are the ones seated in the furthest-back window seats. The second group consists of passengers in middle-rowed window seats and the backmost middle seats and is followed by the third group of passengers seated in more forward window seats, middle-row center seats, and the aisle seats in the rear. Each boarding group contains passengers seated more forward and more towards the aisle than the previous group had, causing passengers to enter their seats in a "pyramid" formation in a "diagonal" (Nyquist & McFadden, 2008, p. 200) from the back and the outsides until the plane is fully boarded. While proven to be highly efficient in theory, this method is also difficult to implement for reasons similar to the ones keeping airlines from using a strict Outside-In boarding method.

3.6 The Steffen Method

Academic researcher Jason Steffen created this method using a Markov Chain Monte Carlo algorithm that essentially iterates through all possible boarding orders in a model to find the fastest boarding patterns (Steffen, 2008). Ultimately, the Steffen Method produces assigned boarding positions that always keep passengers two rows apart with the purpose of freeing up conflicts in finding overhead bin space for carry-on luggage (Jaen & Neumann, 2015). While this separation does save time, it also increases complexity, and passengers who do not follow the specific boarding instructions or passengers who board out of order cause greater negative effects than they would to planes boarded by other methods. All the complex theoretical methods are similar in that they all could become problematic as some passengers arrive after the boarding process has already begun or attempt to board out of order. All are also difficult if not impossible for a major airline to put into practice.

3.7 Practiced Boarding Methods

While major airlines do not typically publish their exact boarding procedures, let alone their boarding or seating algorithms, many of their processes are easily identifiable as being related or similar to one or multiple of the main theoretical processes discussed above. All airlines, however, are actively attempting to reduce the number of slowdowns that occur during the boarding process and often do so by enacting policies to reduce the number of carry-on bags passengers bring onto the aircraft and stow overhead (Jaen & Neumann, 2015).

For several years, American Airlines used a method similar to the Back-to-Front method of boarding, where they boarded the aircraft in several boarding groups. The first group would take the last few rows, and the subsequent groups would successively move up the plane (Nyquist & McFadden, 2008). After 2011, however, American Airlines stopped using this practice in favor of a less-discernable and more-random boarding method (Jaen & Neumann, 2015). Like most non-budget airlines, American also boards its first-class customers first. This is not done to save time, but rather to provide a sense of preferential treatment to the higher-paying passengers. Airlines like American Airlines use their strategic boarding methodologies for the remainder of economy-class passengers after their first-class passengers are comfortably seated.

Southwest Airlines' boarding process is the easiest to identify. It is the only major US airline to employ a completely open-seating platform. Southwest is known for their boarding efficiency, even though their open-seating method can cause some passengers to be anxious about choosing a seat (Jaen & Neumann, 2015). Their process remains unique and desirable to some passengers who want to select a better seat without paying extra for it.

United Airlines has changed its procedures a few times in the last several years, but since 2013 has utilized a variation of the Outside-In boarding method (Jaen & Neumann, 2015). Delta uses a method that is thought by some to be a back-to-front method (Jaen & Neumann, 2015) and by others in the past not to be discernable as any particular method (Nyquist & McFadden, 2008). When an airline uses a method that doesn't appear to be similar to any of the theoretical methods, it is likely that that airline using a modified randomized method designed to meet their specific enplanement goals.

4. Model Development

In order to provide a well-supported recommendation as to which theoretical boarding process is the most effective method for use on commercial aircrafts, this research models the boarding of a notional aircraft using the three specific methodologies mentioned in sections 3.1 through 3.3. This section describes the distinct characteristics of the created model.

4.1 Modeling Characteristics

The model used to evaluate the boarding times of the three focused boarding methodologies evaluates a plane consisting of 28 rows of six seats each that is completely booked such that every seat will be taken. The model lists all 168 passengers in the order they will board in and describes several relevant characteristics of every individual. In a method similar to a queuing theory analysis, the model establishes a running clock that sums the times required by each passenger to enter their assigned row. It is designed to account for passenger differences in agility, luggage possession, row assignment, and a variety of less-predictable incidents that frequently occur and slow the process.

4.2 Modeling Assumptions

The model relies on several assumptions regarding both the passengers and the plane itself. First, the model assumes the time required by each passenger to walk down the aisle from one row to be normally distributed with a mean of 2.4 seconds and a standard deviation of 0.2 seconds (Landeghem & Beuselinck, 2002.) All modeled passengers carry one personal item and between 60 and 80 percent (Zeineddine, 2017) of passengers will carry a bag that requires stowage in an overhead bin or under a seat. Because overhead storage is limited, the plane's cabin is assumed to only hold 75 large carry-on bags (Helkey, 2013), and the model assumes that flight attendants will check additional large bags at the gate.

The model also assumes that the time required by passengers to stow their luggage overhead, if they have any, will follow a normal distribution with a mean value of 7.2 seconds and a standard deviation of 1 second, or the average time taken to travel down the aisle past three rows of seats (Zeineddine, 2017). To account for any number of the potential issues discussed in section 2, the model assumes that 10 percent of passengers will slow the process by an additional 8 seconds. This value is based upon the required time for the stowage of an additional bag, although it is arbitrary in nature. The value affects all models similarly and does not significantly affect any final conclusions, however. Finally, the model assumes that all passengers board the plane continuously and that there are no first or business class sections.

4.3 Modeling Process and Simulation

The process used to model the total time required for 168 passengers to board the simulated aircraft is iterative by nature. Using the assumptions stated above, it seeks to define each passenger's motion through the plane and to his or her specified row. The amounts of time needed by each passenger are ultimately aggregated to calculate the total time required to board the airplane using each of the three theoretical boarding methods. The model uses Microsoft Excel and the assumed parameters to describe the motion of each individual passenger. These characteristics are assigned and applied sequentially in a total of 15 Excel columns culminating in a single, running clock for each of the three modeled boarding methodologies.

Using a program called SIPmath, the model runs a Monte Carlo simulation with 500 complete repetitions for each boarding method. It assigns different characteristics based on the defined distributions to each passenger in every simulation. The average durations of time required to board the same theoretical aircraft with each process were recorded and compared in order to draw specific conclusions regarding the differences between the three boarding methods.

5. Modeling Results

Over the course of 500 simulated boarding iterations of the same notional plane using each of the theoretical strategies, the model provided the average boarding times and standard deviations highlighted below in Table 1.

Table 1. Simulation Results

Boarding Method	Average Boarding Time	Boarding Time Standard Deviation
Front-to-Back	34 Minutes; 21.4 Seconds	19.7 Seconds
Back-to-Front	33 Minutes; 11.2 Seconds	21.4 Seconds
Random	29 Minutes; 43.7 Seconds	25.9 Seconds

5.1 Data Analysis

This model exclusively demonstrates general trends within the simulated boarding data, as it in no way accounts for all variables affecting the boarding process. As expected, however, the Front-to-Back method of boarding proved to be perpetually slower than the Back-to-Front and Random boarding methods by approximately 4% and 12%, respectively. These results do seem logical, as the Front-to-Back boarding method requires all passengers from each boarding group to enter their assigned rows before any passengers from the next group are able to reach their seats. In the Back-to-Front method, passengers frequently reach their assigned rows before being blocked by the passengers who boarded ahead of them. This reduces the number of interferences occurring in the plane's aisle that cause passengers to wait. Passengers boarding a plane using the Random method may be seated in any row and thus experience the least interferences in the aisle. Additionally, passengers are frequently assigned to seats far ahead of or far behind the passengers boarding immediately before or after them, allowing more passengers to simultaneously reach their seats, begin stowing their hand luggage, and make themselves comfortable before sitting down. The greater immediate dispersion of passengers throughout the cabin of a plane boarded in random order also attests to why the Random method had the highest standard deviation of total time values within the simulation.

The histogram shown below in Figure 2 displays major data trends between the three boarding strategies. In the histogram, the Front-to-Back, Back-to-Front, and Random boarding methods are abbreviated as FtB, BtF, and Rnd, respectively. This histogram depicts the number of trials for each method that fall in each of the boarding time ranges denoted on the horizontal axis. It clearly demonstrates both the normality of each boarding time distribution and the simulated trends described above. All results appear logical and maintain similar trends when scaled by manipulating any variables, as discussed in the following section.

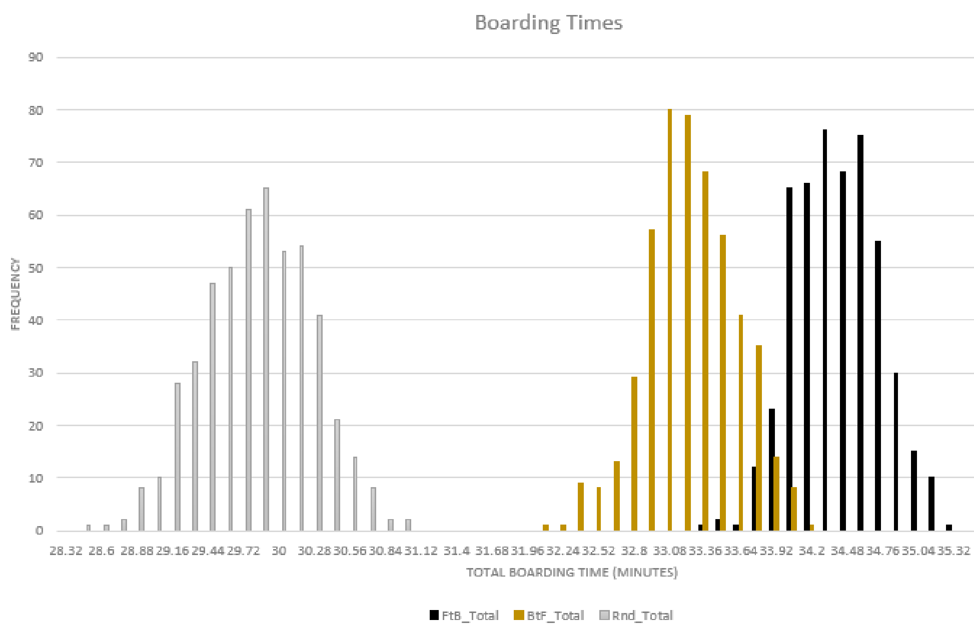

Figure 2. Boarding Data Histogram

5.2 Sensitivity Analysis

Sensitivity Analysis is a practice that varies a single parameter across a specified range and recalculates the modeled results with all other parameters held constant. The practice is used to determine a single variable's effect on a trend within data. It is particularly useful for the analysis and validation of data that relies on one or more uncertain values.

As discussed above, the model assigns point estimates to the probabilities that any given passenger will either carry a full-size carry-on or experience am 8-second slowing event. These parameters are uncertain in nature, as major US airlines have different carry-on baggage policies and the slowing event is simply an arbitrary estimation of any number of variables otherwise left unaccounted for. Because of this, it is necessary to conduct sensitivity analysis on the modeled results to determine if the described trends are dependent on, or sensitive to, relevant changes in either of these estimated probabilities.

To verify the validity of the modelled results, Figure 3 below displays the graphs of the three theoretical boarding times as functions of changes to both the 'Luggage Probability' and 'Slowing Event Probability' variables. Figure 3 uses the same abbreviations for the three boarding strategies from Figure 2.

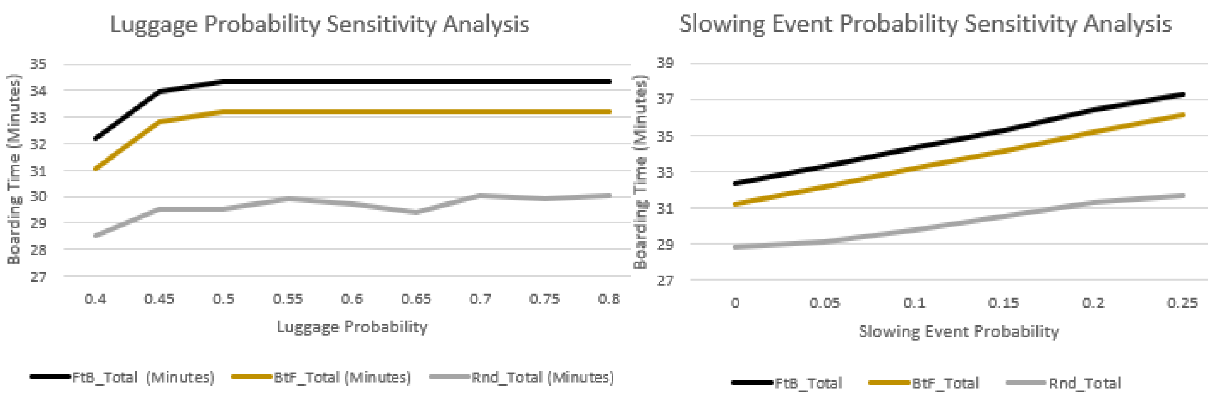

Figure 3. Sensitivity Analysis of Modeled Results

The conducted sensitivity analysis varies the probability that a passenger will carry a full-size carry-on from 0.4 to 0.8 and the probability that any given passenger will experience an eight-second slowing event from 0 to 0.25. Because none of the lines representative of each theoretical boarding method's average boarding time over the 500 simulations ever cross each other, the general trend in the modeled results is definitively not significantly sensitive to the described swings in either of the model's two probabilistic point estimates. Regardless of the value of either probability, Random boarding proves to be faster than Back-to-Front boarding and Back-to-Front Boarding proves to be faster than Front-to-Back boarding.

It is important to note, however, that the slopes of the lines do describe the relative sensitivity of the boarding time of any method to alterations in one of the identified probabilities. For example, in the graph depicting the variation of luggage probability, the average slope of the Random method is noticeably steeper those of the Back-to-Front and Front-to-Back methods as the luggage probability increases from 0.5 to 0.7. This signifies that airlines utilizing a randomized boarding method may be more interested in decreasing the number of bags carried on by their passengers than airlines boarding their planes with one of the other two methods may be. Airlines using the Random method should expect to see greater resultant reductions in total boarding times after decreasing the number of large carry-ons in their cabins.

5.3 Identified Inaccuracies

The boarding process is exceptionally complex and this model does not account for all possible scenarios. No specific consideration is given to passengers who board out of order, passengers who allow faster passengers to walk past them, or passengers who reach their seat before the passenger who boarded three or more seats ahead of them reaches theirs. This last scenario would be likely to reduce the relative time taken to board a plane using the Back-to-Front or Random methods more so than it would the Front-to-Back method, as the entirety of the aisle is utilized in the Back-to-Front and Random methods. Additionally, no consideration is given to passengers who are not able to find overhead space for their bags near their assigned seats and who then have to move about the cabin to find acceptable storage. All of these inaccuracies are mitigated by the model's inclusion of non-specific slowing events, however.

6. Conclusions and Recommendations

While the boarding process accounts for a significant portion of the time a plane spends on the tarmac between flights, several other processes must also occur. After the passengers from an incoming flight deplane, flight attendants and other contracted airline staff clean the aircraft cabin and make other related preparations before boarding the flight's passengers. Despite proving to be the slowest method of boarding modeled by this research, the Front-to-Back method may be extremely useful to airlines if employees and contractors are able to successively clean and prepare the plane as passengers are boarding. This would not be possible with other methods in which passengers quickly occupy the entirety of the plane's aisle space.

A similar advantage only associated with Front-to-Back boarding is the ability of the flight attendants to always be directly attentive to the passengers who are actively stowing their bags and entering their seats. Flight attendants could easily move towards the back of the plane as the passengers board, helping to mitigate conflicts of seating, baggage stowage, or anything else. Additionally, this will prevent some flight attendants from having to travel through the parts of the aisle that are occupied by the boarding passengers.

If the Front-to-Back method shortly increases boarding times over a randomized method but then allows for other time-intensive processes to run concurrently, a significant amount of the plane's idle time could be cut. Additional research is necessary to determine the exact quantity of time that could be saved by running other necessary turn-around processes simultaneously with boarding, but it is highly likely that the Front-to-Back method would save airlines time and money if implemented correctly.

Front-to-Back boarding is easy to implement and still facilitates the sale of premium seats or boarding positions. It also allows families and other groups of travelers to board together. For these reasons, major airlines should consider a larger change to their pre-flight processes that accounts for and optimizes boarding and other necessary preparations alike as a single system. The processes associated with preparing an incoming plane for its follow-on outbound journey should be viewed as a holistic system in order to ultimately save time and money.

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