QuickBoard: the Airplane Boarding Problem

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Abstract

Central to turn around time for a plane (the time required to successfully land and then to take off) is passenger boarding time. Due to ever increasing plane sizes, effective procedures must be developed to minimize the time required for all passengers to board. Current boarding procedures include back-to-front, reverse pyramid, block style, outside-to-inside, and random. Among these, the most distinct seem to be back-to-front, outside-to-inside, and random procedures. The purpose of this report is to examine whether there is a significant difference on the mean boarding times of three different size planes using these three specific procedures.

Our approach is to:

- Develop a computer program, henceforth to be referred to as QuickBoard, to effectively simulate the boarding of small, mid-size, and large passenger planes.

- Produce 50 data values for each boarding procedure for each size plane using QuickBoard to be used to perform a statistical analysis (Analysis of Variance) to compare the mean boarding times for each boarding procedure per plane.

Our analysis supports the hypothesis that for small planes and midsize planes, the random procedure works the most efficiently; whereas, for the large size plane, the outside-in procedure works the most efficiently. This provides evidence that there is a need for a more structured boarding procedure as the plane sizes increase. Keep in mind, however, there is a delicate balance between passenger satisfaction and airline profit; over strenuous procedures can turn customers away from an airline.

Based upon the conclusions of this study, we highly recommend fading out the use of the standard back-to-front boarding procedure and suggest the implementation of a less structured boarding procedure.

Introduction

The limiting factor in airplane turn around time is the passenger. The inbound passengers must collect their belongings and exit the plane before the cleaning crew can board to clean and restock the plane. Outbound passengers may then enter the plane, stow carry-on luggage, and take their seats. Therefore the objective is to effectively minimize boarding and deboarding time. Typically boarding times are substantially longer than deboarding times and present a more challenging problem. The spacious environment of the airport terminal effectively allows for many more options in manipulating boarding procedure. The goal is to get some number of passengers who begin unorganized in the airport terminal seating area onto the airplane and seated as quickly as possible. On boarding, it is noted that the airline is allowed freedom to organize passengers however they see fit before they enter the plane. The standard commercial plane is designed to maximize seating capacity and not necessarily seating efficiency. Once on board the airplane, passengers enter narrow aisles where it is usually impossible to rearrange the order of passengers in line. Thus, once on the plane each passenger's individual boarding time, and consequently the total time for all passengers to board, is relative to the progress of the line from front to back. Therefore a boarding structure designed to provide a constant flow of the line should be optimal. Current boarding procedures include back-to-front, reverse pyramid, block style, outside-to-inside, and random. Among these, the most distinct seem to be back-to-front, outside-to-inside, and random procedures; thus, these three shall be the procedures analyzed in the following pages for airplanes of varying sizes.

In a typical back-to-front boarding procedure, each passenger already knows exactly what his/her seat and row numbers are before the boarding process really begins. Passengers board the plane in groups according to their row number i.e. where they are located along the length of the plane. The plane company has predetermined how many blocks of rows to board in one group starting with the rows in the back of the plane, and working with the block size until all of the rows are accounted for. As each group of rows is called, the passengers in appropriate rows will form a line ready to board the plane. The order of people in each group is not further prearranged.

In a general outside-to-inside boarding procedure, each passenger, like in a back-to-front, already knows his/her seat and row numbers before the boarding process really begins. Again, passengers board in predetermined groups. The groups will always include passengers on all rows of the airplane and are selected by passenger seat number within his/her respective row. All passengers with seats on the outside of the plane i.e. the window seats are called to line up first to prepare for boarding. Subsequent groups are called consisting of the second, third, etc. seat inward until all passengers are accounted for. On planes with two or possibly more aisles the process is similar. Passengers with seats in the middle of the center group of seats will be boarded beginning in the middle of the center group working towards the aisle.

In a true random boarding procedure, the passenger only learns his/her seat and row numbers once he/she is seated. Passengers line up to board the plane in no particular order and board almost continuously until all are accounted for. Once on the plane, the passenger is free to choose any seat he/she likes.

Regardless of the boarding procedure, there is no accounting for an order of the passengers within a specific group called. This means that, although rows 6 through 12 may be called simultaneously, there is no way to tell if the first person in line will have a seat in row 6, or if he/she will be seated in an aisle seat, or, really anything except that he/she has a seat in the aforementioned rows. Also somewhat uniform to each procedure is a lag time between customers due to ticketing, walking speed of each individual, and possible confusion as to what exactly is required of him/her.

Based on the discrete nature of passengers boarding an airplane and the possible success of the random boarding procedure, a statistical approach is the most appropriate method for accurately assessing which boarding procedure is more efficient on the mean. In order to proceed with a statistical approach, one must have data that represents accurately plane boarding times relative to procedure. In order to obtain this data, a computer program was developed in a Java environment that will further be referenced to as QuickBoard (contact authors for implementation). QuickBoard runs an algorithm that models the boarding procedure.

Assumptions

In order to model the boarding process of an airplane, some base assumptions should be made. In order to make these assumptions, a mock airplane aisle, using measurements obtained from www.Boeing.com, was set up and average ranges for speeds and times are used. These assumptions are incorporated into the coding of QuickBoard:

- A constant average walking speed of 0.96 m/s (roughly 1.9 mph)
- A passenger shall require a space of 0.6096 m (2 ft) while still in a aisle, not to be intruded by other passengers in the same aisle
- Time shall be integer values of seconds
- Every seat in the plane shall be occupied ("worst case" scenario)
- A lag time of five seconds between each passenger to simulate the continuous flow of passengers after the ticket checking process shall be added to each individual passenger's boarding time. In a plane consisting of two decks, there will be two service counters checking tickets effectively cutting stagger time to two sec
- The percent of passengers with carry-on shall be random
- The time a passenger uses to stow their carry-on shall be no less than five seconds and no greater than twenty seconds
- If a passenger arrives at his/her row, and only one passenger is obstructing his/her path to his/her seat, then an interval of no less than thirteen seconds and no greater than seventeen seconds shall be required to bypass the obstructing passenger
- If a passenger arrives at his/her row, and two passengers are obstructing his/her path to his/her seat, then an interval of no less than fifteen seconds and no greater than twenty-five seconds shall be required to bypass the obstructing passengers
- In a plane having two aisles, no passenger shall inappropriately enter one aisle as to cross unnecessary seats

- In a plane having two aisles, no passenger in one aisle shall obstruct a different passenger in the other aisle upon entering the plane (i.e. there is enough room in each aisle to hold the line of waiting passengers)
- In a plane consisting of two decks, a greater number of seats shall be contained in the bottom deck
- In a plane consisting of two decks, no passenger on one deck shall obstruct a different passenger on the other deck upon entering the plane (i.e. there is enough room on each deck to hold the line of waiting passengers)

QuickBoard

Building from these assumptions, QuickBoard creates a model of an airplane based on input parameters. These include the plane size and type (one or two deck), number of seats on the plane (if applicable top and bottom), the number of seats in a row and the row-aisle configuration, row pitch (distance between consecutive rows). This plane object holds the above specification information as well as a diagram of seat occupancy. This plane will be used by the algorithm of the model.

QuickBoard then creates an array of passengers which will completely fill the plane. It assigns to each passenger a list of characterizes of that will be necessary to run the model. Characteristics of a given passenger, "A", include:

1. Seat number -- row number
2. Whether or not A has a carry on
3. An appropriate time for A to stow the carry on
4. The given constant walk speed and "personal" area
5. A random assigned number

Each passenger is assigned a seat and row number in a systematic fashion so that each seat on the plane will be occupied. The passenger is randomly assigned a carry on from a skewed distribution giving roughly 60-100 of the population of passengers at least one carry on item that must be stowed in the overhead compartments with the possibility of having two items. Those passengers whom are assigned carry on luggage then randomly receive a competency level in the form of a time interval for how long it will take them to stow their luggage. This time interval ranges from 5 to 15 seconds. The entire population of passengers is assumed to all have a constant walk speed and to desire the same amount of “personal” area. These traits were not randomized based on their small affect on the total time given small perturbation. The person is last given a random number. This number will later be used during the model to provide a method for randomly organizing passengers who are asked to board the plane at the same time.

Once the plane and passengers are created, the boarding procedure is considered. QuickBoard takes the array of passengers and groups them according to how they are called to board the plane. Each group is sorted according to the individual passengers are randomly assigned number effectively creating a random order within each group called to board the plane. The groups are devised based upon the boarding procedure selected. QuickBoard can model the Back-to-Front, Random, and Outside-to-Inside boarding procedures.

In its Back-to-Front procedure, QuickBoard creates separate arrays based on seating five rows at a time from back to front. QuickBoard sorts each of these arrays based on the random number assignment to simulate the random nature of a group of passengers forming a line, then concatenates all of the arrays into a final array to be ready to board the plane. The Back-to-Front procedure is the most widely used procedure for boarding planes. It is widely considered to be the most efficient and intuitive methods for boarding a plane. The people on the back of the plane should get on before the people sitting in front them. The primary downfall of this method is that it requires a large number of passengers boarding the plane in one group and attempting to sit close proximity to one another. Due to the disorder within the group a passenger can potentially encounter many obstruction interactions both in the aisle and in getting to his/her seat. In addition, the line that forms far down the aisle of passengers in a preceding group will obstruct a group from arriving at its block of rows on the plane.

In its Outside-to-Inside procedure, QuickBoard separates the passengers into separate arrays based on seat position, as opposed to aisle number. These arrays are then put onto the plane with those sitting nearest the window first and moving inwards to the aisle until all are seated. This boarding procedure is considered to be greatly more efficient than either method mentioned thus far as it ideally eliminates the possibility of an already seated passenger obstructing another passenger from reaching their seat and producing a significant time delay. This boarding process is the most stringent and often times cause temporary separation of passengers traveling together.

In its Random procedure, QuickBoard creates only one array of all of the passengers, arranges the passengers, and boards the passengers in a continuous fashion as they have lined up regardless of where they are assign to sit on the plane. The Random boarding procedure at first consideration is the most inefficient boarding procedure as it can be imagined that if a large number of passengers are assigned a seat near the front of the plane they will block the path to the rest of the plane for a length of time. The need to analyze this procedure greatly influenced a statistical simulation approach.

QuickBoard, having now established a plane and an array of passengers arranged in order according to a particular boarding style, being the simulation of the model. The model predicts the boarding process based upon all the assumptions made thus far. Each passenger in the "line" array of passengers are spaced backwards to account for the lag between each passenger as they pass through the final ticket check and proceed across the air bridge to the plane. QuickBoard's boarding process increments time in one second intervals, checking each passenger's position versus the passenger immediately in front of him/her. Each second can result in one of several updates to a passenger at one of several positions:

- If a passenger is at his/her row he/she will begin/continue to stow his/her carry on (if applicable).
- If his/her carry on has been stowed he/she will check to see if his/her seat is obstructed by another passenger already seated. If obstructed, passenger will continue to wait for the obstructer to create a sufficient path.
- If stowage time and obstruction time have all passed, he/she will sit in the appropriate seat
- If a passenger is not at his/her row, he/she will check to see if moving forward at their walk speed for one second will cause another passenger to enter his/her "comfort zone"
  if not - he/she shall move forward said distance
  if so - he/she shall move forward up to the boundary of the comfort zone

After each second, QuickBoard then checks to see if all passengers have been seated or if at least one still remains in the aisle. When all passengers have seated, QuickBoard will then report the amount of time required to seat all passengers. In this way, QuickBoard simulates each passenger boarding the plane and the interactions between them effectively modeling the boarding procedure. Code has been modified to run 50 trials of the model for each boarding procedure for a given plane size. This provides the needed data for the statistical methods used in the process. Data reported from QuickBoard is the total time to completely board the input plane using the given boarding procedure.

Analysis of Model

Planes are usually classified as being small, midsize, or large depending on the number of passengers they carry. A small plane carries 85—100 passengers. A midsize plane is described as carrying 210—330, and a large plane carries 450—800. In order to statistically test the difference of the three boarding procedure means, an Analysis of Variance is used on a plane from each size classification. Planes of size near the midpoint of each size interval are used:

1. Small: 150 passenger
2. Mid-Size: 270 passenger
3. Large: 740 passenger, Air-Bus A380

For planes of small classification, the data values gathered from QuickBoard, in seconds, are:

Out to In	Random	Back to Front
1143	968	1566
1123	932	1548
1115	974	1481
1221	995	1540
1079	959	1402
1090	861	1415
1245	975	1421
1062	927	1500
1038	905	1621
1179	939	1493
1199	957	1307
1169	923	1410
1117	975	1459
1054	969	1521
1171	974	1628
1094	957	1596
1126	915	1569
1158	953	1599
1133	919	1534
1146	973	1611
1120	964	1537
1145	911	1694
1068	943	1606
1157	973	1485
1102	1010	1565
1255	950	1412
1177	968	1345
1011	972	1586
1037	917	1449
1118	886	1515
1086	896	1513
1029	947	1533
1141	988	1542
1096	1001	1566
1181	934	1583
1099	1111	1441
1187	927	1472
1228	947	1626
1098	985	1465
1086	888	1572
1036	936	1393
1092	914	1639
1179	1021	1684
1176	973	1458
1235	982	1468
1090	937	1555
1111	1037	1550
1068	924	1335
1048	966	1492
1128	912	1566

Some descriptive statistics based on this data are:

Out to In		*Random*		*Back to Front*	
Mean	1124.92	Mean	953.4	Mean	1517.36
Standard Deviation	59.6301	Standard Deviation	42.36094	Standard Deviation	87.42408

Thus, for a 150 passenger plane, using the three different boarding procedures,

- A mean of 1124.92 seconds (approximately 18.8 minutes) was obtained for the Out to In procedure with a standard deviation of 59.6 seconds
- A mean of 953.4 seconds (approximately 15.9 minutes) was obtained for the Random procedure with a standard deviation of 42.4 seconds
- A mean of 1517.36 seconds (approximately 25.3 minutes) was obtained for the Back to Front procedure with a standard deviation of 87.4 seconds (approximately 1 minute and 27 seconds)

The ANOVA for this data will test the following null (H_0) and alternate (H_1) hypotheses:

$$H_0 : \mu_1 = \mu_2 = \mu_3$$
$$H_1 : \mu_i \neq \mu_j$$

Where each μ_i, μ_j correspond to a particular boarding procedure.

The ANOVA table for the 150 passenger data is:

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8357986	2	4178993	964.8901076	2.95E-85	3.057621
Within Groups	636665.2	147	4331.056			
Total	8994651	149				

Based on the P-value given (2.95 E-85, or 2*10^(-85) which is approximately 0), the null hypothesis can be rejected. This means that there is sufficient evidence to conclude that at least two boarding procedure means for the 150 passenger plane differ.

Based on the Central Limit Theorem, it can be concluded that this sample follows an approximately normal distribution. Hence, a sample of any size greater than 50 should lead to same conclusion.

Some descriptive statistics based on the data gathered for the mid-sized plane are:

Out to In		*Random*		*Back to Front*	
Mean	1733.78	Mean	1539.4	Mean	2768.96
Standard Deviation	68.8640453	Standard Deviation	57.6506014	Standard Deviation	134.3036401

Thus, for a 270 passenger plane, using the three different boarding procedures,

- A mean of 1733.78 seconds (approximately 28.9 minutes) was obtained for the Out to In procedure with a standard deviation of 68.9 seconds (approximately 1 minute and 9 seconds)
- A mean of 1539.4 seconds (approximately 25.7 minutes) was obtained for the Random procedure with a standard deviation of 57.7 seconds
- A mean of 2768.96 seconds (approximately 46.1 minutes) was obtained for the Back to Front Procedure with a standard deviation 134.3 seconds (approximately 2 minutes and 14 seconds)

The ANOVA for this data will again test the same hypothesis:

$$H_0 : \mu_1 = \mu_2 = \mu_3$$
$$H_1 : \mu_i \neq \mu_j$$

Where each μ_i, μ_j correspond to a particular boarding procedure.

The ANOVA table for the 270 passenger data is:

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	43686650.2	2	21843325.1	2510.408043	2.3429E-114	3.057621
Within Groups	1279062.5	147	8701.10544			
Total	44965712.7	149				

Based on the P-value given (2.3429E-114, which is approximately 0), the null hypothesis can be rejected. This means that there is sufficient evidence to conclude that at least two boarding procedure means for the 270 passenger plane differ.

Some descriptive statistics based on the data gathered for the large plane are:

Out to In		*Random*		*Back to Front*	
Mean	1538.74	Mean	1591.7	Mean	1589.98
Standard Deviation	12.86636	Standard Deviation	21.31996	Standard Deviation	16.53751

Thus, for a 740 passenger Airbus A380, using the three different boarding procedures,

- A mean of 1538.74 seconds (approximately 25.6 minutes) was obtained for the Out to In procedure with a standard deviation of 12.9 seconds
- A mean of 1591.70 seconds (approximately 26.528 minutes) was obtained for the Random procedure with a standard deviation of 21.3 seconds
- A mean of 1589.98 seconds (approximately 26.4997 minutes) was obtained for the Back to Front Procedure with a standard deviation 16.5 seconds (approximately 2 minutes and 14 seconds)

The ANOVA for this data will once again test the same hypothesis:

$$H_0 : \mu_1 = \mu_2 = \mu_3$$
$$H_1 : \mu_i \neq \mu_j$$

Where each μ_i, μ_j correspond to a particular boarding procedure.

The ANOVA table for the 740 passenger Airbus A380 data is:

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	90554.29	2	45277.15	152.0092579	1.64E-36	3.057621
Within Groups	43785.1	147	297.8578			
Total	134339.4	149				

Based on the P-value given (1.64E-36, which is approximately 0), the null hypothesis can be rejected. This means that there is sufficient evidence to conclude that at least two boarding procedure means for the 740 passenger Airbus A380 differ.

An overall conclusion from the statistical analysis can be drawn that no matter what the size plane, boarding procedure is a significant factor for total boarding time. It can also be concluded that in each of the different size planes, there is a boarding procedure that performs superior to the other two based on average boarding time. In both the small (150 passenger) and mid-size (270 passenger) classifications, the Random boarding procedure proves to be the most efficient as far as boarding time. In the large (740 passenger Airbus A380) classification, however, the most efficient boarding procedure is Out to In.

It is thus recommended, based on this model, that for the following plane sizes the respective boarding procedure is used:

1. Small, 150 passenger - Random
2. Mid-Size, 270 passenger - Random
3. Large, 740 passenger Airbus A380 - Out to In

Conclusion

The model developed here gives precise measurements for a given procedure and size of plane. It is robust to the variability of passenger carry on items and stowage time. The model predicted fairly accurate results compared to the work of Bachmat *et al*. Due to limited development time, the model only considers the boarding time of the most populous economy class of the airplane. For the purpose of comparison between boarding procedures first class, business class, and passengers with special needs are not considered since they do not present the same issue of overcrowding of the narrow airplane.

The model is discrete by design which has both benefits and downfalls. Being discrete, the model resembles airplane boarding in its true nature. The model allows for corrections to the distribution of passengers with carry on luggage and the random interactions between the discrete passengers boarding the plane. The stability of this model could be tests by varying the many parameters and assumptions involved. The model predicts a distinct difference between different boarding procedures. Statistical conclusions have been drawn about which boarding procedure minimizes boarding time. The random boarding procedure should not be discredited as and effective boarding procedure.

The time being discrete has a possible negative effect. The model does not allow for the passenger to switch tasks within the one second time increment potentially losing fractions of a second per passenger. For example, if a passenger took the final steps to arrive at his row in only a half a second instead of needing to walk for a full second the passenger must wait until the next second increment to begin stowing carry on or taking his/her seat. This issue could be resolved by reducing the size of the time increment. With each order of magnitude reduction the accuracy of the model will increase but the runtime of the code will increase. The current algorithm’s runtime is much less than a second per plane per boarding procedure and it would certainly be reasonable to decrease the time increment be one or two orders of magnitude.

One of the most difficult aspects of airplane boarding is considering “human nature”. Any model that is created to accurately describe airplane boarding must assume some set of expected behavior. For example, the model developed here discounts the potential for a passenger sitting in the wrong seat, thus it always assumes that a passenger will proceed directly to his/her correct row and seat; and although this is not what always happens, passengers sitting in the wrong seats have little overall effect on the difference between mean times to board a plane if it is assumed that such effects will cause a delay in boarding time that is equal regardless of boarding procedure. Other random behavior may have a larger effect. To make accurate "human nature" corrections to the model, empirical data would be necessary to develop a random distribution from which to sample these human traits. This correction could be easily added to the model.

Although a rigorously organized boarding procedure in which passengers are arranged in a complex pattern before boarding the airplane could potentially further optimize boarding time, they are highly impractical. There is a delicate balance between passenger satisfaction and airline profit. While increasing profit by decreasing boarding time it is also important consider the possible loss of passengers due to an over strenuous boarding policy.

The optimization of boarding time is a complex task involving many assumptions and simplifications. The method proposed in this paper should be appropriately tested against actual boarding times for airplanes. Many of the assumptions about passenger behavior should be determined experimentally by observing passengers during boarding of planes to improve the effectiveness of those assumptions. Ultimately any boarding procedure will rely on the behavior of the passengers.

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References

E. Bachmat, D. Berend, L. Sapir, S. Skiena, and N. Stolyarov. Analysis of Airplane Boarding Times. 2006. Working paper.

J. Susan Milton and Jesse C. Arnold. Introduction To Probability and Statistics. 4th Ed. New York: McGraw-Hill, 2003

Scott Marelli, Gregory Mattocks, Remick Merry. The Role of Computer Simulation in Reducing Airplane Turn Time. Feb. 9 2007. <http://www.boeing.com/commercial/aeromagazine/aero_01/textonly/t01txt.html>