BOARDING/DEBOARDING AIRPLANES

MATH 380 - Professor Kaul

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INTRODUCTION

Airline turnaround times and schedules rely heavily on their boarding and deboarding strategies. How passengers line up and enter the plane, as well as how they exit the plane once the flight is over, can be slow and inefficient, and airlines prefer to minimize these times to increase their flight numbers per day and save money. In the past, there have been multiple different strategies each airline uses, such as the front-to-back method, by rows, or even random boarding, where passengers walk onto the plane in any order they choose, and stand up and leave the plane whenever the aisle permits them to.

In this report, we examine the history of boarding and deboarding to develop possible solutions to this problem. Prior research has shown that how long it takes to board a plane depends on the seat and aisle interferences, or when passengers prevent another from sitting down and standing up. Also, various strategies such as the Steffen Perfect method prove to be highly effective, but too complex for passengers to realistically board. With this in mind, we develop three main strategies for plane boarding: randomly allowing passengers on the plane, boarding based on rows (Model 1), and boarding based on type of passengers (Model 2): first class, business, economy, and family boarding. This involved simplifying the floor plans of existing airplanes, and labeling seats based on our strategy. From this, we defined the order of passengers within the boarding line. Additionally, we considered larger planes, seating up to 276 passengers for a medium plane, and 550 passengers for a large plane. For deboarding, we considered the standard front-to-back method as our baseline model. The other two models were simply based on some of our boarding models, but done in reverse order.

For our models, we had to simulate data to measure how well each strategy performed for boarding/deboarding. Written in Python, the simulation first initializes how passengers line up according to our models. Then, the boarding timer begins as passengers simultaneously move from the front of the airplane to their seat, and ends once everyone is seated. We used various assumptions for the simulation, including equal spacing between rows and seats, and no delays within the line. For the deboarding process, the simulation ran similarly, with the same time mechanism. Passengers stand up based on how we defined their seat, and move into the aisle for simultaneous movement, and finally, exiting the plane. We ran the simulation multiple times for each model, plane type, and boarding vs. deboarding.

At the end of our simulations, we find that in general, random boarding has the fastest overall time, across all three plane types. Our boarding model based on passenger classification proved to be the most consistent, having the least amount of variation within its simulation runs. However, for the large plane, all three models had relatively similar results, ranging from 15-20 minutes. We conclude that the random model is best for the absolute shortest time, followed by Model 1. If airlines would prefer less variation, they could opt for Model 2. For our deboarding simulations, which we ran using the smallest plane, we found that all three models (front-to-back, Model 1, and Model 2) had similar times, varying at most around 2 minutes. Then, we would recommend using the model that the plane had used to board. For instance, if passengers boarded randomly, they may deboard based on the standard front-to-back method. If boarding based on Model 1 or 2, then they may deboard the same way as they boarded, but in reverse. This could avoid confusion within the passengers, and lead to the smallest deboarding time.

STATEMENT AND ANALYSIS OF PROBLEM

"Airlines are free to seat passengers waiting to board an aircraft in any order whatsoever. It has become customary to seat passengers with special needs first, followed by first-class passengers (who sit at the front of the plane). Then coach and business-class passengers are seated by groups of rows, beginning with the row at the back of the plane and proceeding forward. Apart from consideration of the passengers' wait time, from the airline's point of view, time is money, and boarding time is best minimized. The plane makes money for the airline only when it is in motion, and long boarding times limit the number of trips that a plane can make in a day. The development of larger planes, such as the Airbus A380 (800 passengers), accentuate the problem of minimizing boarding (and deboarding) time. Devise and compare procedures for boarding and deboarding planes with varying numbers of passengers: small (85-210), midsize (210-330), and large (450-800)."

Airplane boarding and deboarding depends on the order in which passengers arrive on the plane. In any boarding procedure, there are two lines for passengers. The first line is formed outside of the airplane, in the plane terminal. Passengers are usually sorted into certain groups, labeled by letters, that dictate when they will board. For instance, Group A would consist of first class, Group B would consist of families, and Group C would consist of economy fliers. Groups A, then B, then C line up in that order, and sometimes airlines will only call up one group at a time to avoid crowding out the terminal. The second line consists of passengers inside the plane, and this line is consistently moving down the airplane's aisle as passengers make their way from the front to back, filling in their designated seats. In deboarding, there is only one line; however, it is not consistent like the boarding process. It consists of a line of people in the aisle as they exit their seats; however, they can enter the "line" at different times, and movement down the aisle is not necessarily as consistent as with boarding.

Depending on how these groups and lines are formed, boarding and deboarding times could vary considerably. Airlines prefer to minimize this time to maximize the amount of flights made in one day. We approach this problem by considering three types of planes: the Airbus 320, the Boeing 757, and the

Airbus A380. We look at each plane's seat configuration and devise a simplified floor plan, consisting of more uniform spacing between rows and seats. Then, we assign each seat a number based on their location. For instance, six seats in the same row would be assigned the same number. The number of a seat is comparable to the boarding group the passenger in that seat is assigned. Using a simulation, we then line up passengers based on their boarding group, which is defined by their seat, and achieve an end time, or the total boarding time. For deboarding, we allow passengers to move from their seat into the aisle depending on which boarding group they were originally assigned, and achieve a deboarding time when all passengers exit the plane.

How we label seats depends on the method we choose to use. In prior research, mathematicians have modeled this problem by using simulations, mixed integer problems, and other various strategies, and test each model against a certain method. These methods are generally devised by airlines in real life. Some methods include the back-to-front method (BTF: where a plane is split into three equal parts, and passengers in the last third board first, followed by the middle third, and then the first third), the front-to-back method (FTB: a reverse of the BTF method), the row method (boarding one row at at time), and the randomized method.

One notable method, the Steffen Boarding Method, is known for being particularly efficient. In this method, a plane with n rows label their rows in order, from 1 to n, with 1 being the first row at the front of the plane. Additionally, the seats themselves are labeled window, middle, and aisle, and there are generally six seats in row, three on either side of the aisle. The first group to board consists of passengers sitting in window seats, on the right side, of odd rows. They are filed in order, such that the first person entering the plane is seated in the last row, and the last person is in the first row. This is followed by the second group, of the same order but consists of passengers sitting in window seats, on the left side, of odd rows. Passengers then fill in the rest of the window seats on the right, then left side. The rest of the boarding operates in the same way, moving onto middle seats, and finally aisle seats (Kelly & Milne 2013, 93-94).

Although this method's efficiency and speed is considerably an improvement from standard boarding methods, it also had criticism of how specific the line had to be. Human error could easily change the order of the line, affecting how passengers could board. Additionally, it also leads to considerable time being spent in the terminal in order to form the line itself. However, later in this report, we will be using a modified version of the Steffen Method for a few of our models.

Another concept of interest is boarding interferences. This occurs when a passenger prevents another from accessing their seat. In past research, there are two defined types of interferences: seat interference and aisle interferences. Aghajani et al sought to solve the boarding problem using a mixed integer program to minimize such interferences, which contributes to the majority of the boarding time.

Seat interferences are defined as when a passenger seated closer to the aisle prevents another from sitting down, where both passengers are in the same row. Aisle interferences are defined when a passenger sitting closer to the front of the aisle prevents another from sitting down further down the plane or in the same row. Time is lost here while the first passenger is stowing their luggage in the overhead bin, preventing the line from moving down the aisle (2011, 4062). Also in our report, we will be using these interferences to derive models - in particular, Model 1.

DESCRIPTION OF MODELS

Note that we do not have any actual input data for models, considering many airlines utilize the same method for their boarding processes. Then, for our models, we devise predefined groups for each passenger based on their seating, randomize the passenger order within each group, and track how the line moves within our simulation. For each type of plane (small, medium, and large), we have three models to test, for a total of nine.

We consider several variables. The first is the plane size, which in turn, leads to how each seat map varies from plane to plane. Each plane has a different number of seats per row, number of total rows, number of decks, and how each section is defined. For instance, the large plane is the only plane to have one seat per one side of an aisle, presumably designated for first class passengers. Additionally, after we consider each seat configuration, how we choose to define our groups and line up the passengers is the major factor that determines final boarding time.

For our models, we make the following assumptions:

1. We simplify the maps of our different planes to smoothly run our simulations.
2. Each passenger has the same uniform walking speed.
3. Each passenger takes the same amount of time to stow their luggage in the overhead bins.
4. There are no complications in the walking aisle that would alter how passengers move down the plane.
5. There is uniform spacing between rows and seats; it does not vary between different sections of a plane (i.e., planes can have several sections with different seating. However, the space between sections is not significantly large.)
6. The line of the passengers is established in the terminal before the simulation starts.
7. Any family that boards on any plane has a maximum of six passengers, and we set six people as the standard family size.

Our models for the deboarding process are very similar to the boarding process. Two are simply our boarding procedures, but in reverse; one is the standard FTB method. We will discuss deboarding in our analysis and testing of models to describe the simulation better. However, we need not go into detail of our deboarding models after describing the boarding models.

MODEL 1, SMALL PLANE

The design of the seats for our models on the small plane is based on the Airbus 320. This is a one aisle aircraft with exactly three seats on either side of the aisle. Additionally, we assume such an airplane has 30 rows of seats, bringing the passenger total to 180. As stated in our assumptions, there is uniform spacing between each of the 30 rows.

We introduce our first model, Model 1. We designed this model to take into account both types of interferences by avoiding seating passengers in adjacent (across the aisle) rows at a time, as well as front/back row interference.

Row	Window	Middle	Aisle	Entrance	Aisle	Middle	Window
1	4	4	4		2	2	2
2	2	2	2		4	4	4
3	4	4	4		2	2	2
4	2	2	2		4	4	4
5	4	4	4		2	2	2
6	2	2	2		4	4	4
7	4	4	4		2	2	2
8	2	2	2		4	4	4
9	4	4	4		2	2	2
10	2	2	2		4	4	4
11	4	4	4		2	2	2
12	2	2	2		4	4	4
13	4	4	4		2	2	2
14	2	2	2		4	4	4
15	4	4	4		2	2	2
16	3	3	3		1	1	1
17	1	1	1		3	3	3
18	3	3	3		1	1	1
19	1	1	1		3	3	3
20	3	3	3		1	1	1
21	1	1	1		3	3	3
22	3	3	3		1	1	1
23	1	1	1		3	3	3
24	3	3	3		1	1	1
25	1	1	1		3	3	3
26	3	3	3		1	1	1
27	1	1	1		3	3	3
28	3	3	3		1	1	1
29	1	1	1		3	3	3
30	3	3	3		1	1	1

The back half

The front half

Figure 1: Model 1 Configuration

We split the passengers into four subgroups, and split the plane into the back half and the front half. Starting with the back half, we start with Group 1. This group fills in rows of three, alternating between left/right halves and skipping every other row. By working with only the back half to begin, we try to avoid major row interferences. Within Group 1, and within the other groups, the order of the passengers will not be considered, and they will board randomly.

We then follow with Group 2, which is a similar process to Group 1, but taking place in the front half of the plane. Again, we are trying to avoid conflicts between those in the front of the plane and those in the back of the plane, as well as those on the left side and those on the right. After Group 2, we introduce Group 3. These passengers are seated in the back half of the plane, filling in all empty seats left by Group 1. Finally, we finish with Group 4, filling in empty seats left by Group 2 in the front half.

In total, we have four subgroups of 45 people each.

MODEL 2, SMALL PLANE

Boarding interferences are a major problem in the boarding process. Therefore, it may be easy to simply create different subgroups. However, many airlines utilize a class system when sorting passengers. There usually exists business class passengers, consisting of loyal customers and those who can afford better seats. These passengers generally board first, followed by families of passengers, and in particular, children who must be boarded with their parents or guardians. Then, the remaining passengers are generally lone flyers, adult couples, etc.

Then, for our second model, we take into consideration these classes, as we assume airlines are reluctant to change their already existent class system, which could lose them customers. We split the airplane into three sections: Business, Economy Single, and Family, with the first group located closer to the front (as many airlines place such passengers here), the second in the middle, and the last in the back.

Within these groups, however, we further define how they are lined up. For both Business and Economy Single, we draw upon previous research and implement the Steffen Perfect Modified Boarding Method.

Row	Window	Middle	Aisle	Entrance	Window	Middle	Aisle
1	1	1	1		2	2	2
2	3	3	3		4	4	4
3	1	1	1		2	2	2
4	3	3	3		4	4	4
5	1	1	1		2	2	2
6	3	3	3		4	4	4
7	1	1	1		2	2	2
8	3	3	3		4	4	4
9	1	1	1		2	2	2
10	5	5	5		6	6	6
11	7	7	7		8	8	8
12	5	5	5		6	6	6
13	7	7	7		8	8	8
14	5	5	5		6	6	6
15	7	7	7		8	8	8
16	5	5	5		6	6	6
17	7	7	7		8	8	8
18	5	5	5		6	6	6
19	7	7	7		8	8	8
20	5	5	5		6	6	6
21	17	17	17		14	14	14
22	17	17	17		14	14	14
23	11	11	11		12	12	12
24	11	11	11		12	12	12
25	15	15	15		10	10	10
26	15	15	15		10	10	10
27	13	13	13		16	16	16
28	13	13	13		16	16	16
29	9	9	9		18	18	18
30	9	9	9		18	18	18

Rows 1-9 (business class)
Rows 10-20 (economy)
Rows 21-30 (families)

Figure 2: Model 2 Configuration

The Steffen Modified Method is similar to its original method, in that we alternate rows and aisles. The difference is that whether a seat is an aisle, middle, or window seat does not matter; passengers from an entire row (three seats) may board at the same time. It boards people according to the following rules:

1. Left Side Odd Rows
2. Right Side Odd Rows
3. Left Side Even Rows
4. Right Side Even Rows

For the Business section, we split passengers into four equal subgroups, 1-4. We board Group 1 first, filling up the plane's left side, in odd rows, for the first section. Likewise, we do the same for groups 2-4.

The second group that boards consists of families, which will be placed towards the back of the plane. Our assumptions state that six people per family are flying together. We then split this section further into 10 subgroups of six people each, Groups 9-18. Then, because we want to group together all families, we board each group into a cluster of six seats, in consecutive rows on the same side. For each group, we alternate which side they are located, while also allowing each consecutive group to be at least one family, or two rows, away from the previous one in the vertical direction. Additionally, a family will not be seated directly across the aisle from the previous group.

For the Economy section, or in the middle of the plane, we also split passengers into four subgroups, 5-8. Like the first section, we board according to the Steffen Perfect Method, starting with Group 5 and finishing with Group 8.

Like Model 1, we arrange the passengers in line according to our model, with Groups 1-4, 9-18, and 5-8.

MODEL 3, SMALL PLANE

For our previous models, we predefined how the passengers are lined up before they enter the airplane. This was done by dividing the plane into various sections, defining the groups passengers are in based on their seat, and utilizing the idea of seat/aisle interferences. To serve as a baseline to compare the above models, we introduce Model 3, or the Random Model. Numerous airlines use this method, where passengers board randomly and no "groups" are formed. For this, we would take a flight of passengers and randomly assign them the order in which they enter the plane.

MODEL 1, MEDIUM PLANE

For our medium plane, we draw the seat design from a Boeing 757. This differs from the small airplane in a few ways. There are 18 more rows, bringing the total to 42. Additionally, the first six rows of the plane have exactly two seats on either side of the aisle, while the remaining 36 have the standard three on each side. This new section generally seats first class passengers. To adapt this size to our existing models, we simply treat the first six rows as its own section, while breaking down the rest of the plane into sections similar to Model 1 and 2. The total number of seats is 276.

	Window	Middle	Aisle	Window	Middle	Aisle
1	α	α			α	α
2	α	α			α	α
3	α	α			α	α
4	α	α			α	α
5	α	α			α	α
6	α	α			α	α
7	4	4	4	2	2	2
8	2	2	2	4	4	4
9	4	4	4	2	2	2
10	2	2	2	4	4	4
11	4	4	4	2	2	2
12	2	2	2	4	4	4
13	4	4	4	2	2	2
14	2	2	2	4	4	4
15	4	4	4	2	2	2
16	2	2	2	4	4	4
17	4	4	4	2	2	2
18	2	2	2	4	4	4
19	4	4	4	2	2	2
20	2	2	2	4	4	4
21	4	4	4	2	2	2
22	2	2	2	4	4	4
23	4	4	4	2	2	2
24	2	2	2	4	4	4
25	4	4	4	2	2	2
26	2	2	2	4	4	4
27	4	4	4	2	2	2
28	3	3	3	1	1	1
29	1	1	1	3	3	3
30	3	3	3	1	1	1
31	1	1	1	3	3	3
32	3	3	3	1	1	1
33	1	1	1	3	3	3
34	3	3	3	1	1	1
35	1	1	1	3	3	3
36	3	3	3	1	1	1
37	1	1	1	3	3	3
38	3	3	3	1	1	1
39	1	1	1	3	3	3
40	3	3	3	1	1	1
41	1	1	1	3	3	3
42	3	3	3	1	1	1
43	1	1	1	3	3	3
44	3	3	3	1	1	1
45	1	1	1	3	3	3
46	3	3	3	1	1	1
47	1	1	1	3	3	3
48	3	3	3	1	1	1

Figure 3: Model 1 Configuration for medium-sized plane

From rows 1 to 6, we board the passengers at random (denoted α). From rows 7-28, we board passengers in Groups 1, 2, 3, and 4 according to Model 1, splitting this part of the plane in half, 21 rows on each half.

MODEL 2, MEDIUM PLANE

Row	Window	Middle	Aisle		Window	Middle	Aisle
1	α	α				α	α
2	α	α				α	α
3	α	α				α	α
4	α	α				α	α
5	α	α				α	α
6	α	α				α	α
7	1	1	1		2	2	2
8	3	3	3		4	4	4
9	1	1	1		2	2	2
10	3	3	3		4	4	4
11	1	1	1		2	2	2
12	3	3	3		4	4	4
13	1	1	1		2	2	2
14	3	3	3		4	4	4
15	1	1	1		2	2	2
16	3	3	3		4	4	4
17	1	1	1		2	2	2
18	3	3	3		4	4	4
19	1	1	1		2	2	2
20	3	3	3		4	4	4
21	5	5	5		6	6	6
22	7	7	7		8	8	8
23	5	5	5		6	6	6
24	7	7	7		8	8	8
25	5	5	5		6	6	6
26	7	7	7		8	8	8
27	5	5	5		6	6	6
28	7	7	7		8	8	8
29	5	5	5		6	6	6
30	7	7	7		8	8	8
31	5	5	5		6	6	6
32	7	7	7		8	8	8
33	5	5	5		6	6	6
34	7	7	7		8	8	8
35	17	17	17		12	12	12
36	17	17	17		12	12	12
37	15	15	15		20	20	20
38	15	15	15		20	20	20
39	11	11	11		18	18	18
40	11	11	11		18	18	18
41	21	21	21		14	14	14
42	21	21	21		14	14	14
43	19	19	19		10	10	10
44	19	19	19		10	10	10
45	13	13	13		22	22	22
46	13	13	13		22	22	22
47	9	9	9		16	16	16
48	9	9	9		16	16	16

Figure 4: Model 2 Configuration for medium-sized plane

From rows 1 to 6, we board passengers at random. From rows 7-48, we board passengers in groups similar to Model 2. In the second (red) section, we board passengers in Groups 1-4. In the fourth, we board passengers in Groups 9-22, presumably families. Finally, we board the last section in Groups 5-8.

MODEL 3, MEDIUM PLANE

For Model 3, or the Randomized Model, every passenger will board randomly.

THE LARGE PLANE

The design for the large plane is based off of an Airbus A380. Compared to the smallest airplane, it has 40 more rows on a second floor, bringing the total number of rows to 70. Additionally, it has two aisles passengers may walk through. For the first half of the lower deck, there is a configuration of 1 | 2 | 1 (| denotes an aisle). This generally holds first class passengers. The second half contains 2 | 2 | 2, holding business class passengers. Finally, the upper deck has a configuration of 3 | 4 | 3, holding economy passengers and families.

Since this plane has two aisles, we consider splitting the entire plane in half down the center. This happens directly between the two aisles, leaving one or two seats directly left and right of the line. Then, we treat the two halves as separate planes, and run the simulation twice. If passengers were lined up according to our groups, as soon as they entered the plane, they would enter either aisle, depending on if they are seated on the left/right half. Because these two lines will then happen simultaneously, we run the simulation and take the maximum of the two times for overall boarding.

Airplanes with two decks of seats have at least two entrances: one for each deck. Additionally, the bottom deck (hosting both first class and business passengers) has considerably less seats in it. It both has less total rows, but also less seats per row. Because we are splitting the plane vertically, this further decreases the number of seats on each aisle. Then, any boarding interferences are considerably less common than in the top deck. It is because of this that we opt to ignore the bottom deck entirely, even though most passengers will board randomly. Then, we focus on the top deck. It has 40 rows, and when we split the plane, each subplane will have a 3 | 2 or a 2 | 3 configuration. This plane seats 550.

MODEL 1, LARGE PLANE

Row	Window	Middle	Aisle		Aisle	Middle	Middle	Aisle		Aisle	Middle	Window
1	α					α	α					α
2	α					α	α					α
3	α					α	α					α
4	α					α	α					α
5	α					α	α					α
6	α					α	α					α
7	α					α	α					α
8	α					α	α					α
9	α					α	α					α
10	α					α	α					α
11	α					α	α					α
12	α					α	α					α
13	α					α	α					α
14	α					α	α					α
15	α					α	α					α
16	α	α				α	α				α	α
17	α	α				α	α				α	α
18	α	α				α	α				α	α
19	α	α				α	α				α	α
20	α	α				α	α				α	α
21	α	α				α	α				α	α
22	α	α				α	α				α	α
23	α	α				α	α				α	α
24	α	α				α	α				α	α
25	α	α				α	α				α	α
26	α	α				α	α				α	α
27	α	α				α	α				α	α
28	α	α				α	α				α	α
29	α	α				α	α				α	α
30	α	α				α	α				α	α

Row	Window	Middle	Aisle		Aisle	Middle	Middle	Aisle		Aisle	Middle	Window
1	4	4	4		2	2	4	4		2	2	2
2	2	2	2		4	4	2	2		4	4	4
3	4	4	4		2	2	4	4		2	2	2
4	2	2	2		4	4	2	2		4	4	4
5	4	4	4		2	2	4	4		2	2	2
6	2	2	2		4	4	2	2		4	4	4
7	4	4	4		2	2	4	4		2	2	2
8	2	2	2		4	4	2	2		4	4	4
9	4	4	4		2	2	4	4		2	2	2
10	2	2	2		4	4	2	2		4	4	4
11	4	4	4		2	2	4	4		2	2	2
12	2	2	2		4	4	2	2		4	4	4
13	4	4	4		2	2	4	4		2	2	2
14	2	2	2		4	4	2	2		4	4	4
15	4	4	4		2	2	4	4		2	2	2
16	2	2	2		4	4	2	2		4	4	4
17	4	4	4		2	2	4	4		2	2	2
18	2	2	2		4	4	2	2		4	4	4
19	4	4	4		2	2	4	4		2	2	2
20	2	2	2		4	4	2	2		4	4	4
21	3	3	3		1	1	3	3		1	1	1
22	1	1	1		3	3	1	1		3	3	3
23	3	3	3		1	1	3	3		1	1	1
24	1	1	1		3	3	1	1		3	3	3
25	3	3	3		1	1	3	3		1	1	1
26	1	1	1		3	3	1	1		3	3	3
27	3	3	3		1	1	3	3		1	1	1
28	1	1	1		3	3	1	1		3	3	3
29	3	3	3		1	1	3	3		1	1	1
30	1	1	1		3	3	1	1		3	3	3
31	3	3	3		1	1	3	3		1	1	1
32	1	1	1		3	3	1	1		3	3	3
33	3	3	3		1	1	3	3		1	1	1
34	1	1	1		3	3	1	1		3	3	3
35	3	3	3		1	1	3	3		1	1	1
36	1	1	1		3	3	1	1		3	3	3
37	3	3	3		1	1	3	3		1	1	1
38	1	1	1		3	3	1	1		3	3	3
39	3	3	3		1	1	3	3		1	1	1
40	1	1	1		3	3	1	1		3	3	3

Figure 5: Model 1 Configuration for large plane

From rows 1-30, labeled α, passengers board randomly, though we won't run the simulation for this section. For the second deck, we file according to Model 1: Groups 1-4, splitting the upper deck into two halves of 20 rows each. The right side of the plane runs as a separate simulation run.

MODEL 2, LARGE PLANE

For this model, note that we defined the original model as having a business class section. In the large plane, it is important to note it has a designated section for such passengers, rows 16-30 on the bottom deck. We still board these with the bottom deck, and we can define their groups according to Model 2, but again, we will not run a simulation for them. Additionally, because the center of the plane has four seats, we allow families to also board in groups of four, holding two seats in two rows on the left/right side.

row	Window	Mid	Aisle		Aisle	Middle	Middle	Aisle		Aisle	Middle	window
1	α					α	α					α
2	α					α	α					α
3	α					α	α					α
4	α					α	α					α
5	α					α	α					α
6	α					α	α					α
7	α					α	α					α
8	α					α	α					α
9	α					α	α					α
10	α					α	α					α
11	α					α	α					α
12	α					α	α					α
13	α					α	α					α
14	α					α	α					α
15	α					α	α					α
16	1	1				2	1				2	2
17	3	3				4	3				4	4
18	1	1				2	1				2	2
19	3	3				4	3				4	4
20	1	1				2	1				2	2
21	3	3				4	3				4	4
22	1	1				2	1				2	2
23	3	3				4	3				4	4
24	1	1				2	1				2	2
25	3	3				4	3				4	4
26	1	1				2	1				2	2
27	3	3				4	3				4	4
28	1	1				2	1				2	2
29	3	3				4	3				4	4
30	1	1				2	1				2	2

Row	Window	Middle	Aisle	Aisle	Middle	Middle	Aisle	Aisle	Middle	Window
1	5	5	5	6	6	5	5	6	6	6
2	7	7	7	8	8	7	7	8	8	8
3	5	5	5	6	6	5	5	6	6	6
4	7	7	7	8	8	7	7	8	8	8
5	5	5	5	6	6	5	5	6	6	6
6	7	7	7	8	8	7	7	8	8	8
7	5	5	5	6	6	5	5	6	6	6
8	7	7	7	8	8	7	7	8	8	8
9	5	5	5	6	6	5	5	6	6	6
10	7	7	7	8	8	7	7	8	8	8
11	5	5	5	6	6	5	5	6	6	6
12	7	7	7	8	8	7	7	8	8	8
13	5	5	5	6	6	5	5	6	6	6
14	7	7	7	8	8	7	7	8	8	8
15	5	5	5	6	6	5	5	6	6	6
16	7	7	7	8	8	7	7	8	8	8
17	5	5	5	6	6	5	5	6	6	6
18	7	7	7	8	8	7	7	8	8	8
19	5	5	5	6	6	5	5	6	6	6
20	7	7	7	8	8	7	7	8	8	8
21	25	25	25	18	18	25	25	18	18	18
22	25	25	25	18	18	25	25	18	18	18
23	13	13	13	24	24	13	13	24	24	24
24	13	13	13	24	24	13	13	24	24	24
25	15	15	15	20	20	15	15	20	20	20
26	15	15	15	20	20	15	15	20	20	20
27	23	23	23	12	12	23	23	12	12	12
28	23	23	23	12	12	23	23	12	12	12
29	17	17	17	22	22	17	17	22	22	22
30	17	17	17	22	22	17	17	22	22	22
31	11	11	11	26	26	11	11	26	26	26
32	11	11	11	26	26	11	11	26	26	26
33	21	21	21	14	14	21	21	14	14	14
34	21	21	21	14	14	21	21	14	14	14
35	27	27	27	10	10	27	27	10	10	10
36	27	27	27	10	10	27	27	10	10	10
37	19	19	19	28	28	19	19	28	28	28
38	19	19	19	28	28	19	19	28	28	28
39	9	9	9	16	16	9	9	16	16	16
40	9	9	9	16	16	9	9	16	16	16

Figure 6: Model 2 Configuration for large plane

We randomly board the bottom deck, first randomly for rows 1-15, followed by Groups 1-4, in accordance with Model 2; we won't run the simulation for this, however. Then we board the top deck: Groups 9-28, families, and then 5-8. The right side of the plane, again, runs as a different simulation.

MODEL 3, LARGE PLANE

For Model 3, or the Randomized Model, every passenger will board randomly.

ANALYSIS AND TESTING OF MODELS

SIMULATION OVERVIEW

The simulation was coded in python and utilizes a fairly straightforward algorithm for modeling the passengers boarding and deboarding an airplane. The whole purpose of the simulation is to measure the time it takes from when the first passenger enters the airplane until the last passenger has sat down in his seat. In order to discuss the simulator we must first describe the assumptions it is built upon. Firstly we assume that in one time unit (we've defined it to be 2 seconds but can be longer) everyone inside the aisle of the plane will move forward simultaneously. This is not totally unreasonable as people move forward simultaneously in chunks as opposed to the whole line, but it is worth mentioning as it makes our simulation imperfect. The next assumption is that every passenger takes a constant amount of time to store their carry-ons in the overhead compartment and sit down in their seat (given there is no one in their way). We also assume that it takes a constant amount of time to shuffle past a seated passenger to get to your seat (in other words if I have a window seat and someone is already seated in the middle seat they are in my way). The final assumption we made is in regards to the large plane simulation. We assume that the two main aisles and deck board independently. As Can be seen in the image below.

As for the algorithm itself in general it works as follows:

1. We initialize the order in which passengers are lined up (ie. boarding groups) as well as where their seat is based upon the model we are trying to simulate.
2. The timer begins as the first passenger enters the plane's aisle. From there as every passenger moves forward (simultaneously) the time elapses in discrete units (for our trials we used 2 seconds).
3. Once a passenger arrives at the row that contains their seat, a separate timer starts whereby they have to wait 8 seconds to store their luggage, additionally if there are passengers blocking their way in the row then an additional 2 seconds is added per passenger. During this waiting time, all passengers behind the one storing his luggage cannot move past him until the appropriate time has elapsed.

Describing this more concretely:

```
while(those_that_have_seated != seat_map):
        for i in the_aisle:
                if the_aisle[i] !=-1                                          isn't empty
                        if the_aisle[i] == seat_map[i]: arrived_row_action()       if passenger at proper
```

aisle, call action procedure function

Else:

move_passenger_forward()

move_people_from_outside_plane_to_aisle()

increment_time()

This is the general outline of the algorithm and it is important to note that the actual implementation for each plane type is slightly different due to the varying numbers of rows and aisles. In addition the code requires a number of helper functions to: initialize maps, line passengers up, figure out what to do with them once they've arrived at their row, etc. Also in order to verify that our algorithm is lining up and seating passengers correctly we implemented a visualization to track the progress of each passenger into the plane. Each passenger is assigned a unique id however for the visualization they are simply represented as an X, empty seats are O's and a person sized gap in the plane's aisle is represented using an _. The simulator is written in Python inside a Jupyter Notebook so that the components of the code are more understandable. The smallest plane was modeled as having 30 rows and 3 aisles of seats (window, middle aisle) on both sides of the plane. The medium sized plane had 6 rows at the front of the plane with two aisles of seats each, along with 42 additional rows for a total of 48 rows and the ability to seat 276 passengers. These first two planes had only 1 main aisle and ran as 1 simulation. With the largest plane we mainly focused on the main deck of the airplane as the additional deck had much less seats, meaning that the time was going to be dominated by the boarding of the main deck. With the main deck having two aisles that were boarded independently we decided to run the largest planes simulation as two simulations. The plane is split down the middle with each simulation accounting for 40 rows and 5 aisles of seats each. Though the timer is global between the two halves of the airplane.

MODEL 1

We use Monte Carlo simulation to estimate total time for seating passengers based on each group of three passengers within each subgroup. For each subgroup, we assume that the lineup of groups of three passengers does not matter, but passengers within each group of three passengers who are assigned sitting in one specific row need to stick and align together (standing order of three passengers is random).

As the above assumption of model 1, we divide passengers into 4 subgroups with 45 passengers per each subgroup, which implies 15 groups of three passengers within each subgroup. For each group of passengers in a single subgroup, we create a random order in which they walk into the plane.

We line the trio's up randomly but maintain their subgroup ordering. In other words although the trio's are lined up randomly all of the subgroup 1 trio's will board before subgroup 2 and so on. The way we do this in the simulation is we store the trio of passengers in a list inside a dictionary:

{trio_id: [pass_1, pass_2, pass_3]}
And once we've randomly selected their seats from those available to the subgroup, we line them up, so we simply select a random trio id, and then append the three passengers to our line outside of the plane. Once everyone is lined up the first passenger enters and the simulation begins. The rest of the simulation follows the general rules.

MODEL 2

The passengers are lined up according to the model with First class going through the Steffen Modified method sequence. Essentially there are 4 subgroups and they are lined up so that the first passengers will end up at the end of first class and the passengers are lined up so that when the first passenger arrives at their seat (in the back of first class) the passengers in the middle and beginning of first class will be able to sit as well. Steffen is also performed for Economy class and runs similarly. For the family class, each family consisting of 6 people is lined up next to each other and each family of 6 is seated in their place as outlined in the spreadsheet diagram.

The key to the simulation is that the timing mechanism is the same between all of them (so the results are comparable) while the order in which passengers are lined up (in relation to where they will be seated) is what differentiates how each model will run.

DEBOARDING

The algorithm behind the deboarding simulation is very similar to the one that runs the boarding. Firstly the methods for deboarding that the simulation evaluates are front-to-back (standard way of deboarding, also abbreviated FTB) as well as our two models but in reverse. The assumptions for the deboarding simulator are identical to that of boarding. We also assume that people would actually follow instructions and get out of the plane when their particular row is called. Also we assume everyone would leave their rows in aisle-middle-window order. The algorithms itself will begin by moving the first passenger into the aisle and having him grab his luggage (this is simulated by simply waiting 8 seconds). Once the first passenger grabs his carry-ons, the next passenger (the passenger is selected based on the method we are using) is moved into the aisle and "grabs his luggage". Now it is worth mentioning that we assume in the later rows aisle seats will have stood up and gotten their luggage, though they may not move forward until their row is "called". The timing mechanism is identical with everyone in the aisle moving forward constituting the passage of one time unit (which we've defined as 2 seconds). We decided to only develop the deboarding simulation for small sized planes as we hypothesized the results would transfer similarly as was the case with boarding.

For the “regular” deboarding it is run as front to back meaning that the passengers in the first aisles are the ones that leave the plane first. They exit in alternating fashion ie. aisle, aisle, middle, middle, window, window for the adjacent aisle, and this pattern holds throughout the plane.

Our Model 1 is run in reverse with random aisles from the ordered subgroups deboarding. Our Model 2 is the same way with Steffen being run in reverse on the first two aisles and then the family subgroups disembarking in their assigned order.

The core algorithm is as follows:

```
passenger_next_to_deboard=0
while(those_that_have_exited != everyone):
    for i in aisle:
        if aisle[i] == passenger_next_to_deboard:
            grab_luggage()    //really this starts a timer and makes the passenger wait at this i
                                                                          until it is up
            move_forward_1_spot()
            passenger_next_to_deboard++
        elif aisle[i] != -1 and aisle[i] < passenger_to_deboard    //is this index empty, do they
                                                                    have their luggage
            move_forward_1_spot()
    increment time   // after for loop complete, if passengers still on plane run for loop again
```

RESULTS AND QUALITY OF MODELS

For each of the models, we ran 11 boarding simulations, resulting in a total of 99 data points. Below is the raw data collected from our simulation, and charts for comparison between the models within each plane type.

SMALL PLANE

Small Plane			
Run	Random	Model 1	Model 2
1	928	1106	1362
2	944	1172	1362
3	876	1092	1362
4	910	1126	1362
5	948	1056	1362
6	936	1074	1362
7	930	1144	1362
8	920	1186	1362
9	960	1164	1362
10	1000	1108	1362
11	898	1202	1362
AVERAGE	931.8182	1130	1362
VARIATION	124	146	0
MAX	1000	1202	1362
MIN	876	1056	1362

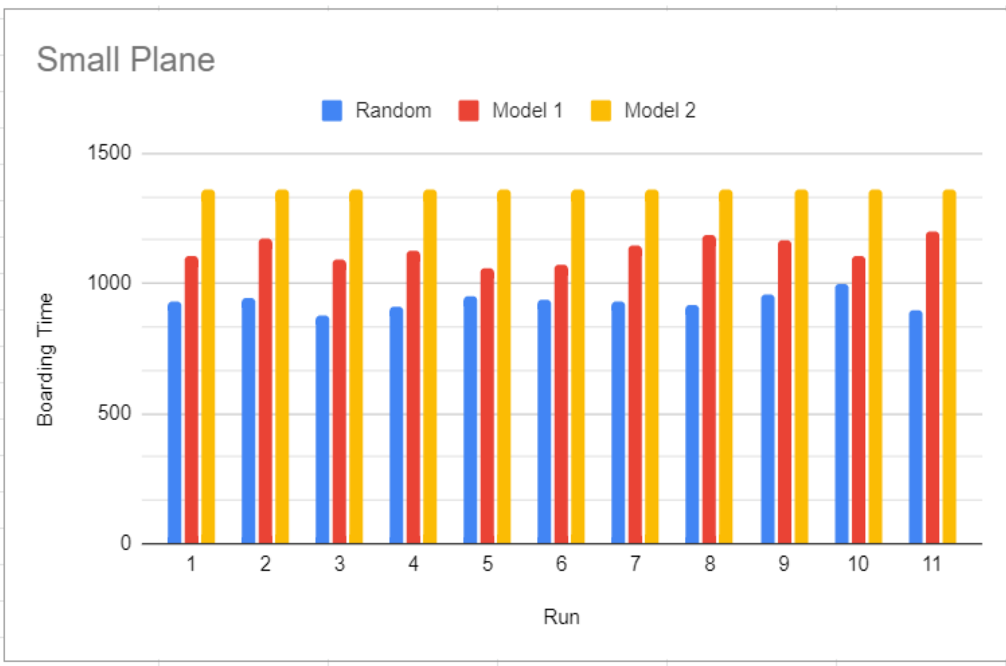


Figure 7: Results and Comparing Graph of Simulation for the Small Plane

MEDIUM PLANE

Medium Plane			
Run	Random	Model 1	Model 2
1	1192	1632	1940
2	1254	1772	1950
3	1274	1686	1964
4	1252	1698	1976
5	1238	1708	1964
6	1340	1686	1948
7	1272	1684	1942
8	1256	1616	1962
9	1220	1728	1940
10	1258	1754	1938
11	1288	1650	1942

AVERAGE	1258.5455	1692.1818	1951.4545
VARIATION	148	156	38
MAX	1340	1772	1976
MIN	1192	1616	1938

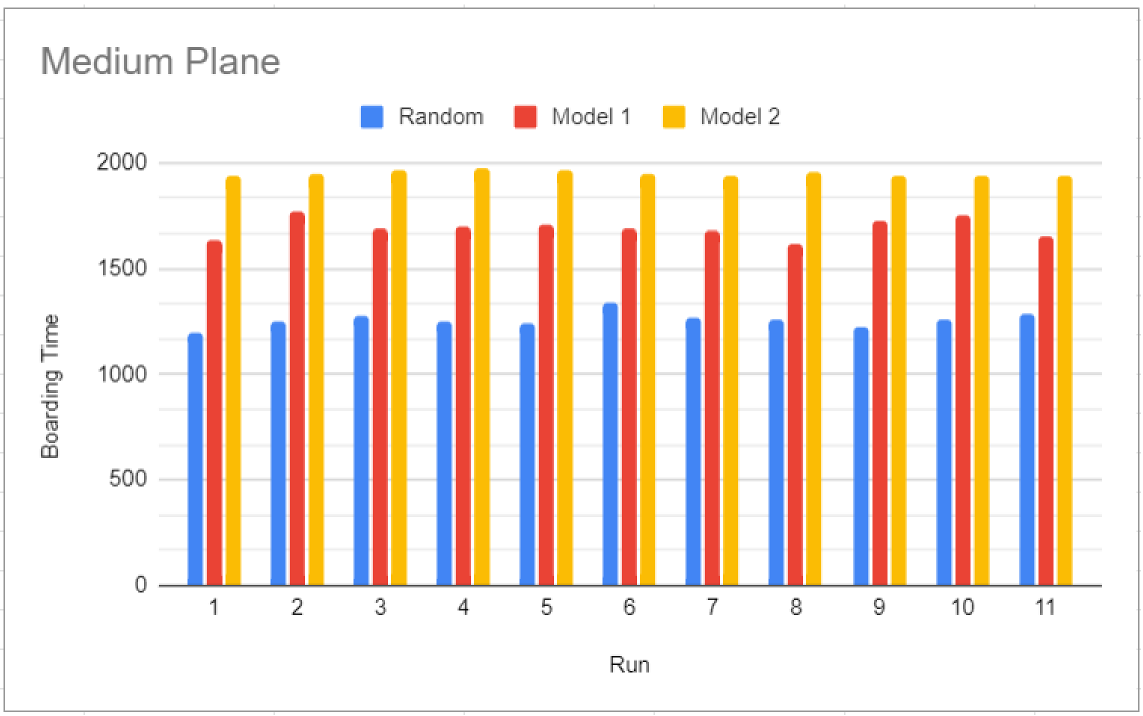


Figure 8: Results and Comparing Graph of Simulation for the Medium Plane

LARGE PLANE

Large Plane			
Run	Random	Model 1	Model 2
1	926	1144	1208
2	988	1106	1208
3	968	1136	1208
4	934	1082	1208
5	950	1108	1208
6	974	1108	1208
7	930	1156	1208
8	972	1160	1208
9	962	1122	1208
10	958	1140	1208
11	954	1106	1208

AVERAGE	956	1124.3636	1208
VARIATION	62	78	0
MAX	988	1160	1208
MIN	926	1082	1208

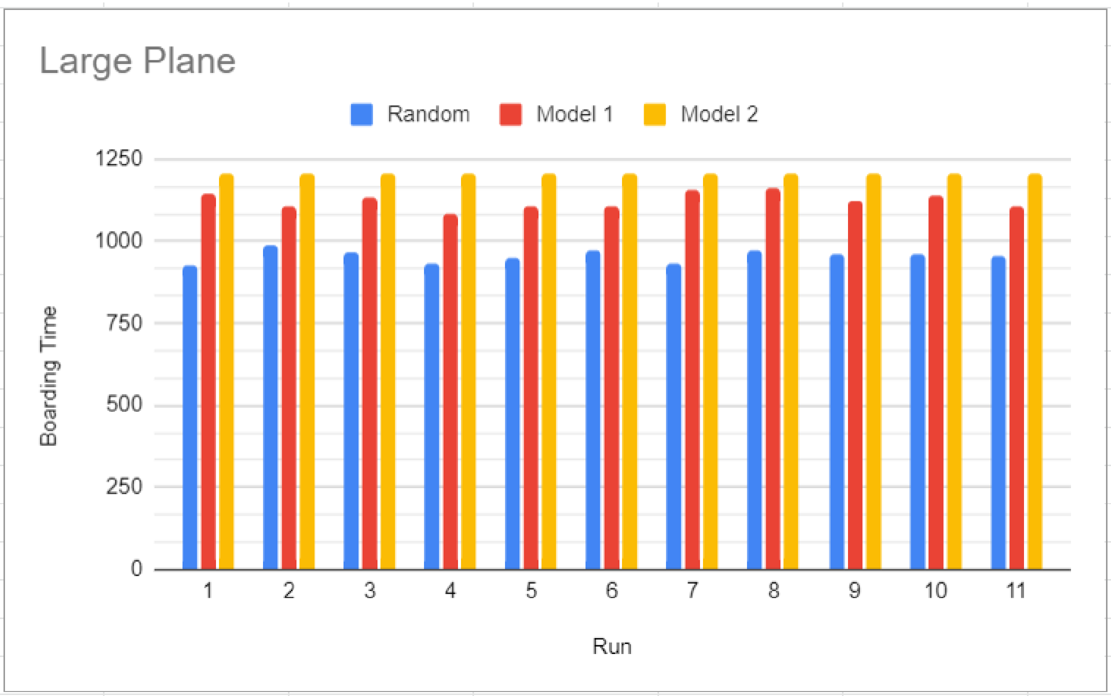


Figure 9: Results and Comparing Graph of Simulation for the Large Plane

Note that for Model 2, the boarding time is the same for small and large groups. This is because for this model, the number of interferences remains consistent for each simulation. However, the medium plane introduced the new section of first class passengers, which we boarded randomly, leading to variation in the boarding time. Variation is defined as the maximum boarding time - minimum boarding time per model, per plane type, in the 11 simulation runs.

RESULTS BY PLANE

Looking at the smallest plane, Model 1, 2, and 3 have average times of 1130, 1362, and 931.8182, respectively. When using a randomized model, we achieve both the lowest maximum and lowest minimum boarding times compared to the other two. Additionally, Model 2 has the largest boarding time, both in max/min values and in averages (note they are the same). Model 1, notably, as the highest variation out of the models, at 146 seconds. The difference between the average times is about 199 seconds between Random and Model 1, and 232 seconds between Model 1 and 2. Essentially, our randomized model fared the best.

For the medium plane, Model 1, 2, and 3 have average times of 1951.4545, 1692.1818, and 1258.5444, respectively. Again, the randomized model has the lowest maximum and minimum boarding times. Model 2 has the largest boarding time, but has the least variation, at 38 seconds. For Model 2 and Random, variation was about the same, averaging 152 seconds. The difference in times is about 434 seconds between Random and Model 1, and 259 seconds between Model 1 and 2. The randomized model had the best time.

Lastly, for the large plane, Model 1, 2, and 3 have average times of 956, 1124, and 1208. The randomized model had the lowest minimum and maximum boarding times. Model 2 has the least variation and highest boarding time (average, max, and min are all the same values). However, the variation for Model 2 and Random was relatively small, only at about a minute or two. Additionally, average times between models were not particularly large; the difference between Random and Model 1 is about 2.8 minutes, and the difference between Model 1 and 2 is 1.4 minutes. The randomized model had the best time.

RESULTS BY MODEL

By using the Random Model, the average time of the small plane is 931.82 seconds, 1258.88 seconds is the average time of the medium plane, and 956 seconds is the average time of the large plane. Clearly, the small plane has the shortest time. From the result, noticing that the difference of average times of small plane and the large plane are not significant, the small plane is about 24.19 seconds faster than the large plane. However, the medium plane needs about 5 more minutes to complete the progress compared to the small and large plane. In addition, the variation for this model between the planes was some kind of difference; variation of the small plane was 124 seconds, 148 seconds for the medium plane, and only 62 seconds for the large plane. Even though the small plane fared a shorter time rather than the largest, the Random model seemed to work well on the large plane.

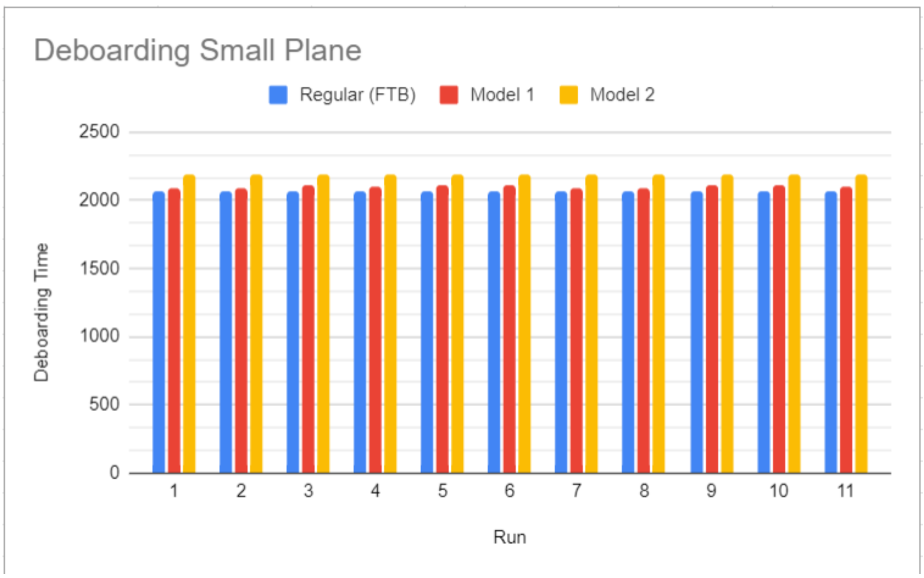
Next, by using the Model 1, the small plane needs an average time of 1130 seconds, 1692.18 seconds for the medium plane, and 1124.36 seconds for the large plane. Clearly, the large plane takes the shortest time, which is different to the Random model. Similar to the Random model, the average times of the small plane and the large plane were pretty close, only with 5.64 seconds in difference. On the other hand, with this model, the medium plane needs about more than 9 minutes rather than the time of the small and large plane in comparison. Also, this model has the largest variation compared to the Random model and Model 1, followed by 146 seconds for the small plane, 156 seconds for the medium plane, and lastly 78 seconds for the large plane. From the results, this model apparently might not work well to the medium plane.

Last, by implementing Model 2, the small plane needs an average time of 1362 seconds, 1951.46 seconds for the medium plane, and 1208 seconds for the large plane. Surprisingly, the large plane has the shortest time for boarding with about 3 minutes faster than the small plane and 12 minutes faster than the medium plane, and so we need to consider the size of airplanes when using this Model 2. Additionally, the Model 2 gives a smallest variation with other two models with 0 second for the small plane, 38 seconds for the medium plane, and 0 seconds for the large plane. Overall, Model 2 works well on large planes.

DEBOARDING RESULTS

For our deboarding models, we ran our simulation 11 times for each model type: standard FTB method, reverse Model 1, and reverse Model 2. This was for the small plane, and we did not simulate these models for larger planes, as we assume the models' results would transfer appropriately across the size of the plane.

Deboarding Small Plane			
Run	Regular (FTB)	Model 1	Model 2
1	2062	2092	2184
2	2062	2090	2184
3	2062	2108	2184
4	2062	2102	2184
5	2062	2114	2184
6	2062	2108	2184
7	2062	2090	2184
8	2062	2094	2184
9	2062	2114	2184
10	2062	2116	2184
11	2062	2100	2184
AVERAGE	2062	2102.5455	2184
VARIATION	0	26	0
MAX	2062	2116	2184
MIN	2062	2090	2184



Note that our FTB and Model 2 deboarding times are all the same, because how passengers left their seat was predetermined, leaving no element of randomness. As we can see, however, all deboarding times were relatively similar across the three models. The FTB method took 2062 seconds, the shortest time, while Model 2 took 2184 seconds, the longest. The difference between these times is 122 seconds, or only about 2.03 minutes. Switching from the FTB method leads to a 6% time increase and a 2% time increase, if switching to Model 2 and 1, respectively. Therefore, we would recommend any of the three models for deboarding.

OVERALL RESULTS

Overall, Random is the best model in general. In terms of average boarding time, it was faster than our other models for all three plane types. Additionally, times for boarding the medium plane was particularly longer than either the small and large plane, as it had the disadvantage of having a larger number of rows than the smaller, and not having two aisles like the large airplane. This meant interferences were more likely to happen, so the Random model is the best option.

Model 2 took the longest across the three planes; however, it had the advantage of a consistent time, due to interferences being set based on how the model was developed. Then, if airlines were to prefer a method that had the least variation (at most, it was 38 seconds on the medium plane) over a method that was the fastest, we recommend Model 2. Airlines may do this to better schedule departure flights, reducing the possibility of a very large, unexpected boarding time and causing delays.

Note that for our large plane, the boarding times across our models were fairly similar. The times were either about the same as the small plane, or in the case of Model 2, even shorter. The shortest time was with Random, at 15.43 minutes, and the longest time was with Model 2, at 20.13 minutes, with a difference of 4.7 minutes. The variation for the models for the large plane was also small, at a max of 78 seconds of variation. Therefore, we could recommend any of the models. Random and Model 1 would be the best for absolute boarding time, and Model 2 would be best for consistency.

As discussed earlier, deboarding times were fairly similar. If airlines prefer the absolute shortest time to deboard, we recommend the standard FTB method. However, if they boarded according to Model 1 or 2, then it would follow passengers deboard in the same fashion. This would avoid confusion within passengers as they deboard, since they already know their boarding group beforehand. If they deboarded differently than how they got on the plane, any hesitation or confusion may overcome the 2.03 minute difference when using FTB instead of Model 2, or the .68 minute difference when using FTB instead of Model 1.

ADVANTAGES/DISADVANTAGES OF MODELS

Based on our results of simulations, with the minimum average time, the Random model is inferred as the best model in the proposed models. With the optimal time, this model can bring many benefits to airline companies and passengers, where companies could reduce cost for landing processes and passengers would be more comfortable for lessening boarding time. Accompanied by boarding randomly, this model can conduct advantages to passengers who travel with a group or family, giving them freedom to line up before boarding as they wish. However, if using this model, it could be a challenge to airline's employees in terms of arranging seats and organizing passengers. Sometimes, passengers could have difficulty finding their assigned seats.

Unlike the Random model, we used a certain sequence for the Model 1 and divided passengers into small groups. With the entering sequence, the passengers can easily know the location of their seats, and flight attendants somehow help and guide passengers effectively. Also, this model has the average time not far from Random model's average time, and so it can bring advantages to passengers and airline companies. Yet, one disadvantage of this model is how to organize and line passengers up as subgroups of three passengers.

Model 2 is introduced as a diversity model that we split the aircraft into three sections: Business, Economy Single, and Family. From this division, its advantages to passengers who travel with a big group or family is that they will not worry about separating from their family or friends, and they can alway stick together. However, using this model, it might take longer than other methods, about 5 minutes to 10 minutes, and it's a big disadvantage of this model.

IMPROVEMENTS OF MODELS

For Model 1, if we could decide the optimal ordering for us to line people up and reduce interference between the groups of three, it will help to reduce the total time taken.

For Model 2, in the Family section, we forced sets of 6 passengers as a group family. However, in reality, sometimes families can have less or more than that set, and so we think we could be more flexible about the number of each set. Also, instead of choosing order for sets, we would like to randomize which families board first.

We assumed that the time to walk down the aisle would be consistent across each passenger, as well as how long it took for them to put away bags. In the future, we could also consider a normal distribution of time. Then, the time unit per passenger would be taken from the distribution, slowing down the line of passengers. Each passenger's storage time would also be evaluated based on a normal distribution. From there, we could evaluate how much the time unit affects the models, and improve from there.

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APPENDIX

Simulation code has been submitted in a zip file along with this report.