Degree Project in Computer Science and Engineering

First Cycle, 15 credits

Evaluating the Effect on Boarding Time by Carry-on Luggage and Priority Boarding

An agent-based approach to boarding efficiency

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Abstract

Companies in the airline industry are continuously working on improving their turnaround time. An important factor that can improve turnaround time is the airplane boarding process. This report presents a study conducted to assess the influence of (1) carry-on luggage and (2) priority boarding on the efficiency of the boarding process in airline operations. The two factors affecting boarding time were analysed using agent-based simulation within the Unity 3D platform. The research focused on how the presence of carry-on luggage and priority boarding affects five different boarding methods (Back-to-front, Block, Random, WILMA and Steffen). The study aims to evaluate how the five different boarding methods react to the carry-on luggage and priority boarding simulations on the Boeing 777-300ER.

The results show that the average boarding time increased with a higher ratio of passengers with carry-on luggage for all boarding methods, with variations in the magnitude of the increase across different strategies, with Steffen and WILMA being affected the least. Additionally, the study found that the impact of priority boarding on the boarding time varied among the different boarding methods, with Back-To-Front having a decrease in boarding time. These findings offer valuable insight for choosing the fastest boarding process depending on the percentage of carry-on luggage and priority boarding.

Keywords

Boarding efficiency, Agent-based simulation, Airline operations, Turnaround time, Carry-on luggage, Priority boarding, Boarding strategies, Aircraft boarding, Simulation modelling, Crowd simulation

Sammanfattning

Flygindustrin arbetar ständigt med att effektivisera sina vändtider mellan flygningar. En viktig faktor som kan förbättra vändtiden är ombordstigningsprocessen. Denna rapport presenterar en studie som genomförts för att bedöma påverkan av (1) handbagage och (2) prioriterad ombordstigning på effektiviteten av ombordstigningsprocessen i flygverksamhet. De två faktorerna som påverkar ombordstigningstiden analyserades med hjälp av agentbaserad simulering inom Unity 3D-plattformen. Forskningen fokuserade på hur förekomsten av handbagage och prioriterad ombordstigning påverkar fem olika ombordstigningsmetoder (Back-to-Front, Block, Random, WILMA och Steffen). Studien syftar till att utvärdera hur de fem olika ombordstigningsmetoderna reagerar på simuleringar av handbaggage och prioriterad ombordstigning i en Boeing 777-300ER.

Resultaten visar att medelombordstigningstiden ökade med en högre andel passagerare med handbagage för alla ombordstigningsmetoder, med variationer i ökningsgraden mellan de olika strategierna, där Steffen och WILMA påverkades minst. Dessutom fann studien att påverkan av prioriterad ombordstigning på ombordstigningstiden varierade mellan de olika ombordstigningsmetoderna, med en minskning av ombordstigningstiden för Back-to-Front. Dessa resultat ger värdefulla insikter för valet av den snabbaste ombordstigningsprocessen beroende på andelen handbagage och prioriterad ombordstigning.

Sökord

Agentbaserad simulering, Prioriterad boarding, Handbaggage, Boarding, Simulering, Flygplan, Vändtid, Simuleringsmodellering

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1 Introduction

Airlines are constantly working on how to give their passengers the most satisfactory experience possible, while at the same time having budgets to work within and profit margins to uphold. A shorter turnaround time for the airplane results in a quicker journey for the passengers and more flights for the airline. Studies also show that increasing the turnaround time causes increased carbon emissions [1]. Thus a shorter turnaround time would make the airlines more money, improve customer satisfaction, and lessen carbon emissions. There are multiple factors which can improve the turnaround time for an airplane, one of which is the boarding process. Studies show that an airline can save up to 90% of its turnover costs if it improves its boarding strategies, although some of the improvements won't be practical in reality [2].

To identify the most effective airplane boarding strategy, previous research has been conducted in the field. There are multiple ways to go about finding the most effective strategy. One of the methods to evaluate and compare different boarding strategies is to use agent-based simulation. It is a far more resource-effective approach as opposed to conducting tests with real people and a real airplane. Simulation can be used to model the behaviour of passengers in a controlled environment to test different scenarios, such as luggage handling, seat interference, and aisle congestion, that affect boarding time and efficiency.

Previous research has found that the most effective boarding strategy differs when boarding a single-aisle airplane, such as a Boeing 737, and a two-aisle airplane, such as a Boeing 777 [3]. There is also research showing that outside factors affect different boarding strategies in varying ways when boarding a single-aisle airplane [2]. However, there is not as much research on how different factors, such as carry-on luggage and priority boarding, affect different airplane boarding strategies for two-aisle airplane fuselages.

1.1 Research question

This paper aims to identify how the boarding time of five different boarding methods (Back-to-front, Block, Random, WILMA and Steffen) on the twin-aisle airplane Boeing 777-300ER are affected by carry-on luggage and priority boarding. This is done by repeated simulation of the different boarding methods and the two factors will be conducted in Unity 3D. In this study we aim to answer the following research questions:

- **RQ1:** *How does the percentage of passengers with carry-on luggage impact the total boarding time for the five different methods?*

  The study will test how 0%, 50% and 100% of passengers having carry-on luggage will impact the total boarding time of the five different boarding methods tested. The results will be analysed and discussed in section 5.1.

- **RQ2:** *How does the percentage of passengers using priority boarding, meaning that they will board in a separate group before all other passengers, impact the total boarding time for the five different methods?*

  The study will test how 0%, 10% and 20% of passengers having priority boarding will impact the total boarding time of four of the five different boarding methods tested. The random method will not be tested due to it not being affected by priority boarding by the nature of how the method is constructed [4]. The results will be discussed in section 5.2.

1.2 Approach

To compare the different boarding methods, the total boarding time of the boarding method will be timed. Carry-on luggage and priority boarding will be taken into account due to these factors being common occurrences

in a real-life scenario. To test the impact of each of the factors, the different factors will be tested with varying levels, to see if any trends can be detected.

To visualize and simulate the boarding process a real-time Unity engine will be used. The engine is used to recreate a scene representing the Boeing 777-300ER fuselage and using a crowd simulation model based on the built-in path finding of Unity.

To simulate agents stowing their carry-on luggage, the agents will pause for a few seconds to stow their bag, as a passenger would in real life. This will create a hold-up where all other agents who are standing behind the agent stowing their baggage have nowhere to go. Similarly, if an agent is seated in an aisle seat, and another agent wants to get to their window seat, the standing agent will have to move past the seated agent to get to their seat, creating another holdup.

1.3 Scope

This study does not consider another airplane other than the Boeing 777-300ER. All passengers are travelling in economy class, hence the study does not look at any other seating arrangements. All passengers are assumed to be able-bodied adults, therefore no wheelchairs or strollers impact the boarding time of the passengers. The boarding does not include children or elderly people. The study also ignores the cleaning and deplaning part of the turnaround time and only considers the boarding phase. When evaluating the results, the total boarding time is the time that passes from when the first agent walks onto the airplane, until all agents have reached their assigned seat.

2 Background

In this section information about boarding methods and related work will be presented.

2.1 Boarding methods

When the passengers have arrived at the gate at the airport they have to wait for their turn to board. The boarding method is the method that determines the order in which the passengers of a commercial airplane board the plane. Most airlines use some form of priority boarding where for example disabled people and parents with small children get to board first. Some airlines extend this priority boarding to passengers in business class who get to board before everyone else [5]. There are many different boarding methods which can be utilized. Some boarding methods may be faster, although they may not be welcomed by passengers in reality due to the fact most of the fastest boarding methods tend to separate up neighbouring passengers, which can result in people who are travelling in groups being separated during the boarding process [2]. This thesis looks at five different boarding methods; Random boarding, back-to-front boarding, the WILMA method, block boarding and the Steffen method.

2.1.1 Random method

In the random boarding method, all passengers that are not in priority boarding are let onto the airplane in a random order, regardless of their assigned seat.

3	3	3		3	3	3	3		3	3	3
3	3	3		3	3	3	3		3	3	3
3	3	3		3	3	3	3		3	3	3
3	3	3		3	3	3	3		3	3	3
2	2	2		2	2	2	2		2	2	2
2	2	2		2	2	2	2		2	2	2
2	2	2		2	2	2	2		2	2	2
2	2	2		2	2	2	2		2	2	2
1	1	1		1	1	1	1		1	1	1
1	1	1		1	1	1	1		1	1	1
1	1	1		1	1	1	1		1	1	1
1	1	1		1	1	1	1		1	1	1
1	1	1		1	1	1	1		1	1	1

(a) Boarding order for block method.

13	13	13		13	13	13	13		13	13	13
12	12	12		12	12	12	12		12	12	12
11	11	11		11	11	11	11		11	11	11
10	10	10		10	10	10	10		10	10	10
9	9	9		9	9	9	9		9	9	9
8	8	8		8	8	8	8		8	8	8
7	7	7		7	7	7	7		7	7	7
6	6	6		6	6	6	6		6	6	6
5	5	5		5	5	5	5		5	5	5
4	4	4		4	4	4	4		4	4	4
3	3	3		3	3	3	3		3	3	3
2	2	2		2	2	2	2		2	2	2
1	1	1		1	1	1	1		1	1	1

(b) Boarding order for back-to-front method.

Figure 1: Boarding order for the block method (1a) and back-to-front method (1b). The grey squares represent the aisles and the white represents the seats. Passengers with seats assigned "1" board first, then "2" and so on. Passengers board from the top of the figure.

2.1.2 Block method

The block method divides the 13 rows into three blocks of 4-5 rows each. The passengers are let onto the airplane in these blocks, starting from the block furthest back and moving forward [6]. This method does not need any alterations to be applied on a twin-aisle airplane (see figure 1a).

2.1.3 Back-to-front method

In the back-to-front method, the passengers with seats on the back row of the airplane are let on first, then the second to last row and so on. This method is also known as "by row boarding" [2]. This boarding method is originally designed for a fuselage with a single aisle with rows of three seats on either side of the aisle, though no changes need to be made to apply it to a twin-aisle airplane (see figure 1b).

1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1
1	2	3		3	2	2	3		3	2	1

(a) Boarding order for WILMA method.

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

(b) Boarding order for Steffen method.

Figure 2: Boarding order for the WILMA method (2a) and Steffen method (2b). The grey squares represent the aisles and the white represents seats. Passengers with seats assigned "1" board first, then "2" and so on. Passengers board from the top of the figure.

2.1.4 WILMA method

In the WILMA boarding method, passengers with window seats board first, then middle seats and passengers with aisle seats board last [6]. This method was originally designed for a single-aisle airplane, so it needs to be modified to take the middle block of seats into account. The two middle columns of seats board at the same time as the middle seats of the outer blocks, and the aisle seats of the middle block of seats board at the same time as the aisle seats of the outer blocks of seats (see figure 2a).

2.1.5 Steffen method

The Steffen method was constructed to minimize interference between the passengers. The Steffen method boards the passengers on alternating rows, from back to front and from the windows to the aisle [7]. This method needs a modification similar to the WILMA method, where the two middle

columns of seats board at the same time as the middle seats of the outer blocks, and the aisle seats of the middle block of seats board at the same time as the aisle seats of the outer blocks of seats (see figure 2b). Figure 2b does not show more than 29 boarding groups to give a more clear picture of the order of the boarding groups and to make the figure less cluttered. The pattern continues until boarding group 65.

2.2 Related Work

This section will discuss previous research on the topic of airplane boarding and simulated airplane boarding.

2.2.1 Boarding methods on a Boeing 777

There is no one agreed-upon boarding method that is the fastest when boarding a twin-aisle airplane. The one thing studies can agree on is that some version of WILMA is the most effective method when boarding a twin-aisle airplane [3][4]. No studies have been found that test the Steffen method on a twin-aisle airplane.

It has been shown that as fewer passengers conform with the boarding method, the boarding time converges to that of the random method [4]. When passengers don't conform to the boarding method, they do not board with their assigned boarding group and instead board with a different boarding group. This concept is similar to when passengers opt to pay for priority boarding. The difference is that with priority boarding the passengers board in a separate group before all other passengers, as opposed to boarding with the wrong boarding group. When the conformance rate decreased, the boarding time for back-to-front decreased, the WILMA method (also referred to as the outside-in method) increased in boarding time, and the random method had no change in boarding time [4].

2.2.2 Effects of carry-on luggage

Studies have shown that carry-on luggage has a significant impact on the overall boarding time. When boarding a single-aisle airplane, from a total average boarding time of 19.78 minutes, an airline can save an average of 4.6 minutes by only allowing passengers to have one carry-on bag per person. The boarding time could be further decreased by an average of 7 minutes by not allowing any carry-on luggage at all [2].

2.2.3 Effects of priority boarding

Previous research has found that priority boarding of first-class passengers increases the boarding time for all tested boarding methods on a single-aisle aircraft by on average 2.4% [8]. It is important to note that the first class consisted of 6% of the total capacity and that those with priority boarding all sat in the front two rows of the airplane. All passengers in first class board before the rest of the airplane. Furthermore, around 26% of all passengers on single-aisle airplanes have priority boarding [9].

2.2.4 Cost of turnaround time

Studies have shown that an airline, on average, can save up to 90% of its costs by changing its boarding method to a faster one [2]. Although, it is important to note that this average was calculated using statistics and averages for single-aisle airplanes, and this paper studies twin-aisle airplanes.

3 Method

This section will discuss the method used to simulate the airplane and the agents that board the plane.

As mentioned in Section 1.2, the total boarding time of the boarding method was timed to compare the different boarding methods. Carry-on luggage and priority seating were taken into account as these are common occurrences in a real-life scenario. To test the impact each of the factors had, the different factors were tested with varying levels to see if any trends could be detected.

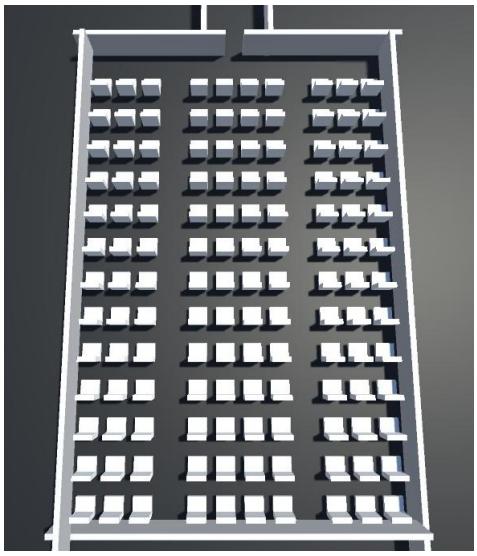
To visualize and simulate the boarding process a real-time Unity engine was used. The engine is used to recreate a scene representing the Boeing 777-300ER fuselage and using a crowd simulation model based on the built-in path finding of Unity 3D.

To simulate agents stowing their carry-on luggage, the agents paused for a few seconds to stow their bag, as a passenger would in real life. This created a hold-up where all other agents who stood behind the agent stowing their baggage had nowhere to go. Similarly, if an agent was seated in an aisle seat or middle seat, and another agent wanted to get past to their seat, the standing agent would have to pause for a few seconds to simulate the seated agent standing up and letting the other agent get to their seat, creating another holdup.

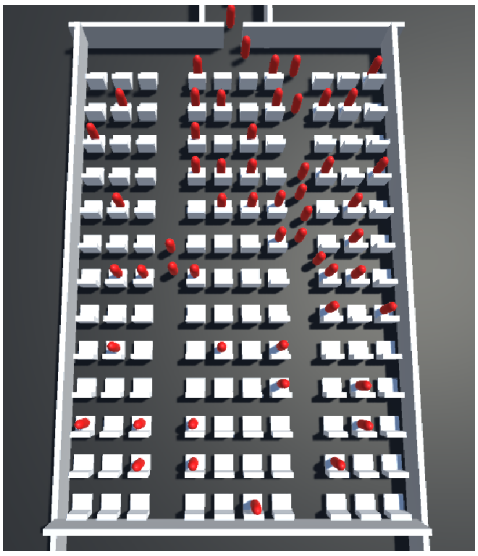
Each boarding method was tested 10 times for each percentage of priority boarding and each percentage of carry-on luggage. An average boarding time was calculated from the 10 simulations. The timing was done with the built-in `C#` function `System.Diagnostics.Stopwatch`. The stopwatch was started when the first passenger was released and stopped when all passengers had reached their assigned seating.

3.1 Scene of the simulation

The scene of the Boeing 777-300ER fuselage was created in the Unity 3D engine. The scene was a basic reconstruction of the fuselage, with 13 rows of 10 seats, separated by two aisles forming three blocks of seats in a 3-4-3 formation as can be seen in figure 3a. At the front of the scene, there was a single opening. The economy class section of a Boeing 777-300ER has 39 rows of ten seats, however the 39 rows are split into three blocks of 13 rows with an entrance at the front or back of each block of 13 rows [1]. Therefore, the total boarding time of the economy class is the same as the boarding of the 13 rows, since the three blocks of 13 rows are boarded in the same way, at the same time.



(a) Layout of fuselage in Unity 3D.



(b) Layout of fuselage in Unity 3D during simulation.

Figure 3: Layout of the fuselage created in Unity 3D. The top of the figure shows the open through which the agents enter the fuselage. 3a shows the fuselage when empty and 3b shows the fuselage when simulation of the random method is in progress. The red tubes in figure 3b are the agents representing passengers.

[1] https://www.emirates.com/se/english/experience/seating-charts/?aircraft=b777-300-two-class-long-range

3.2 Seat shuffling

One of the factors which has a big impact on the boarding time is seat shuffling. Seat shuffling comes as a result of a passenger sitting in the way of another passenger trying to get to their seat. To check for this, the path to each passenger's destination seat is compared to all surrounding seated passengers, if any seated passenger on the same row intersects the path we need to simulate them getting out of their seat and letting the standing passenger pass. To simulate this, the standing passenger trying to get to their seat will be stopped for a random time interval between five and ten seconds to simulate the seated passenger standing up, moving out of the way and both passengers sitting down again. The code in listing 1 is called with a lower and higher limit representing the time they need to wait before they can resume their movement.

```
IEnumerator GoPast(NavMeshAgent agent, float low, float high){
  agent.speed = 0f;
  yield return new WaitForSeconds(Random.Range(low, high));
  agent.speed = Random.Range(1.5f, 2f);
}
```

Listing 1: The function handling agents stopping for a specified time

This creates a momentary holdup in the aisle behind the agent trying to get to their seat. When the agent is out of the way, the agents waiting in line can carry on as usual.

3.3 Stowing luggage

Passengers boarding a commercial airplane usually have cabin luggage, which needs to be stowed in the overhead compartment. In order to simulate the passengers stowing their luggage in the overhead compartment, when the passengers had reached their seats, they paused and stood still for between two and six seconds before reaching their assigned seats. Through testing, we found that two to six seconds was a sensible range for an aver-

age passenger stowing their luggage in an overhead compartment. The code used to implement this is the same as used in listing 1.

When testing how the percentage of passengers with carry-on luggage impacted the overall boarding time for the different boarding methods, we opted for three different scenarios: 0%, 50% and 100% of passengers having carry-on luggage.

3.4 Priority boarding

During the boarding process of an airplane some passengers opt-in to purchase priority boarding to board faster. This allows them to board the airplane before everyone else, essentially lowering the conformity rate of each method. To simulate this, a percentage of the passengers are randomly selected before the ordinary boarding and are allowed to board before ordinary boarding starts. This functionality is defined in listing 2.

```
IEnumerator ReleasePriorityAgents(float percentage){
  int priorityAgents = (int) (agents.Count * percentage);
      int agentId;
      for (int i = 0; i < priorityAgents; i++){
          while(!releasedAgents.Add(agents[agentId = Random.Range(0, agents.Count)]));
          agents[agentId].SetDestination(targets[agentId].position);
          agents[agentId].transform.position = startPos + new Vector3(10f, 0f, 0f);
          yield return new WaitForSeconds(1.5f);
      }
    StartCoroutine(ReleaseGroup(agentTargetGroups[0], 0));
}
```

Listing 2: The function priority boarding passengers

When testing how the percentage of passengers who have priority boarding impacted the overall boarding time for the different boarding methods, we opted for three different scenarios: 0%, 10% and 20% of passengers having priority boarding. These percentages were chosen due to them being accurate representations of how priority boarding works in economy class in real-life scenarios. On average, on short-haul flights in single-aisle airplanes, 26% of passengers have priority boarding [9]. Furthermore, 6% of passengers in these flights are seated in first class [8]. This leads to an average of around

20% of passengers seated in economy class having priority boarding. When testing the effect of priority boarding on the different methods, the random method was not tested. This was due to the fact that priority boarding, as it is constructed, would not change the random boarding method in any way. All passengers would board in a random order, regardless of priority boarding. As discussed in section 2.2.1, priority boarding can be compared to conformance rate. It has been shown that the boarding time for the random boarding method will not change when the conformance rate decreases [4].

3.5 Agents

The passengers we use are represented by creating 3D objects in Unity 3D and then assigning them as *Nav Mesh Agents*. This allowed us to use the built-in path-finding algorithm using A* to find the shortest path to a specified destination.[2] When the boarding process starts, the agents are released one by one and are given a destination seat, after a delay of 1.5 seconds, the next passenger is released. If the previous agent was to close even after the delay, another delay was started until the previous agent had moved forward. The agents were forced to keep an absolute distance of 1.5 units between each other to avoid unrealistic collisions, where each agent is 0.5 units in diameter.

3.6 Software and hardware

The game engine Unity 3D was used to create the simulation scene and run each test. To create the movement of each passenger a script made in `C#` was used with Unity. The reason for using Unity 3D instead of another game engine was our preexisting knowledge of both Unity and `C#`. Each

[2]https://docs.unity3d.com/2021.3/Documentation/Manual/nav-InnerWorkings.html

test was ran on a PC running Windows 11 with an AMD Ryzen 7 5700U 1.80 GHz with Radeon Graphics and 16.0 GB of RAM-Memory.

4 Results

4.1 Effects of carry-on luggage

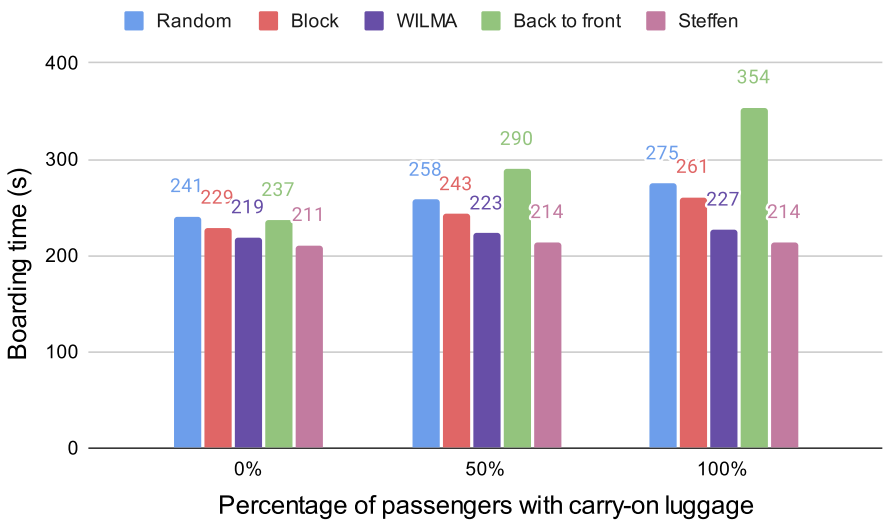


Figure 4: Average boarding of 10 simulations time with 0%, 50% and 100% of passengers having carry-on luggage.

The average boarding time increased with an increased ratio of passengers having carry-on luggage for each of the boarding methods, which can bee seen in Figure 4. Figure 4 also reveals that the WILMA method and the Steffen method had a minimal rise in boarding time. The random method and the block method had a similar increase in average boarding time, which was greater than that of the WILMA and Steffen methods. The back-to-front method had a steep increase in boarding time, with the average boarding time being almost 2 minutes longer with 100% of passengers having carry-on luggage than when 0% of the passengers had carry-on luggage.

Table 1: Change in boarding time with an increased ratio of passengers having carry-on luggage. The percentage change is in respect to the boarding time with 0% of passengers having carry-on luggage.

Boarding method	Boarding time with 0%	Change in boarding time with 50%	Change in boarding time with 100%
Random	241s	+7.05%	+14.11%
Block	229s	+6.11%	+13.97%
WILMA	211s	+1.83%	+3.65%
Back-to-front	237s	+22.36%	+49.37%
Steffen	211s	+1.42%	+1.42%

Table 1 once again shows that the average boarding time for the different methods increased along with an increased rate of passengers having carry-on luggage. The table also amplifies how the boarding methods were affected by carry-on luggage. Steffen and WILMA had a negligible increase with Steffen increasing by 1.42% and WILMA by 3.65% when every passenger had carry-on luggage. Random and Block were slightly more affected by carry-on luggage and saw an increase of 14.11% for Random and 13.97% for Block with every passenger using carry-on luggage. Back-to-front was significantly affected by carry-on luggage with an increase of 49.37% with every passenger using carry-on luggage.

4.2 Effects of priority boarding

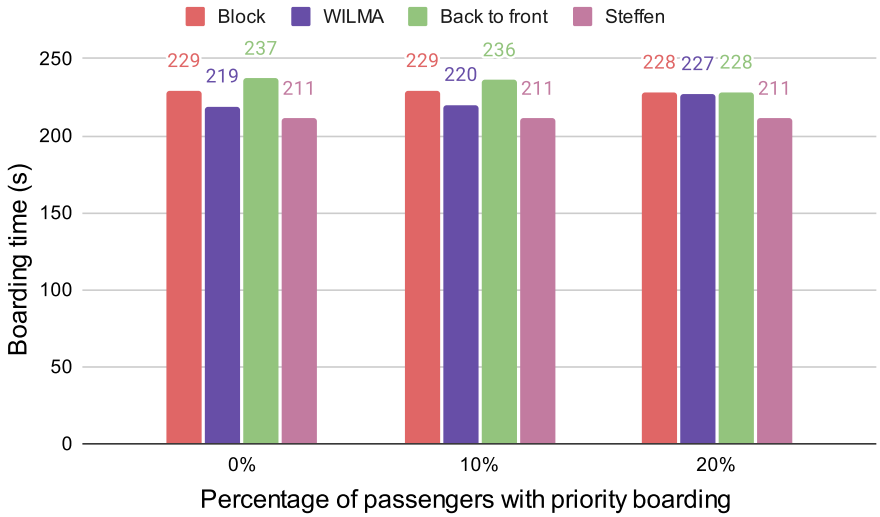


Figure 5: Average boarding time of 10 simulations with 0%, 10% and 20% of passengers using priority boarding.

The average boarding time was not significantly affected by passengers having priority boarding for any of the methods seen in Figure 5. However, there is a slight increase in boarding time for WILMA with 10% and 20% having priority boarding. Furthermore, there is a slight decrease in boarding time using Back-to-front with 10% and 20% using priority boarding.

Table 2: Change in boarding time with an increased ratio of passengers using priority boarding. The percentage change is in respect to the boarding time with 0% of passengers using priority boarding.

Boarding method	Boarding time with 0%	Change in boarding time with 10%	Change in boarding time with 20%
Block	229s	+0.00%	-0.44%
WILMA	211s	+0.46%	+3.65%
Back-to-front	237s	-0.42%	-3.80%
Steffen	211s	+0.00%	+0.00%

Table 2 further emphasises that priority boarding had minimal effect on the Block and Steffen methods, with no increase on Steffen and a 0.44% decrease on Block when looking at 20% priority boarding. However, it also shows the slight effect it had on WILMA and Back-to-front. We can see that the boarding time of WILMA increased by 3.65%, and Back-to-front decreased by 3.80%.

5 Discussion

As could be seen in the results in section 4.1, the back-to-front method had the highest increase in boarding time and the Steffen method had the lowest increase in boarding time when carry-on luggage was introduced.

Furthermore, as can be seen in section 4.2, the back-to-front method had a decrease in boarding time and the WILMA method had the highest increase in boarding time when priority boarding was introduced.

This section will discuss the cause of these results and compare them. The implications of the results will also be discussed. Lastly, limitations of the study and suggestions for future research will be brought up.

5.1 RQ1: Carry-on luggage

RQ1: *How does the percentage of passengers with carry-on luggage impact the total boarding time for the five different methods?*

5.1.1 Back-to-front method

The results in Table 1 shows that the back-to-front had the highest increase in average boarding time. This may be due to each boarding group only containing passengers from one row, as can be seen in Figure 1b. Due to this, when one passenger is stopping by their seat and stowing their luggage, every other passenger in the same aisle has to wait for that passenger to sit down before they can move forward. In the case of 100% of passengers having carry-on luggage, this process is repeated for every one of the passengers. This case is unique for the back-to-front method, as in all other methods multiple passengers can reach their assigned seat at the same time.

5.1.2 Steffen method

Table 1 further shows that the Steffen method had the least amount of percentage increase in average boarding time when the percentage of passengers with carry-on luggage increased. This can be explained by the fact that the Steffen method is designed to have a minimal amount of interactions between the passengers [7]. This is because no passenger has to wait for another passenger to stow their luggage before they can reach their assigned seat. There are exceptions though. For example, in figure 2b, if an agent with the assigned seat "7" is stowing their luggage, the passenger with the assigned seat "8" has to wait for the other passenger to sit down before they can continue moving forward. These interactions are few and far between, which explains the low increase in boarding time even though the percentage of passengers with carry-on luggage increased.

5.1.3 WILMA method

The WILMA method had a low increase in average boarding time when compared to the back-to-front, random and block methods (see Table 1). When using the WILMA method, fewer queues are formed, and these queues last for a shorter time, compared to the back-to-front, random and block methods. This could be explained by the fact that when using this method, at most two passengers per row and aisle board at the same time, as can be seen in Figure 2a. This means that if a queue forms because a passenger needs to stow their luggage, the probability that the queue will last for longer than the 2 to 6 seconds it takes for one passenger to stow their luggage is low. This is due to only one of the 25 other passengers boarding in the same boarding group and in the same aisle, having a seat on the same row. These two passengers need to board right after one another for the queue to last longer than 2 to 6 seconds. The short queues that do form are often disbursed quickly leading to little aisle congestion.

5.1.4 Random method and Block method

The results in Table 1 show that the random method and the block method had a similar increase in boarding time when carry-on luggage was introduced. The similar effect of carry-on luggage can be explained by the nature of how the block method is formed. Since the block method has no strategy to optimize the boarding time within the boarding groups, the boarding within the boarding groups behaves as the random method. The block method is essentially three smaller repetitions of the random method. Thus, the effect of carry-on luggage will be similar between the two boarding methods.

5.1.5 Comparison of methods

Carry-on luggage had a varied impact on the different boarding methods, with some methods being impacted more than others. The back-to-front method was impacted the most and the Steffen method was impacted the least, as mentioned in section 5.1.1 and 5.1.2 respectively. These findings may be used to implement a strategy where airlines may change their boarding strategy to account for the percentage of passengers with carry-on luggage. If a small part of the passengers have carry-on luggage the airline may opt for a boarding strategy in which fewer groups travelling together have to be separated, such as the random or block method. However, if a majority of passengers have carry-on luggage, the airline may opt for a quicker method which is affected little by the presence of carry-on luggage. This way groups travelling together are only separated if the boarding time is significantly impacted by the carry-on luggage. Boarding methods such as the random method and the block method also require less planning and logistics on behalf of the airlines. It would however be a challenge to find an accurate estimate of the percentage of passengers with carry-on luggage.

The results, however, do not show as drastic of a result as previous research

has suggested. It has been shown that, when using the WILMA method on a single-aisle airplane, the boarding time could be decreased by 43.11% if all carry-on luggage was banned [2]. The vast difference in these results compared to the findings of this study may be explained by the fact that this study was conducted on a twin aisle airplane, as opposed to a single aisle airplane which the previous study was conducted on. When boarding a twin aisle airplane the passengers are evenly distributed between the two aisles. This creates small gaps between the passengers in each aisle. Due to these gaps, the queues that form does not last for as long. When the first passenger begins to stow their bag, the passengers behind them haven't reached the passenger stowing their bag yet. Thus, when they reach the passenger stowing their bag, they don't have to wait for as long as they otherwise would have. When boarding a single aisle airplane, all passengers are in the same aisle. Thus all passengers have to wait in the the queues that form and the queues last for longer leading to a more drastic increase in boarding time when carry-on luggage is introduced.

5.2 RQ2: Priority boarding

RQ2: *How does the percentage of passengers using priority boarding, meaning they will board in a separate group before all other passengers, impact the total boarding time for the five different methods?*

5.2.1 Back-to-front method

The results in Table 2 shows that the back-to-front method had a decrease in average boarding time when priority boarding was introduced. When a percentage of passengers board before the actual boarding method is started, there are fewer passengers per boarding group boarding when the "general boarding" has begun. This leads to shorter queues in the aisle which leads to a shorter waiting time in these queues which leads to a decreased average

boarding time.

5.2.2 WILMA method

The WILMA method had the highest increase in average boarding time out of the four methods tested, as can be seen in Table 2. This can be attributed to the fact that priority boarding compromises the strength of the WILMA method. With 0% priority boarding, the WILMA method has no aisle congestion as a result of passengers having to get out of their seats and letting other passengers pass since the columns of seats are filled from the window seats to the aisle seats. When priority boarding is introduced, there is a chance that passengers in middle seats and aisle seats board before passengers with seats further in. This creates more aisle congestion, leading to an increase in average boarding time.

5.2.3 Steffen method and Block method

Table 2 reveals that the Steffen method had no change in average boarding time and the block method had a minimal change in boarding time. The results in the Steffen method can be explained by the that the Steffen method is designed to have a minimal amount of interactions between the passengers [7]. Since the boarding is done from the back of the airplane to the front, even if a passenger with priority boarding has to get out of their seat and let another passenger get past, this interaction will in no case delay the boarding time for any other individual passengers enough for it to impact the total boarding time.

The block method has its explanation. The block method can be seen as three instances of random boarding, with each boarding group being one instance. With priority boarding, there is one small group of random boarding before the block boarding has begun. This will make the three

boarding groups in the block method a fraction smaller, but the boarding method will essentially work as it would with no priority boarding. The 0.44% decrease in average boarding time could be attributed to the random nature of where the priority boarding passengers are seated. An increase in the number of simulations for the boarding method could give a more accurate result, that may be closer to that of 0% priority boarding.

5.2.4 Comparison of methods

Overall priority boarding had little to no impact on the different methods. Priority boarding had a small positive impact on back-to-front boarding, and no, or a small negative impact on the other boarding methods. It is important to note that the study only considered at most 20% of passengers having priority boarding. Since in most cases, priority boarding does not negatively impact the boarding time, priority boarding is a tool that can be used to increase passenger satisfaction. Those who pay for priority boarding get to board before everyone else, and the others don't have to wait longer than they otherwise would. The airline's profits from priority boarding could theoretically be reinvested into working for a more sustainable future in air travel.

These results differ slightly from the previous research done in the field, where it was found that priority boarding increases the boarding time slightly, by on average 2.4% for the methods that were tested [8]. However, this research was conducted on a single-aisle aircraft, where all passengers with priority boarding were seated in the front two rows of the airplane [8]. These differences in scenarios may explain the slightly different results.

The effect of priority boarding could be compared to the effect of conformance rate on different boarding methods. 10% of passengers having priority boarding is comparable to 10% of passengers not conforming with the boarding method. When looking at the results in this way, they follow the same trend as the results of previous research, with the back-to-front

method improving and the others having little to no impact [4]. This suggests that as the number of passengers who have priority boarding increases the boarding time will converge toward that of the random method [4]. This is supported by the fat that if 100% of passengers had priority boarding, the entire boarding process would be equal to that of the random method, regardless of which boarding method was used. This further argues for the fact that as the percentage of passengers with priority boarding increases, the boarding time converges towards that of the random method. It is worth noting that as the number of passengers with priority boarding increases the change in boarding time is not as drastic as in previous research. This could be explained by the fact that the conformance is not performed in exactly the same way as priority boarding. When passengers are not conforming with the boarding method, they board with another boarding group, as opposed to before all boarding groups [4]. Additionally, the study takes carry-on luggage into account, which impacts the effect of conformity [4]. This study does not take carry-on luggage into account, instead, it isolates priority boarding on its own to see the effect of just priority boarding. These two differences could be a factor which impacts the effect on the boarding time.

5.3 Limitations

While this study has provided valuable insights into the impact of carry-on luggage and priority boarding on the boarding time for a Boeing 777-300ER, several limitations should be acknowledged. One limitation of the study is the focus on analyzing these factors in isolation, without considering potential interactions between carry-on luggage and priority boarding. This narrow scope may limit the applicability of the findings to real-world boarding scenarios where these factors may interact.

Another limitation is the assumption that all passengers are able-bodied adults travelling in economy class which may not fully capture the diversity

of passenger demographics and needs that can influence boarding efficiency. The agents in the study also know exactly where their seats are, which would not be a fair representation of the average passenger who could enter the wrong aisle or accidentally walk past their assigned seat. Additionally, the study did not account for external factors such as weather conditions or airport layout, which could impact boarding time in real-world scenarios.

Furthermore, the simulation-based approach used in this study may not fully replicate the complexities and dynamics of actual boarding processes, leading to potential discrepancies between simulated and real-world outcomes. The study has not taken human error and interference into account. For example the problem of passengers not finding available space in the overhead compartment for their carry-on luggage. This would force the passengers to walk around the airplane looking for space for their luggage, creating more aisle congestion. These limitations highlight the need for future research to address these constraints and enhance the understanding of boarding procedures in airline operations.

5.4 Future research

A potential area for future research involves examining the synergistic effects of various factors on boarding efficiency within the airline industry. This could entail investigating how the combination of factors such as carry-on luggage, and priority boarding collectively impact boarding times. Furthermore, exploring novel boarding methods or technological solutions, such as automated boarding systems or predictive analytics, may provide valuable insights for optimizing the boarding process. Conducting empirical studies to validate simulation outcomes and integrating real-world data into modelling approaches could enhance research findings' practical relevance and applicability in airline operations.

6 Conclusions

This report has investigated how carry-on luggage and priority boarding affect the boarding time on a Boeing 777 300ER. The results show that the average boarding time increased with a higher ratio of passengers with carry-on luggage for all boarding methods, with variations in the magnitude of the increase across different strategies. The Steffen and WILMA methods were affected the least and back-to-front being affected the most. Additionally, the study found that the impact of priority boarding on the boarding time varied among the different boarding methods, with Steffen, WILMA and block having little to no change in boarding time and Back-To-Front having a decrease in boarding time.

Using these results, it is clear that some boarding methods are affected more than others by carry-on luggage. It is therefore beneficial for an airline to change their boarding method if they are confident that a certain number of passengers will bring carry-on luggage onto the airplane. The results also show that priority boarding has next to no impact with the small numbers of passengers with priority boarding that was tested. We suspect that there would be a greater change in boarding time when the percentage of passengers with priority boarding increases further. The results would then converge toward the boarding time for the random method [4]. It would therefore be beneficial for an airline to change their boarding method to the random method if there is a great number of passengers who have opted for priority boarding. Furthermore, if less than 20% of passengers have priority boarding, priority boarding could be used as a tool to increase passenger satisfaction.

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