SMOOTH SKIES AND SWIFT BOARDING: ANALYSING THE INFLUENCE OF FAMILY, PRIORITY, AND LUGGAGE ON COMMON BOARDING STRATEGIES

Bachelor's Project Thesis

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Abstract: While aircraft boarding may seem like a routine part of air travel, the efficiency of the boarding process plays a crucial role in ensuring on-time departures and a smooth passenger experience. In this paper, we will examine the impact of in-cabin luggage handling alongside family and priority boarding on the overall boarding time of five common boarding strategies (random, window-middle-aisle, back-to-front, front-to-back, and window-middle-aisle combined with back-to-front). The research employs an agent-based modeling approach using the NetLogo platform to simulate and analyze the different boarding scenarios. The study begins by establishing a baseline scenario without any special considerations, where passengers board the plane according to the desired strategy. Subsequently, family boarding is introduced, allowing families with young children to board first. Priority boarding is then incorporated, giving priority to passengers with special needs or premium status. Finally, the influence of luggage management is examined, considering the time required for passengers to stow their carry-on bags. The simulations revealed that when all mentioned factors are present, the window-middle-aisle strategy provides the least boarding delay, closely followed by the random strategy, and that luggage affects boarding time the most. The results suggest that airline companies should focus on allowing concurrent luggage stowing, without piling up groups of passengers into one zone. These findings have practical implications for airlines, airports, and industry stakeholders, informing decision-making regarding the implementation of strategies aimed at minimizing boarding time and improving the overall passenger experience.

Keywords: boarding strategies, family boarding, priority boarding, luggage management, NetLogo, agent-based modeling.

1 Introduction

During the last two decades, air travel has become increasingly accessible to the general public, making it one of the most popular modes of transportation around the world (Flynn, 2022). Bringing in over 800 billion dollars in profit (before the 2020 Covid pandemic) worldwide, the global airline industry market is looking now more than ever to increase its revenue, especially after the hardships the Covid-19 pandemic has brought (Flynn, 2022). As commercial airlines only generate income when a plane is flying, everything else being considered a cost, reducing the passenger boarding time is a major priority. One of the main reasons why boarding is crucial for commercial airlines is that it directly influences aircraft turnaround time. Turnaround time refers to the duration it takes an aircraft to complete one flight and be ready for the next one. The faster an aircraft can be turned around, the more flights it can make and the more revenue it can generate for the airline. Nyquist & McFadden (2008) have estimated that the cost of a minute on the ground for an airplane can be much as $30 and Mouawad (2011) approximated that the average boarding time is somewhere between 30 and 40 minutes for 140 passengers. Thus efficient boarding can help minimize turnaround time and increase an airline's profitability. In the long term, efficient boarding can also boost customer satisfaction, creating more loyal customers. All of this and more are contributing to the development of different boarding strategies and the 'race' between different airlines in finding the best one.

Currently, the most popular airplane boarding strategies are (Ozmec-Ban et al., 2018):

- Random: The most common strategy, where passengers will board the plane in the order that they arrive at the gate. No further specifications or restrictions.
- Zone boarding: This strategy involves dividing passengers into different groups or zones, typically based on seat location or fare class, and then boarding each group one at a time.
- WMA (Window-Middle-Aisle): In this method, the people next to the window seats will board first, followed by the people having the middle seats, and then finally the aisle seats.
- Back-front WMA: Similar to the WMA approach but the boarding starts from the back of the plane.

In this paper, we will explore and compare several different boarding strategies and evaluate their effectiveness in reducing plane boarding time, thus answering our main research question: "How do family boarding, priority boarding and luggage affect the time-efficiency of different boarding strategies?". In order to do this, we will create an agent-based model in NetLogo focusing on the strategies mentioned above while also adding a couple of new and important variables such as: luggage, priority boarding, and family boarding.

There has been extensive research into plane boarding strategies, with a particular focus on developing mathematical and computational models to simulate the boarding process. Previous research has compared multiple boarding strategies and has taken into consideration more external variables such as airport organization (Bidanda et al., 2017), different plane configurations and multiple entry options (Delcea, Cotfas, & Paun, 2018) or concentrated on the time delays caused by seat and aisle interferences (Delcea, Cotfas, Crăciun, & Molanescu, 2018). In this paper, we will focus on a set type of airplane, the Boeing 727, with one entry point and will compare five boarding strategies ranging from common to less common.

2 Model description

For this study, we have developed an agent-based boarding model with the aim of comparing various boarding methods, particularly those that involve specific passenger arrangements during the aircraft entry phase. The model is centered around agents, self-governing entities with distinctive characteristics and behavior that operate within an environment. In this context, mobile passenger-agents are used to represent actual passengers, and their primary objective is to navigate through the aircraft to reach their designated seats. Another important element are patches, representing the basic building block of the environment that can be individually accessed and manipulated by agents. In our context, the plane itself (with the seats and aisle) represents the multiple patches our agents interact with in order to reach their goal. The whole model was implemented in NetLogo 6.2.2 due to its agent-based modeling capabilities, making it ideal for simulating complex systems that involve the interactions between multiple agents, and its visualization properties, making it easy to interpret and communicate the results of our model (Wilensky, 1999). An overview of the environment can be seen in Fig.2.1.

2.1 Model development

To develop the model, we first created an aircraft cabin with a seating arrangement similar to that of a Boeing 727. We created seats using the NetLogo patches and defined the seating arrangement within the cabin. Each seat has a unique XY coordinate combination and is assigned a label from the set A, B, C, D, E, F based on its position. As mentioned above, the passengers will be represented as agents and will board the plane from one entry point at the front of the plane in an orderly manner. The number of passengers is defined as a variable and can be modified to simulate different boarding scenarios. In order to simulate the most difficult, time-intensive scenario, we will work with

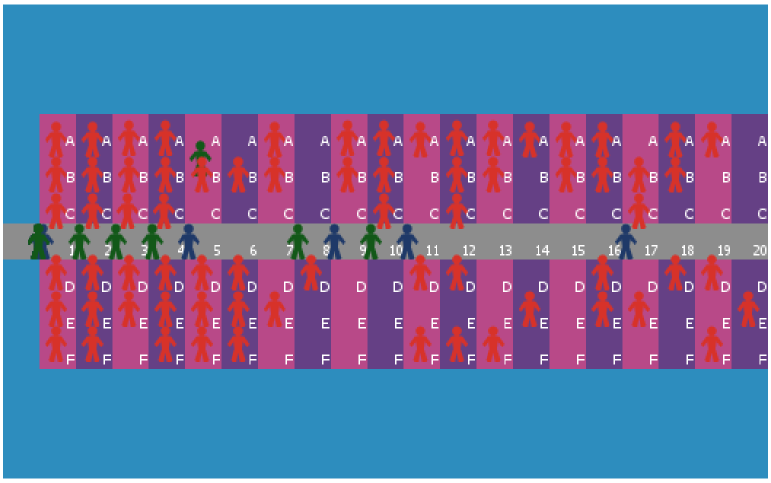

Figure 2.1: A basic overview of the model interface with passengers (green) boarding from the left, in a manner set by the embarking strategy, with some (blue) having luggage that needs to be stowed in the overhead compartment before getting seated (red).

a full plane of 120 passengers for all our simulations.

After having developed the agents and the environment, we then created the rules for the different boarding strategies and finally added special constraints such as priority and family boarding, and a luggage counter indicating what is the percentage of passengers with baggage that has to be stored before being seated. In order to compare the amount of time it takes to board for the different scenarios, we will compare the average amount of ticks every iteration has during multiple runs. A run is considered complete when all the passengers are seated. In order to visually differentiate between a seated and a non-seated passenger, once an agent has found their seat and reached it, its color will turn from green to red (see also Fig.2.1).

In a simulation study on airplane boarding, Van Landeghem & Beuselinck (2002) found that the most efficient method of boarding passengers, was to do so by calling their row and seat number individually. While this is an approach we will lightly touch on in this paper (elements of this can be seen in the priority boarding or in the strategies involving splitting people into groups), there are other interesting models which take into consideration variables which we will not reproduce in this study such as: seat interferences (Delcea, Cotfas, Crăciun, & Molanescu, 2018), boarding strategies that are rarely used in practice, such as by-half-row-front-to-back or half-block back-to-front (Delcea, Cotfas, & Paun, 2018), and different passenger behaviour (Jafer & Mi, 2017).

2.2 Implemented strategies

Before comparing the different plane boarding methods that were implemented, it is important to have a basic understanding on how the agents broadly behave:

1. All agents queue and board at the front of the plane. (left side in Fig.2.1)

2. They move forward through the aisle (indicated as the grey color which can be seen in Fig.2.1), until they are at the designated seat. Once at their seat row, they can leave the aisle and move towards the seat.

3. While in the aisle, agents are not allowed to overtake any agent that is directly in front of them.

4. Passengers will not get up for other passengers once they have taken their seat. That is, we do not model seat interference. Instead, all agents will start moving 60% slower when heading towards their seat in their designated seat row.

Despite ongoing research efforts aimed at developing new and improved boarding methods, the airline industry has been relatively slow to adopt such practices in recent years (Bazargan, 2007). Instead, the majority of airlines have continued to rely on traditional boarding methods. Having now a basic understanding of how the simulation is structured, we will discuss more in-depth about the five different boarding strategies implemented, with some being more commonly practiced than others in the real world:

- Random boarding: In this first strategy, the passengers/agents simply board the plane in random order. This strategy is often used by airlines because it requires no special arrangements and is easy to implement. In our model, this method is the least restrictive one.
- Back-to-front boarding (BTF): The second strategy, back-to-front boarding, involves passengers entering the plane in reverse seat order, starting from the back rows and moving backwards. This strategy is based on the assumption that passengers sitting in the back of the plane will not have to wait for passengers in front of them to store their bags or get seated, and therefore will board more quickly. This method is highly used by Asian and American airlines (Delcea, Cotfas, & Paun, 2018). In our model, we divide the plane into four big sections, one section having five full rows, each with six seats. We have chosen to split the seating arrangement into four zones based on how it is done in everyday practice on similar planes (Hilsz-Lothian, 2019). Therefore the first people to board are seated somewhere in rows 20-16, then the people having rows 15-11 will board, and so on until the front of the aircraft.
- Front-to-back boarding (FTB): Similar to the BTF method, the FTB strategy will group passengers into different zones and let them board the plane starting from the front rows and moving forward. This strategy is often used by airlines in order to prioritize certain groups of people. In our model, the plane will be divided into the same four sections as the BTF strategy, but now the people having seats in the rows 1-5 will board first, then the people having the 6-10 rows and so on until the back of the plane.
- Window-middle-aisle boarding (WMA): This strategy involves dividing the passengers into three main groups: those which have the window seats, those with the middle seats, and the rest with the aisle seats. As the name suggests, the passengers with the window seats will board first, followed by the passengers with the middle seat, and finally the passengers with the aisle seat. The implementation of this strategy is based on the assumption that it will effectively reduce the time passengers have to wait for others to take their seats, by avoiding seat interference (Nugroho & Asrol, 2022). For our model, the agents with the assigned seat label of A or F will board first in a random manner, followed by the people having seats with label B or E and then C or D.
- Window-middle-aisle with Back-to-front boarding (WMA-BTF): Lastly, as the name suggests, this strategy is a combination of the WMA one with the BTF one and it involves passengers being once again divided into zones. The first passengers to board will be the people that have a window seat at the back of the plane, followed by the people having the aisle seat, still at the back of the plane, and so on. This strategy is not as common as the ones mentioned above, but having combined the advantages of BTF and WMA boarding, we have decided to implement it to see if it would perform better than them by being more selective with its procedure. In our model, the plane will be once again divided into the four big zones we have seen before, and the agents will board keeping the BTF strategy in mind while also keeping track of their seat distribution just like in WMA. For us, this strategy was the most involved rule-wise.

2.3 Experimental variables

Boarding an airplane is a complex process that involves a variety of factors beyond the chosen boarding strategy. Passengers carry different amounts and types of luggage, which affects the time required for them to stow their items in overhead compartments or under their seats. Additionally, airlines may offer priority boarding to certain passengers based on factors such as frequent flyer status or disability, which can disrupt the planned boarding sequence. Other factors such as the size and layout of the aircraft, the number of doors available for boarding, and the efficiency of the ground crew can also impact the boarding process. Consequently, a successful boarding strategy must take into account these and other variables in order to optimize the boarding process and minimize passenger inconvenience.

Therefore, in order to make our model represent more accurately a day to day aircraft boarding, we have decided to implement three additional variables besides the existing strategies, which will be described in the following subsections.

2.3.1 Luggage

Luggage plays a significant role in the boarding process of an airplane (Ren et al., 2020). Passengers typically bring a variety of bags and items, ranging from small carry-on bags to larger suitcases and special items such as sports equipment. As passengers enter the aircraft, they must find a place to store their luggage, either in overhead compartments or under their seats. The amount and size of luggage that each passenger brings can have a major impact on the boarding time, as it can slow down the process of stowing and retrieving items. Airlines have attempted to solve this issue by enforcing limits on the size and number of carry-on bags allowed, as well as charging fees for checked luggage. However, these policies have not eliminated the problem entirely, and the boarding process can still be delayed by passengers struggling to fit their luggage into the available storage space.

For the current model, in order to implement passengers with luggage we have created a slider indicating what percentage of the passengers will have carry-ons. A person with luggage will be represented as a blue-ish color in order to visually differentiate them and will differ from a person without baggage in the sense that while at their seat, a person with no luggage can just go to their seat without waiting, while a person with luggage blocks the aisle while stowing their luggage for the amount of time mentioned in TableA.2. A visualization of this can be seen in Fig.2.2

In order to better simulate the different amount of time each person takes in order to stow some type of luggage either big or small, each person will wait a different amount of time (between 100 and 210 ticks) before getting seated. It is worth remembering that an agent will not be able to overtake another one, so we expect this feature to have a significant effect on the total boarding time.

It is also important to note that we assume that everyone will have space in their overhead compartment to stow their luggage and they will not have to search for space somewhere else on the plane.

2.3.2 Family Boarding

Family boarding is a boarding process where airlines allow families with small children to board the plane before other passengers. This process is aimed at providing families with more time to get settled and avoid the rush of boarding. Most airlines provide families with children to board first, even if it often requires more time for them to get situated and seated on the plane, which can delay the boarding process for other passengers.

For our model, we can have anywhere from 0 to 5 families present, ranging from a size of 3 to 6 people in a family. The families will always board after the priority passengers (see next section) and before all other passengers. They will also advance slower on the aisle since we assume that moving with children will always be a bit more difficult. In order to showcase that they are a family, instead of randomly placing passengers, we have created for every family size a specific seating arrangement. For example, if a family contains 4 people, in order to not leave any family member alone, we have implemented that they will sit in pairs of 2, one pair behind the other. If they are for example 5 people in a family, 3 people will occupy a full row, while the other 2 people will sit behind them. The most important aspect of family boarding is that a whole family boards together at a time and all the members of a family will sit next to each other. A nice visualization of how some of the different seating configurations for the different family sizes can be seen in Fig.2.3

It is worth noting that the family boarding will override the existing boarding strategies in the sense that families will not take their places according to the boarding strategies mentioned above, but

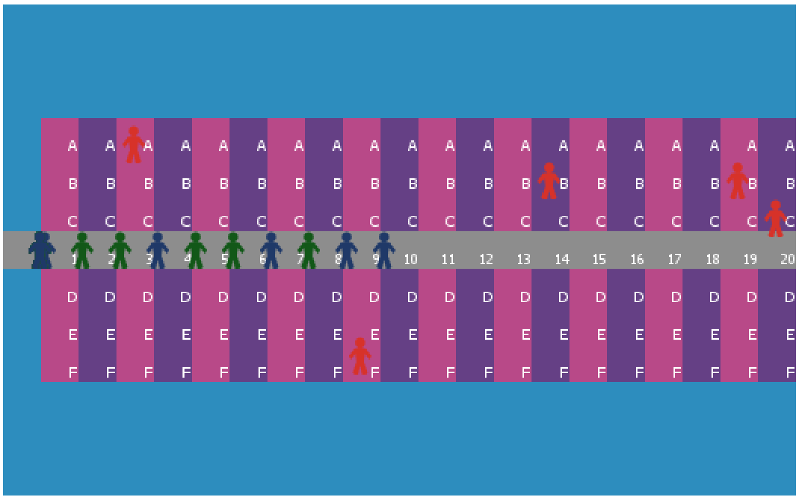

Figure 2.2: Example of boarding with luggage showcasing how other passengers have to wait for the passenger in row 10 to stow their luggage.

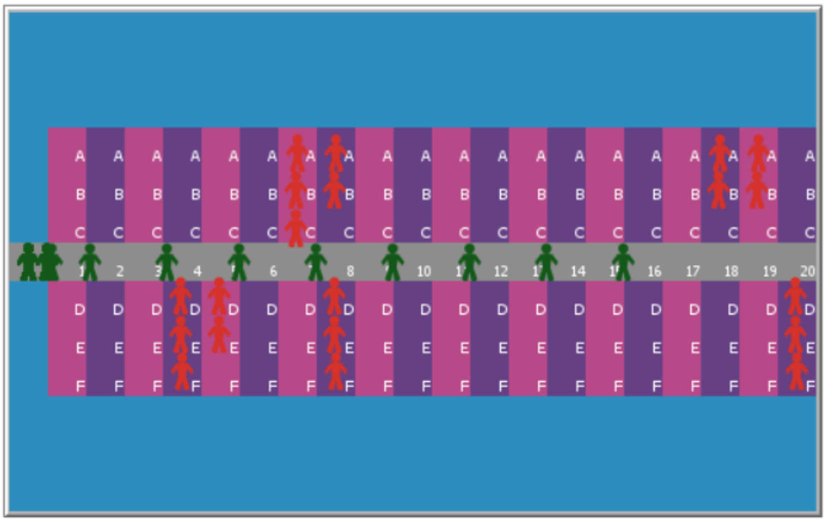

Figure 2.3: Example of family seating arrangements. All the seated passengers constitute different families.

rather according to the pre-set configuration based on size. The families will also never take any of the seats assigned to the priority passengers (the first two rows), so that interference between the two groups will not appear. One important assumption is that unless in a family, each passenger-agent will move independently. Finally, in order to better visualize the families in the simulation, the color of the agents being in a family will be black.

2.3.3 Priority Boarding

Priority boarding is a service offered by many airlines to passengers who pay extra or have achieved certain status or loyalty with the airline and it allows these passengers to board the aircraft before others. This service is often promoted as a way to provide convenience and comfort to passengers, but it can also have implications for the overall boarding process. In terms of the overall impact on boarding time, the effect of priority boarding depends on the number of passengers with priority status and the efficiency of the boarding process. If the number of priority passengers is small and the boarding process is well-organized, priority boarding may not have a significant impact on the overall boarding time. However, if the number of priority passengers is large or the boarding process is inefficient, priority boarding can increase the boarding time and cause delays for all passengers (Kisiel, 2020).

In our model, due to the size and configuration of the chosen plane, the first two full rows will be reserved for priority passengers. This is an accurate real-life representation of how the first class passengers will always have their seats at the front of the plane due to boarding convenience and faster service if applicable (Oancea, 2018). In order to enable this feature we have created a switch called *priority?* and once turned on, all the strategies mentioned in the previous section will get overwritten, enabling the first two rows to be fully occupied first by the priority passengers in a random manner. Once all these passengers have boarded, the strategies will resume their usual course of action. While it might seem like a constraint that the priority passengers will board randomly, this accurately describes how it happens in real life (Kisiel, 2020).

2.3.4 Model Variables

It is necessary to make certain assumptions and simplifications in order to create a model that is both practical and useful for analyzing the impact of boarding strategies. Therefore, in order to have a full picture of how the model works, it is important to keep in mind the assumptions we have made so far, and for a better understanding, we will also describe some of the most important variables of our simulation in Table A.2, which can be found in the appendix.

3 Results

Having now all the information on how the model operates, the simulations presented in this section have considered the situation in which the Boeing 727 airplane is fully-boarded, having 120 passengers seated. All of the 5 methods presented above have been considered, although literature suggests that some of them, specifically the front-to-back boarding approach, produce sub-optimal results in terms of boarding time (Delcea, Cotfas, Crăciun, & Molanescu, 2018; Jafer & Mi, 2017). We have decided to keep it in our study in order for us to have a more complete picture of the boarding process. Given that certain strategies involve splitting passengers into distinct groups, it is important to note that when initially boarding, there will be 2 patches dividing the different groups, in order ensure a clear division between them (this gap of 2 patches becomes smaller as the passengers board the plane and have to wait in the aisle). Each of the 5 strategies has been run 400 times using the Behaviour Space tool integrated in NetLogo.

3.1 Boarding strategies alone

The analysis has been carried out first of all in terms of the boarding strategies alone, without priority/family boarding or luggage. We wanted to see how the strategies behave at a baseline, and if adding extra variables changes the ranking in any way. The results of this first situation are shown in a boxplot format in order to get a better sense of distribution of boarding times rather than merely the average and can be seen in Fig.3.1.

The results below suggest the fact that the WMA_BTF strategy is most effective when no other external factors are at play (median of 2450 ticks), followed really closely by BTF with a median of 2460 ticks, WMA with 2500 ticks, random with 2570 and finally FTB with a median of 2630 ticks. These results are somewhat unsurprising, similar papers also suggesting that WMA_BTF is a good and fast strategy (Delcea, Cotfas, & Paun, 2018) and just like WMA, it minimizes the waiting in the aisle thanks to its minimal seat interference, contributing to its reduced number of ticks. It is also interesting to note that the random strategy showcases the biggest variation in boarding time amongst all the other methods. This is most likely due to its unpredictable nature. We can also observe a somewhat small number of outliers amongst the strategies, suggesting that our methods are stable.

There is no overlap in the data between the WMA_BTF and BTF strategies compared to the FTB one, the boarding time being significantly

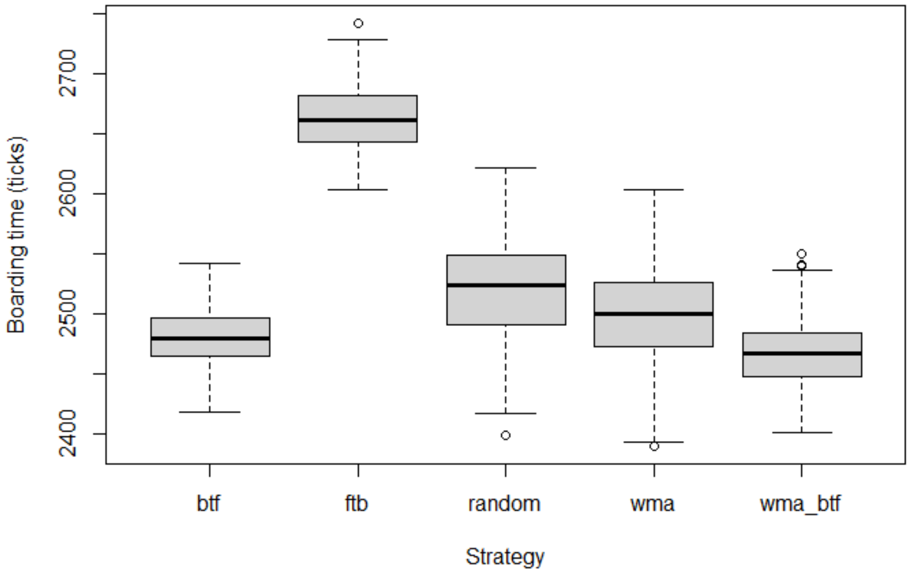

Figure 3.1: Boarding times of the different strategies without priority/family boarding or luggage. Each strategy was ran 400 times.

higher for the latter, showcasing a clear difference between the three. Overall we can notice that for this situation, there is little overlap between all the presented strategies. Lastly, the range for this scenario is between 2380 and 2780 ticks.

3.2 Priority boarding

After having seen how the boarding strategies behave by themselves, we will start adding the experimental variables one by one for a better understanding and visualization of the results. We will first add the priority boarding passengers since we believe that they might affect the results presented in the previous sub-section the least, due to their isolated nature (they do not follow any strategy, but rather board at random in the first rows) and small number, thus we will have a more natural transition. The results for this second situation can be seen in Fig.3.2.

As expected, the ranking of the boarding strategies remains the same as previously stated, with the predictable observation that the average amount of ticks will increase for every method presented. The WMA_BTF strategy will now have a median of 2500 ticks, followed by BTF with a median of 2540 ticks, WMA with 2580 ticks, random with 2600 ticks, and finally FTB with a median of 2720 ticks. We can conclude that when having a rather small number of priority passengers, their impact on the overall boarding time is quite limited, even if a new group has to be formed and seated, making all the other passengers wait just a bit longer. The average time of boarding will increase with about 66 ticks which is approximately a 2.4% growth in time from the previous situation.

Once again, there is little to no overlap between the data of the strategies, indicating that there is a clear difference between their medians and that they behave differently. It is also interesting to note that compared to the results in Fig.3.1, the gap between the WMA_BTF strategy and the BTF/WMA ones has increased quite a bit. The range for this scenario will be between 2450 and 2800 ticks.

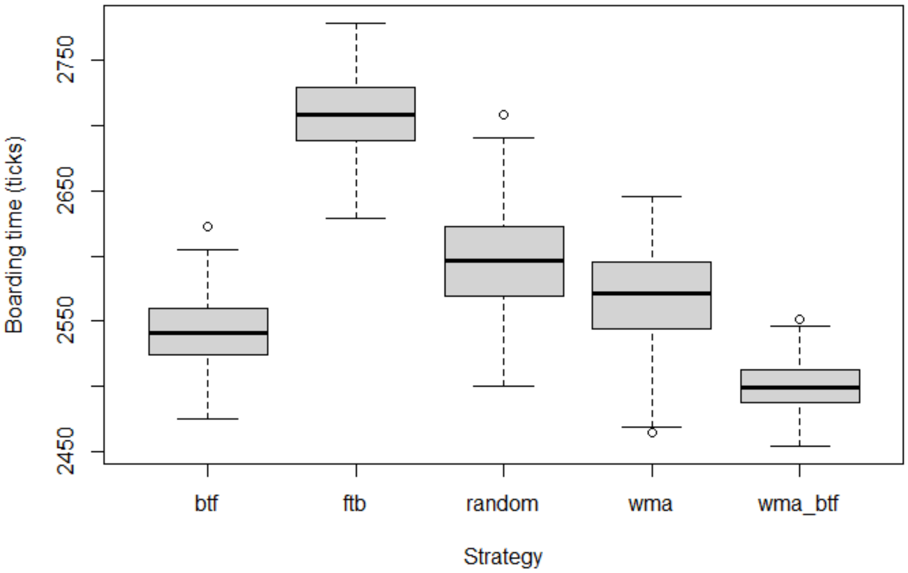

Figure 3.2: Boarding times of the different strategies with priority boarding but without families and luggage. Each boxplot represents 400 simulation runs.

3.3 Family boarding

After having observed how our strategies behave with priority passengers, it is time to implement a more drastic change: family boarding. As mentioned above, this experimental variable is different than the priority passengers one, in the sense that while families will also not abide by the rules of the current strategy, members of a family will board together at the same time, and based on size, will occupy a certain seat arrangement in the plane. It is worth remembering that these passengers will board after the priority ones and before anyone else. After having run our simulations, the current results of this scenario can be observed in Fig.3.3.

For the first time in our results we can now observe a greater variance for each of the different strategies, and much bigger whisker bars. This is most likely due to the fact that families are stochastic. The sizes of the families can vary and the number of families will do so as well. Looking at the average amount of ticks per strategy, it appears that the difference between them has become significantly smaller. The ranking of the strategies has changed a bit, the WMA_BTF method is once again the best and has a median of about 2750 ticks, followed by WMA with a median of 2900 ticks, BTF and random appear to have the same median of about 2920 ticks, and finally FTB with a median of 2970 ticks. Judging by these values, we can conclude that family boarding has a noticeable impact on the total boarding time. The average time of boarding will increase by 290 ticks, which is approximately a 11.2% increase in time from the previous scenario. These results were somewhat expected, given the fact that we will now have multiple groups of passengers which have to be formed and seated before others can proceed further. Not only that, but we also assumed that families move slower since they have to be accompanied by kids and that they will take a random place/zone in the plane. Given the fact that the data between the strategies overlaps quite significantly, we can no longer say that there is a clear difference between the strategies. Therefore we have decided to do a one-way ANOVA test on all five methods, with the null hypothesis (H0)

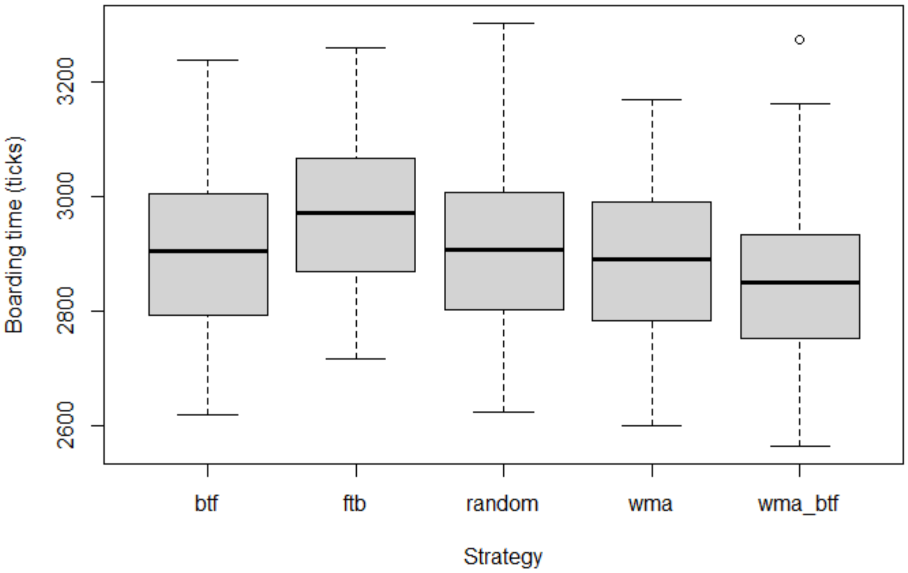

Figure 3.3: Boarding times of the different strategies with priority and family boarding, but without luggage. Each boxplot represents 400 simulation runs.

stating that the mean boarding times (number of ticks) for all five methods are equal.

Given the fact that the recorded p-value was less than the significance level of 0.05 (see Table A.1 in the appendix for the full ANOVA table), we can safely reject the null hypothesis, and conclude that at least one of the means was significantly different. In order to see which strategies are statistically different from one another, we have decided to perform a Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc test for pairwise comparisons. This showed us that on average, the FTB strategy takes significantly longer than any other strategy ($p < 0.0005$) and WMA_BTF takes significantly shorter than any other strategy ($p < 0.0005$). We also saw that random, WMA, and BTF do not seem to differ significantly in boarding time. Finally, the range for this scenario will be between 2580 and 3300 ticks.

3.4 Luggage

Now that we have seen how the strategies behave when implementing step by step the priority and family boarding, it is time to implement our most demanding extra variable, giving a percentage of the passengers luggage. United Continental reports that the percentage of passengers who bring bags on board has remained around 85% in recent years (Freed, 2013), therefore for our simulation we will stick to that value. Additionally, Freed (2013) stated that the size of the carry-on has increased. As a brief reminder, before getting seated, passengers will have to wait the specified *luggage-time*, in order to stow their baggage in the overhead compartment. Any type of passenger can have luggage, whether it is priority, family or just regular. This is the scenario where we will get as close as possible to how boarding takes place in real life, and the results can be observed in Fig.3.4 on the next page.

Judging by our results we can see that the rankings of the strategies has changed drastically. WMA_BTF is no longer the best strategy as it has been previously (current median of about 13080

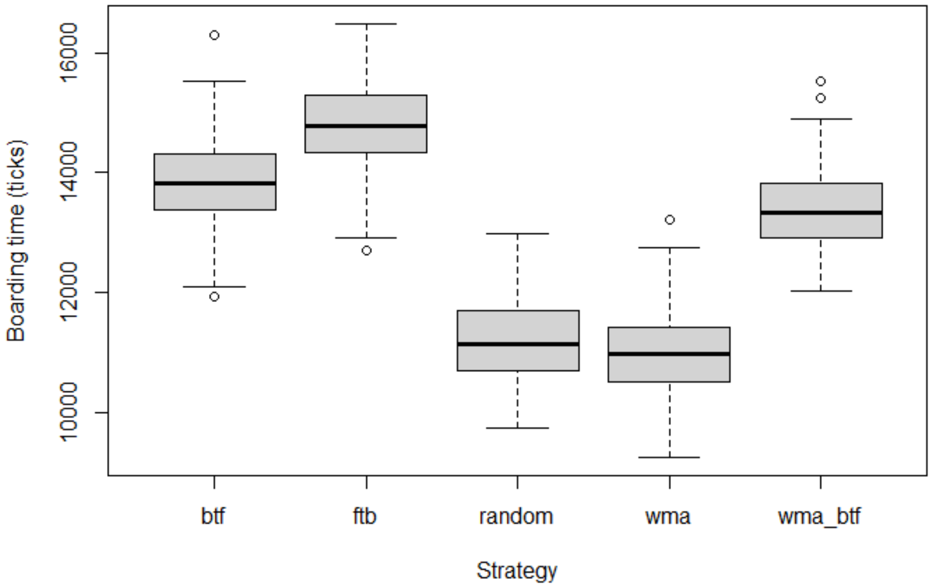

Figure 3.4: Boarding times of the different strategies with priority and family boarding, and with luggage.

ticks), but has rather been replaced by WMA (median of 10200), followed closely by the random strategy (median of 10500). The worst performing strategies will be BTF with a median of about 13800 and FTB as expected, with 14700 ticks. It is clear from these results that luggage has the biggest impact on the boarding time from our experimental variables, the average time of boarding increasing by approximately 380% from the previous scenario. While the final ranking of the strategies might look surprising at first, the outcomes were to be expected, since judging by related papers (Schultz et al., 2008; Delcea, Cotfas, & Paun, 2018), the WMA boarding method exhibits consistently high efficiency alongside with the random method. Closer inspection reveals that the other strategies cause piling up of the passengers, either at the front (FTB) or at the back (BTF/WMA_BTF) which is most likely the reason for their poorer performance. That is, spreading out the passengers performs better because it allows multiple passengers to stow their luggage at their seat at the same time. Despite the absence of seat interference implementation, which is a big factor in everyday boarding, it is intriguing to observe the remarkable performance of the WMA strategy. The WMA strategy demonstrates quite an advantage in terms of its ability to streamline the boarding process, even without considering the potential hindrances posed by seat interference. This finding highlights the effectiveness and robustness of the WMA strategy, suggesting that it possesses inherent qualities that contribute to its good performance.

Lastly, we can see little to no overlap between the data of the five strategies, showcasing that there is a clear difference in performance between them. An exception to this would be by looking at the WMA and random strategies, the findings suggesting that both WMA and random demonstrate similar levels of effectiveness in terms of boarding time. This implies that, in practice, the choice between these two strategies may not meaningfully impact the overall efficiency of the boarding process. The similarity in performance between the WMA and random strategies could be attributed to several factors. Firstly, the random strategy introduces an

element of unpredictability, which can lead to a more evenly distributed flow of passengers during boarding. On the other hand, the WMA strategy utilizes a weighted approach that prioritizes certain passenger groups or sections of the plane, optimizing the boarding process in a different way. Overall, the findings suggest that both the WMA and random strategies can be viable options for achieving efficient boarding, providing flexibility for airlines to choose the strategy that aligns best with their circumstances and goals.
Lastly, the range of boarding times for this scenario falls between 9500 and 16400 ticks.

4 Discussion and conclusion

The current research considers five of the most common boarding strategies employed by big airline companies and offers an agent-based model developed using NetLogo as a means of establishing a shared framework for testing the efficacy of these methods. The biggest challenge when creating the model was designing agents that would behave similar to humans when being put in the similar situations. In order to accomplish this, we have looked into how other researchers have modelled passengers in similar simulations (Oancea, 2018) and have consulted papers on people's queuing behavior (Maister, 1984). Since our main focus was on finding the most time-efficient strategy to board a plane, judging by our results, we can say that for our conditions, the best performing strategy when it comes to a boarding that tries to resemble real-life as much as possible is the window-middle-aisle (WMA) strategy, closely followed by the random one. Our agent simulations reveal that the success of these boarding strategies can be attributed to the fact that passengers will not have to all stow their luggage at the same time in the same section, but rather they will be more spread out, allowing for a more concurrent luggage stowing. Schultz et al. (2008); Delcea, Cotfas, & Paun (2018); Nyquist & McFadden (2008) found similar results to ours, further reinforcing that WMA has a good time performance overall. Our results suggest that WMA is a time-efficient boarding strategy even if factors such as seat interference are not taken into account. It is worth noting that the three papers just mentioned also further solidify our results by pointing out that the back-to-front (BTF) and front-to-back boarding strategies (FTB) are consistently bad strategies when it comes to efficiently boarding an airplane. Thus, when coming up with a new boarding strategy, one should consider minimizing piling up groups of passengers into the same section and should focus instead on allowing for more concurrent luggage stowing. It is important to reiterate that luggage was the factor that had the biggest impact on the boarding time of all the strategies, thus if airline companies decide to change significantly their policy regarding cabin baggage, we expect the rankings of the boarding methods to change (based on how the rankings behaved in our intermediate results which can be seen in the previous section).
When it comes to limitations, we acknowledge that our model does not fully encompass everything that takes place in a real-life boarding situation. Thus, it would be interesting to extend this model in the future with features such as: seat and aisle interference (cf. Delcea, Cotfas, Crăciun, & Molanescu (2018)), customer satisfaction (cf. Hiemstra-Van Mastrigt et al. (2019)) and having the possibility to board from two doors (which is a big aspect especially for low-cost airlines). In the end, we believe that the findings of this study can be used to improve the efficiency of the boarding process, which can lead to shorter wait times for passengers and a more efficient use of resources for airlines.

References

Bazargan, M. (2007). A linear programming approach for aircraft boarding strategy. *European Journal of Operational Research*, *183*(1), 394-411. doi: https://doi.org/10.1016/j.ejor.2006.09.071

Bidanda, R., Winakor, J., Geng, Z., & Vidic, N. (2017). A review of optimization models for boarding a commercial airplane. In *Proceedings of 24th International Conference on Production Research. Poznan, Poland* (pp. 1–6).

Delcea, C., Cotfas, L.-A., Crăciun, L., & Molanescu, A. G. (2018). Are seat and aisle interferences affecting the overall airplane boarding time? An agent-based approach. *Sustainability*, *10*(11), 17-42.

Delcea, C., Cotfas, L.-A., & Paun, R. (2018). Agent-based evaluation of the airplane boarding strategies' efficiency and sustainability. *Sustainability*, *10*(6), 18–79.

Flynn, J. (2022, Aug). Airline industry statistics [2023]: 28 facts to know before you fly. *Zippia Airline Industry Statistics 2023*.

Freed, J. (2013). Bulky suitcase? Overhead bins are getting bigger. *NBC News*.

Hiemstra-Van Mastrigt, S., Ottens, R., & Vink, P. (2019). Identifying bottlenecks and designing ideas and solutions for improving aircraft passengers' experience during boarding and disembarking. *Applied Ergonomics*, *77*, 16–21.

Hilsz-Lothian, A. (2019). *El Al Boeing 787-9 Seat Map.* `https://samchui.com/2019/12/11/el-al-to-\trial\-non-stop-flights-to-melbourne/\el-al-boeing-787-9-seat-map/#.ZEAPA3ZBxEY`. (Accessed on 02/04/2023)

Jafer, S., & Mi, W. (2017). Comparative study of aircraft boarding strategies using cellular discrete event simulation. *Aerospace*, *4*(4), 57.

Kisiel, T. (2020). Resilience of passenger boarding strategies to priority fares offered by airlines. *Journal of Air Transport Management*, *87*, 78–85. doi: https://doi.org/10.1016/j.jairtraman.2020.101853

Maister, D. (1984). *The Psychology of Waiting Lines*. https://davidmaister.com/.

Mouawad, J. (2011, Oct). Most annoying airline delays might just be in the boarding. *The New York Times*. Retrieved from `https://www.nytimes.com/2011/11/01/business/airlines-are-trying-to-cut-boarding-times-on-planes.html`

Nugroho, A. A., & Asrol, M. (2022). The impact of effectiveness of luggage arrangement on the airplane passengers' boarding process. *Periodica Polytechnica Transportation Engineering*, *50*(4), 369–386.

Nyquist, D. C., & McFadden, K. L. (2008). A study of the airline boarding problem. *Journal of Air Transport Management*, *14*(4), 197-204. doi: https://doi.org/10.1016/j.jairtraman.2008.04.004

Oancea, O. (2018). Challenges of pricing luxury in commercial aviation–will first class disappear? *Journal of Revenue and Pricing Management*, *17*(4), 296–300.

Ozmec-Ban, M., Škurla Babić, R., & Modić, A. (2018). Airplane boarding strategies for reducing turnaround time. In *18th International Conference on Transport Science, Portorož* (p. 28-41).

Ren, X., Zhou, X., & Xu, X. (2020). A new model of luggage storage time while boarding an airplane: An experimental test. *Journal of Air Transport Management*, *84*, 70–76.

Schultz, M., Schulz, C., & Fricke, H. (2008). Efficiency of aircraft boarding procedures. In *3rd International Conference on Research in Airport Transportation* (Vol. 371, p. 391-416).

Van Landeghem, H., & Beuselinck, A. (2002). Reducing passenger boarding time in airplanes: A simulation based approach. *European Journal of Operational Research*, *142*(2), 294–308.

Wilensky, U. (1999). Netlogo center for connected learning and computer- based modeling. Northwestern University. Retrieved from `https://ccl.northwestern.edu/netlogo/`

A Appendix

Source of variation	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Strategy	4	2987482	746871	43.27	$< 2e - 16$ ***
Residuals	1995	34433177	17260		

Table A.1: Results of the one-way ANOVA.

Variable Name	**Explanation**	**Value/Range**
planeSections	Indicates the number of sections we divide our plane into for the different strategies and aids in a more organized and clearly divided boarding procedure.	4
numberPassengers	Slider for setting the number of passengers who are set to board the plane. In order to simulate the most time-intensive scenario we will work with a full plane.	120
passengerSpeed	Indicates what the top speed of a passenger is while moving on the aisle. This value is scaled down to size. Worth noting that while stationary, this value becomes 0.	0.1 patches per tick
isSeated	Indicates whether an agent has taken its seat or not. The value becomes true only when the agent is in a certain range of its seat.	true,false
with-bag	Slider for setting the proportion of people who carry luggage in the plane that needs to be stowed in the overhead compartment.	[0.0,1.0]
luggage-time	Indicates the time needed by a passenger to stow their luggage. Different times are meant to indicate variability and randomness of time, of placing a luggage based on how big it is or how fast a person is while stowing it.	[100,210] ticks
between-passengers	Indicates the allowed minimum distance between passengers for the different scenarios in order to prevent overtaking or overlapping on the aisle.	1 patch

Table A.2: Variable explanation for the model