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BOARDING EFFICIENCY IN REGIONAL AVIATION: A COMPARATIVE ANALYSIS OF METHODS

Sophia Possamai Viertel1, Luana Pessini1, Lisa Secomandi1, Renata Cavion1, Francielly Hedler Staudt1

1. Federal University of Santa Catarina

sophiapviertel@gmail.com , luana.pessini@grad.ufsc.br, secomandi.lisa@gmail.com, r.cavion@ufsc.br, francielly.hedler.staudt@ufsc.br

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ABSTRACT

The passenger boarding process constitutes a critical element within aircraft ground operations, exhibiting a high susceptibility to delays attributable to unpredictable passenger behavior and cabin interferences. Such delays directly impact operational costs and an airline's reputation. A notable gap exists in the extant literature, which predominantly focuses on larger airplanes, thereby neglecting comprehensive studies on regional aircraft models such as the ATR 72 and Airbus A220. This study endeavors to address this deficiency by investigating the efficiency of various passenger boarding methodologies for these smaller planes, with the A320 included for comparative analysis, employing agent-based modeling within the NetLogo environment. Six commonly recognized boarding strategies — namely, Random, Back-to-Front, Outside-In (WMA), Reverse Pyramid, Rotating Zones, and Modified Optimal — were rigorously simulated across diverse baggage allowance scenarios (50%, 60%, 70%) and at full occupancy (100%). The simulation outcomes indicate that the Reverse Pyramid and WMA methods generally yielded the most expeditious boarding times. Specifically, the Reverse Pyramid strategy demonstrated superior efficiency for the ATR 72 in scenarios involving higher luggage volumes, while WMA consistently outperformed other approaches for the A220 across all baggage conditions and for the A320 at 50% and 60% baggage levels. Furthermore, the study corroborates that boarding time exhibits a direct proportionality to luggage volume, irrespective of the chosen method or aircraft type. The WMA approach was also identified as being particularly effective in mitigating aisle and seat interferences, thereby enhancing the passenger experience. These findings collectively underscore that optimal boarding strategies are inherently contextual, contingent upon the specific airplane model and the level of baggage, thus necessitating tailored approaches to enhance operational fluidity, minimize costs, avoid delays, and elevate customer satisfaction within the regional aviation sector.

Keywords: Regional Aviation, Passenger Boarding, Simulation, Turnaround Time, Boarding Methods.

GENERATIVE AI USAGE STATEMENT

The authors declare that the use of generative AI tools was restricted to technical support activities, without compromising the originality, analysis, and conclusions presented in the work. All information obtained through these resources was carefully evaluated and integrated into the study, ensuring methodological rigor and academic integrity. Tool ChatGPT was used as support in the NetLogo programming language learning process and to help identify errors in the code. Tool Google Gemini was used to review the text.

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1 INTRODUCTION

The passenger boarding phase stands as one of the most critical processes within an aircraft's ground operations (Ferrari & Nagel, 2005), with 60% or more of its ground time often dedicated to this procedure (Giitsidis & Sirakoulis, 2016). This activity encompasses the individual's movement from the departure lounge in the terminal to their assigned seat on the plane.

Since the total passenger boarding time typically exceeds the time required for refueling and maintenance, its reduction can yield substantial savings for an airline, particularly for aircraft that perform multiple flights per day (Steffen, 2008). Inefficiencies in the boarding process generate interconnected impacts that affect not only airlines but the entire airport capacity system. Prolonged ground time elevates operational costs and, simultaneously, triggers a cascading effect that compromises the punctuality of subsequent flights and passenger connections (Delcea *et al*., 2018). Consequently, the dissatisfaction stemming from a negative customer experience directly impacts the company's reputation (Rahil *et al*., 2017).

Optimizing airline boarding time is crucial due to the unpredictable nature of individual passenger behavior (Soolaki *et al*., 2012). Efficient boarding methods (Jafer & Mi, 2017) are necessary to reduce "aisle interferences" (passengers blocking the aisle) and "seat interferences" (passengers needing to stand for others to sit), which cause discomfort and stress for customers. Therefore, analyzing effective boarding strategies is vital for both improving airline operational efficiency and enhancing passenger service (Jaehn & Neumann, 2015).

The existing literature presents a significant body of research evaluating boarding methods on major aircraft types. In most studies, the model utilized in simulations and analyses features a single aisle with 30 rows and 6 seats per row, totaling 180 seats (as seen in research by Delcea, Cotfas, & Paum (2018), Moreira *et al*. (2023), and Luo *et al*. (2021)). This layout is similar to aircraft such as the Boeing 737 and the Airbus A320, which possess ranges of approximately 5500 km (BOEING, 2025) and 8700 km (AIRBUS, s.d.), respectively, classifying them as medium-haul airplanes.

However, there are few studies exploring boarding methods application for lower-capacity planes, such as the Airbus A220, with an average of 125 seats (AIRBUS, s.d.), and the ATR-72, with approximately 75 seats (ATR, 2025), which primarily operate in regional aviation, a sector that has gained increasing focus in recent years, both in Brazil and internationally. In the Brazilian context, the National Airport Plan 2022-2052 by the National Civil Aviation Agency (ANAC) stands out, establishing guidelines for the development of national airport infrastructure with a keen eye on the needs of regional aviation (BRASIL, 2022).

Despite the governmental stimulus promoting regional aviation, it is important to note that this kind of operation incurs higher costs than routes between major cities, as flight distances are typically shorter and the demand for offered routes is lower (Nakayama, 2011). Understanding this scenario, this article proposes a deeper analysis of the boarding procedure for the main aircraft utilized in regional air transportation, leading to the following research question: *What are the most efficient passenger boarding methods, considering boarding time and number of aisle and seat interferences, when applied to ground operations for Airbus A220 and ATR-72 aircraft?*

The article outlines its structure, beginning in Section 2 by detailing various boarding strategies and reviewing related research. Section 3 justifies the use of NetLogo software and agent-based modeling for the simulation, also describing other simulation parameters. Section 4 presents and interprets the results, and Section 5 provides the concluding remarks.

2 LITERATURE REVIEW

The time consumed by the passenger boarding process is an integral part of the more comprehensive operation known as turnaround time (TAT), and it is identified as a critical component among the activities performed during this period. This stems from the fact that, as one of the final and most unpredictable stages prior to takeoff, it is highly susceptible to the variable behavior of passengers and to bottlenecks within the confined cabin space, potentially causing cascading delays that affect the entire airport system.

A primary cause of extended boarding times is passenger interference, which can happen in two ways: aisle interference and seat interference. Aisle interference occurs due to passengers blocking the aisle, often while stowing luggage. Seat interference is described as passengers already seated needing to stand to allow others into window or middle seats in the same row (Moreira *et al.*, 2023; Delcea *et al.*, 2017). It can assume four different forms, as represented in Figure 1.

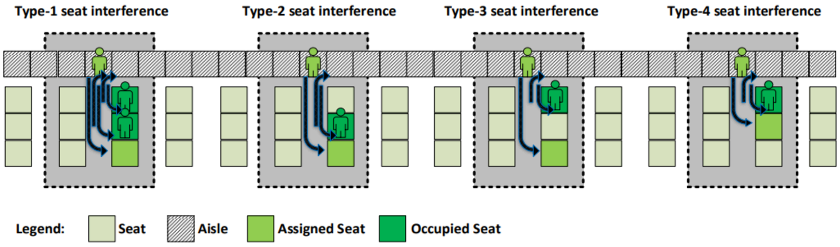


Figure 1: Types of seat interference. Source: Delcea *et al.* (2022).

Methods were developed to simulate and optimize the boarding process, thereby minimizing the required time and the amount of interferences. These methods (Figure 2) typically assume boarding occurs via a single forward door, though larger aircraft might use two doors to separate classes (Mueller, 2009). One such method is "Random", where passengers board in the order they arrive, regardless of seat assignment (Steffen & Hotchkiss, 2012; Moreira, 2021).

The Back-to-Front boarding method involves boarding passengers located in rows furthest from the entry door first, then proceeding sequentially with rows closer to the front. (Steffen & Hotchkiss, 2012; Moreira, 2021; Luo *et al.*, 2021).

The Outside-In strategy, also known as WilMA or WMA (Window-Middle-Aisle), prioritizes boarding passengers in window seats first, followed by those in middle seats, and finally passengers in aisle seats (Jafer & Mi, 2017; Moreira, 2021).

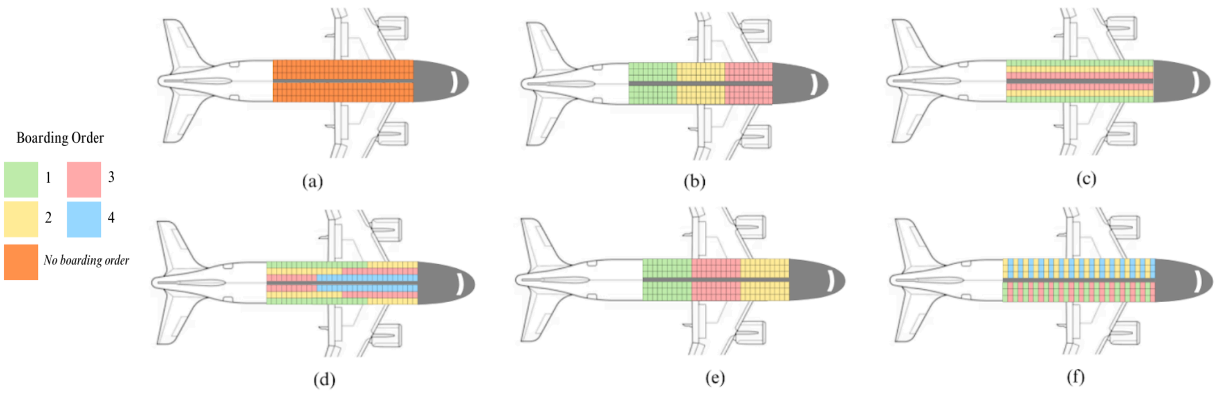


Figure 2: Boarding Methods. (a) Random Method; (b) Back-to-front Method; (c) Window-Middle-Aisle Method; (d) Reverse Pyramid Method; (e) Rotating Zones Method; (e) Modified Optimal Method. Source: Authors.

The Reverse Pyramid method combines the Back-to-Front and Outside-In strategies, simultaneously boarding passengers from the rear to the front and from window to aisle. Consequently, the first passengers to board are those in window seats at the back of the aircraft, while the last are those in aisle seats in the front rows (Jafer & Mi, 2017; Moreira, 2021).

The Rotating Zones (or Blocks) method boards passengers by zone, starting with those in the rear-most rows of the aircraft, followed by those in the front-most rows. Boarding then proceeds from the extremities towards the center of the aircraft (Jafer & Mi, 2017; Moreira, 2021; Mas *et al*., 2013).

The Modified Optimal method involves boarding passengers in alternating rows on each side of the aircraft. Passengers in even-numbered rows on one side form Group 1, followed by Group 2, comprising passengers in even-numbered rows on the opposite side. Groups 3 and 4 follow the same logic, but for odd-numbered rows on each respective side (Jafer & Mi, 2017; Moreira, 2021).

Regarding passenger boarding types, various studies have explored this subject. In Moreira *et al*.'s (2023) article, key boarding methods — Random, Back-to-Front, Outside-In, Reverse Pyramid, Blocks, Steffen, and Modified Optimal — were applied to an A320 configuration with 156 seats. The Arena simulation software was used, assuming 100% aircraft occupancy and 75% of passengers carrying luggage. In this investigation, the Steffen method proved to be the most efficient.

Another comparative study by Delcea *et al.* (2022) analyzed boarding time and contagion risk during the COVID-19 pandemic. Using NetLogo software, classic boarding methods were studied, considering parameters such as the percentage and the size of luggage carried by passengers and, crucially, indicators of general risk experienced by seated passengers due to the passage of potentially infected individuals in the aisle en route to their designated seats.

Further research utilizing NetLogo was conducted by Nugroho & Asrol (2022), who developed an agent-based simulation model to enhance the efficiency of the passenger boarding process by incorporating baggage organization methods. These methods prioritize passenger entry sequence based on the amount of carry-on luggage. The study found that a "Decreasing" type method, where passengers with three pieces of baggage board first, followed by those with two, and then one, was the most efficient when combined with the majority of boarding methods, with the exceptions of Back-to-Front and Rotating Zone.

The study by Delcea *et al*. (2017) adapted known major boarding methods for remote boarding scenarios, where passengers are transported to the aircraft via two buses and enter simultaneously through both front and rear doors. Using NetLogo, 15 methods were simulated on a 180-seat aircraft. The most efficient method identified was one that combined the Outside-In approach with Reverse Pyramid.

Kierzkowski & Kisiel (2017) investigated passenger behavior and human factors affecting total boarding time using real-life simulation recordings, specifically for the random boarding method. Their findings revealed that having empty seats near the aisle reduced "aisle interference" because passengers could use the unoccupied seat space to clear the path for others.

3 METHODOLOGY

The passenger boarding process involves several key stages: it begins with the boarding call and document verification, followed by the path to the aircraft. Once inside, passengers engage in movement down the aisle to find their seats, stow their carry-on baggage, and finally achieve seat occupancy, readying the aircraft for departure. This article proposes the simulation of the final stages of the boarding operation (Figure 3).

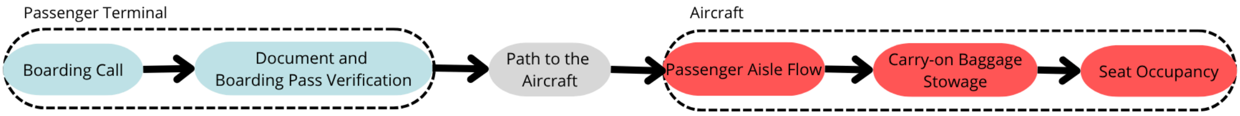


Figure 3: Simulated stages (red) of the boarding operation. Source: Authors.

3.1 Agent-Based Modeling

The selection of agent-based modeling was predicated on its inherent capability to create multiple agent types, each endowed with specific functions and behaviors. This proves particularly advantageous in simulations involving human behavior, such as passenger boarding (Delcea, Milne & Cotfas, 2022). By enabling the association of several variables, the simulation of passenger behavior during aircraft boarding demonstrates remarkable fidelity to real-world scenarios (Delcea, Milne, Craciun, & Molanescu, 2017).

Furthermore, the literature indicates that the NetLogo software is widely utilized by researchers engaged in boarding simulations, owing to its open-source multi-agent programming language, which is ideally suited for modeling natural and social systems (Delcea, Cotfas, & Paun, 2018). Consequently, NetLogo was selected for implementing the methods under investigation.

3.2 Selected Aircraft Models

This article aims to analyze the efficiency of various boarding strategies on commercial aircraft used in regional aviation. Notably, there are few studies that simulate boarding processes for the ATR-72 and Airbus A220 models. In Brazil, besides private aviation, three airlines operate ATR-72 aircraft: Azul Linhas Aéreas (with over 40 units), Total Linhas Aéreas, and VoePass (ANAC, 2023). While the A220 is not yet commercially operated in Brazil, 20 companies already include this model in their fleets (Barbieri-Sandberg, 2024). The decision to simulate these aircraft models is also driven by their inherent differences in passenger capacity and seating configurations: the ATR-72 features a 2-2 layout (four seats per row, two on each side of the aisle), whereas the A220 has a 2-3 configuration (five seats per row, two on one side and three on the other).

To compare the efficiency of boarding strategies between smaller and larger aircraft, the simulation methods were also applied to the Airbus A320 model. The Brazilian commercial air transportation scenario is predominantly characterized by larger aircraft, particularly the Airbus A320 (Dias & Lopes, 2020).

3.3 Boarding Methods

For the simulations, six of the most common boarding methods found in aircraft boarding studies were considered: Random, Back-To-Front, WMA (also called Outside-In), Reverse Pyramid, Rotating Zones and Modified Optimal.

3.4 Parameter Definitions

All simulations assumed 100% occupancy of the aircraft. The study varied the percentages of passengers carrying one piece of luggage at three different levels: 50%, 60% and 70%. Simulations with varying baggage configurations allow for analyzing the impact of baggage quantity on total boarding time (Milne & Salari, 2016). Each passenger was assumed to carry either zero or one piece of luggage. These variations, combined with the three aircraft models and six distinct boarding methods, yielded a total of 54 different scenarios.

Within the NetLogo software, the simulation environment consists of "patches", small squares that can be colored to represent the desired situation. In the model developed for this study, aircraft rows are one patch wide. The software measures time in "ticks", an internal unit that must be adapted to real-world temporal units to define passenger speed and ascertain the total time required for boarding. According to Landeghem and Beuselinck (2001), a passenger takes on average 2.4 seconds to walk through one aircraft row. In the simulation, this is represented by a speed of 1 patch per tick, where each patch corresponds to one row and each tick is equivalent to 2.4 seconds of real time (Nugroho & Asrol, 2022).

For luggage stowage, a study by Delcea, Cotfas, & Paun (2018) considers that 3 to 7 ticks are necessary. This same study equates 1 tick to 5.4 seconds. Based on this, and to maintain consistency in the tick-to-second equivalence for our simulation, it is defined that between 7 and 16 ticks are required for each passenger to stow their belongings.

The time established for resolving seat interferences (where already-seated passengers need to stand to accommodate others designated to the same row) was defined based on Schultz's (2018) study. This study considers that different types of interference necessitate varying numbers of movements from the involved individuals. Assuming each movement equates to one walking patch for passengers, Type 1 seat interference requires 9 movements (i.e., 9 ticks or 22 seconds). Similarly, Type 2 interference takes 5 movements, and finally, Types 3 and 4 require 4 movements (Moreira *et al*., 2023).

Each one of the 54 scenarios was simulated 100 times, consistent with studies by Delcea, Cotfas & Paun (2018), Moreira *et al.* (2023), and Luo *et al*. (2021). The data from each simulation was computed in ticks for subsequent analysis and interpretation of results.

4 RESULTS

From the developed simulation model, it was possible to analyze the behavior of four main variables: overall average boarding time per passenger, average boarding time per passenger per aircraft, and number of aisle and seat interferences.

Figure 4 illustrates the average boarding time (in ticks) per passenger for each method, for each aircraft and for each luggage level, a value that was obtained by dividing the total boarding time by the number of passengers. Converting ticks into real time did not prove to be necessary, since the main goal of this study is comparing boarding times among methods, and not estimating the boarding time.

Figure 4 (a) is derived from the average times across all aircraft and baggage levels. The Reverse Pyramid stands out as the method with the lowest average boarding time per passenger, at 3.53 ticks, closely followed by WMA, with an average of 3.54 ticks. The least time-efficient strategy is Rotating Zones, with an average of 4.68 ticks.

For ATR72, Figure 4 (b) shows the Reverse Pyramid method was the most efficient for scenarios where 50% and 70% of passengers carried overhead baggage, with average boarding times per passenger of 3.54 ticks and 4.22 ticks, respectively. For the 60% luggage level, WMA showed the shortest average time, 3,95 ticks, being 18.2% faster than Rotating Zones, which performed worst in this scenario.

For the A320, Figure 4 (c) indicates that WMA and Reverse Pyramid proved to be the most efficient methods. WMA surpasses Reverse Pyramid in the 50% baggage scenario, with 3,05 ticks per passenger, while Reverse Pyramid stands out at the 60% luggage level, with 3,3 ticks. At the 70% baggage configuration, both strategies achieved equal efficiency, with an average boarding time of 3.58 minutes.

Figure 4 (d) reveals that, for the A220, the WMA strategy consistently excelled across all tested scenarios. At a 50% luggage level, its average boarding time per passenger was 3,09 ticks, 25,7% faster when compared to the least efficient method, Rotating Zones. For the 60% and 70% baggage configurations, WMA maintained its superiority, showing substantial percentage differences of 27.3% and 25.5%, respectively, against the slowest method.

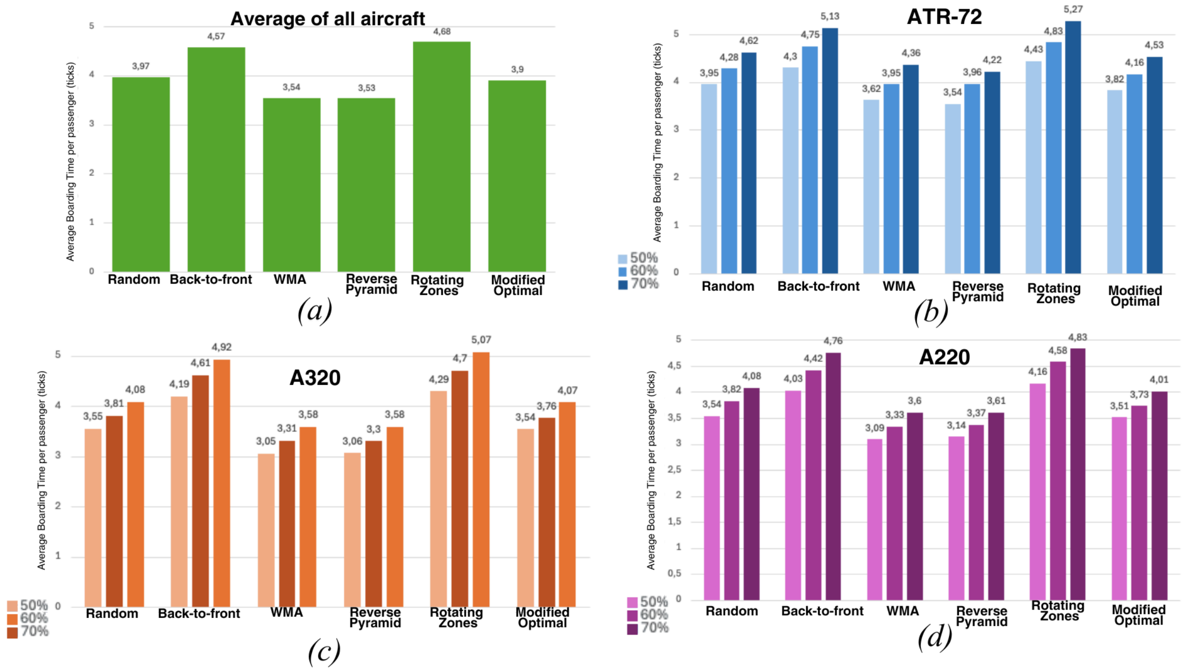
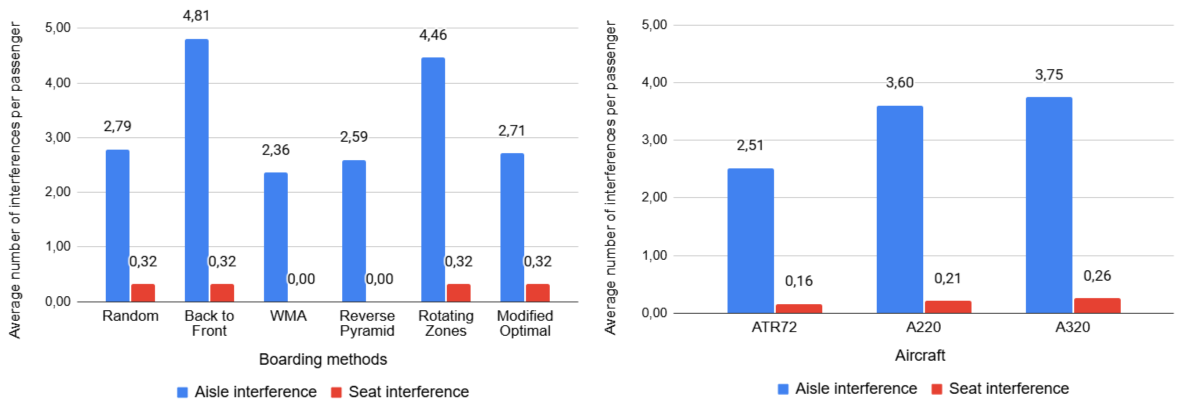


Figure 4: Average boarding times simulated. (a) All aircraft and all baggage levels; (b) ATR-72; (c) A330; (d) A220. Source: Authors.

Generally, the average boarding time directly increases with the percentage of baggage, regardless of the boarding method or aircraft type. This increase is expected, as more luggage implies additional time required for stowage.

Beyond boarding time, another critical factor for passenger experience quality is the number of interferences during the process. Results demonstrate that the WMA method is consistently the most efficient in reducing both aisle and seat interferences across all aircraft and baggage levels, as depicted in Figure 5 (a). By eliminating situations where passengers must wait to be seated, WMA and Reverse Pyramid methods prevent aisle congestion. Figure 5 (b) indicates that the average number of interferences is positively correlated to the number of passengers occupying the airplane.



(a) (b)

Figure 5: (a) Average aisle and seat interferences per passenger for each boarding method; (b) Average aisle and seat interferences per passenger in each aircraft. Source: Authors.

The results clearly show that the efficiency of boarding methods varies significantly depending on the aircraft type and baggage volume. While WMA demonstrated superior performance in many scenarios, particularly in reducing interferences, its relative effectiveness compared to other methods like Reverse Pyramid highlights that there isn't a single optimal solution, but rather approaches optimized for each specific operational context.

5 CONCLUSIONS

This simulation study assessed the efficiency of various boarding methods for smaller aircraft (ATR 72 and A220), as well as the A320, by analyzing passenger boarding time and interferences. The Reverse Pyramid and WMA (Window-Middle-Aisle) methods generally proved fastest. Specifically, Reverse Pyramid was most efficient for the ATR 72 in high-baggage scenarios, while WMA consistently excelled for the A220 across all luggage conditions and for the A320 in 50% and 60% baggage scenarios.

The study confirmed that average boarding time increases proportionally with luggage volume, regardless of the method or aircraft. Additionally, WMA was most effective at reducing aisle interferences, improving passenger experience by minimizing congestion.

The simulations for ATR72, A220, and A320 revealed that the most efficient boarding strategy varies by aircraft model. Furthermore, even for the same aircraft, the fastest method can change based on the proportion of passengers carrying luggage. This highlights the importance of considering diverse factors like passenger baggage volume, cabin layout, and aircraft capacity when selecting the optimal boarding strategy. These aspects directly relate to the characteristics of regional aviation passengers, aligning with the airport's profile and its role in the air network.

The importance of reducing boarding time, aisle and seat interferences becomes clear. Prioritizing strategies that limit interferences is essential to prevent discomfort and stress for passengers. Implementing the appropriate method for each boarding scenario allows airlines to decrease aircraft ground time, consequently reducing costs and the risk of operational delays. Efficient boarding processes also enhance passenger satisfaction, positively impacting the airline's reputation and revenue.

Ultimately, the results of this study, focused on boarding efficiency for regional aviation aircraft like the ATR-72 and Airbus A220, cannot be directly compared with existing literature predominantly investigating larger airplanes (Boeing 737, Airbus A320) at major hubs. This distinction is crucial due to fundamental parametric differences: regional aircraft have lower capacity (the ATR-72, with ~75 seats, is approximately 58% smaller than a 180-seat A320; the A220, with ~125 seats, is about 31% smaller) and diverse seating configurations (the ATR-72 has a 2-2 layout, representing 33% fewer seats per row than a 3-3 A320; the A220, with 2-3, has 17% fewer seats per row), which intrinsically affect movement dynamics and interferences. Furthermore, the passenger profile, luggage volume, and operational dynamics of shorter turnarounds and simpler airport infrastructures in regional aviation diverge from the high-density scenarios of large hubs. Thus, this work fills a gap, offering specific insights and optimizations for a sector with operational characteristics where boarding efficiency has a distinct impact.

This research presents limitations, as it relies on literature-based parameters without formal validation through empirical testing or field trials. Future studies should address this gap by implementing the model using data from regional airports to enhance applicability and accuracy. Additional research opportunities include developing models that incorporate stochastic passenger behaviors, exploring boarding processes using both front and rear doors, particularly relevant in airports with limited or no jet-bridge facilities, and extending the simulation to wide-body aircraft, such as those with two aisles or double decks.

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