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Evaluating Classical Airplane Boarding Methods Considering COVID-19 Flying Restrictions

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Abstract: The novel coronavirus (SARS-CoV-2) has imposed the need for a series of social distancing restrictions worldwide to mitigate the scourge of the COVID-19 pandemic. This applies to many domains, including airplane boarding and seat assignments. As airlines are considering their passengers' safety during the pandemic, boarding methods should be evaluated both in terms of social distancing norms and the resulting efficiency for the airlines. The present paper analyzes the impact of a series of restrictions that have been imposed or mooted worldwide on the boarding methods used by the airlines, featuring the use of jet-bridges and one-door boarding. To compare the efficacy of classical airplane boarding methods with respect to new social distancing norms, five metrics were used to evaluate their performance. One metric is the time to complete the boarding of the airplane. The other four metrics concern passenger health and reflect the potential exposure to the virus from other passengers through the air and surfaces (e.g., headrests and luggage) touched by passengers. We use the simulation platform in NetLogo to test six common boarding methods under various conditions. The back-to-front by row boarding method results in the longest time to complete boarding but has the advantage of providing the lowest health risk for two metrics. Those two metrics are based on passengers potentially infecting those passengers previously seated in the rows they traverse. Interestingly, those two risks are reduced for most boarding methods when the social distance between adjacent passengers advancing down the aisle is increased, thus indicating an unanticipated benefit stemming from this form of social distancing. The modified reverse pyramid by half zone method provides the shortest time to the completing boarding of the airplane and—along with the WilMA boarding method—provides the lowest health risk stemming from potential infection resulting from seat interferences. Airlines have the difficult task of making tradeoffs between economic productivity and the resulting impact on various health risks.

Keywords: airplane boarding; agent-based modeling; one-door boarding; symmetrical boarding; COVID-19 flying restrictions

1. Introduction

The efficiency of airplane boarding methods has been discussed in the scientific literature from different points of view. Most of the literature focuses on reducing the time to complete boarding of an airplane under given conditions: the presence of jet bridges [1–6], the possibility of having different pre-boarding areas in which the passengers can gather in an ordered manner (e.g., the flying carpet [7], classical pre-boarding areas [8]), the presence of apron buses [9–12], boarding through

both doors of the airplane [6,13,14]), offering passengers traveling together the possibility of boarding as a group [15–19], creating a friendly environment while passengers are boarding [20]. Most of the computer simulations of airplane boarding consider the situation in which the airplane is fully loaded with passengers [1,4,21–25], while a few papers have addressed the issue of partially boarded airplanes [12,21,26,27].

COVID-19 is a disease caused by severe respiratory syndrome coronavirus 2 (SARS-CoV-2). The terrible health impacts of COVID-19 have led to many countries requiring their residents to stay at their homes for a period of time. Much of the world has recognized the need for social distancing to mitigate the scourge of the pandemic. This applies to airplane boarding and seat assignments as well. While airlines are considering their passengers' safety while traveling during the COVID-19 pandemic, the improvement or adaptation of the boarding methods to fit the new social distancing norms should also be considered, as well as the resulting costs and efficiencies for the airlines.

According to the news media, a series of rules for social distancing have been imposed or have been discussed as possible ideas to increase airplane passenger safety during the pandemic. Some of the airlines have already changed their practices, while additional changes are being considered as possible strategies.

The International Air Transport Association (IATA) Medical Advisory Group has recently released a document with recommendations for restarting aviation safely in the presence of COVID-19 among some of the general public [28]. Among the recommended safety norms are: Symptom screening, use of masks and personal protective equipment (PPE), physical distancing, cleaning and disinfection, COVID-19 testing, antibody testing, immunity passports, and a series of measures created to assist contact tracing and crew members' safety [28]. In terms of physical distancing, the IATA report recommends an ideal distance among passengers which can range from 1–2 m, as well as modifying the airport check-in, security, immigration, departure lounge, and boarding processes, to ensure social distancing. Among the measures strictly related to physical distancing while boarding the airplane, the IATA Medical Advisory Group report underlined the following [28]: management of the boarding process, which will ensure a limited number of passengers passing each other, limit of carry-on luggage, sequential boarding starting from passengers with seats in the rear of the airplane and window seats. Furthermore, the IATA Medical Advisory Group report underlines the fact that: "some airlines are currently, while load factors are low, also achieving a degree of distancing by leaving every second seat empty, or similar". [28]. However, this measure is cataloged as "questionable", considering the in-flight transmission of the virus. Another option presented by the IATA Medical Advisory Group report suggests the "benefit in leaving empty seats in the region where the crew is seated (in their jump seats) face to face with passengers." [28].

As a result, the general recommendation of the IATA Medical Advisory Group for the airlines is the use of a multi-layered approach, based on a combination of the abovementioned safety norms, which can achieve "high-levels of risk reduction" [28], with some of the norms potentially including aspects related to physical distancing.

The European Union Aviation Safety Agency (EASA) states, in a recent report that it is the duty of the airplane operators to ensure, as much as possible, sufficient physical distance among passengers [29], while the World Health Organization (WHO) has asserted that social distancing is one of the most important measures for mitigating the impact of the COVID-19 pandemic [30].

The Civil Aviation Administration of China (CAAC) guidelines report discusses a potential "cabin area division" to impose social distancing [31]. In this approach, the CAAC recommends that the cabin area be divided into four spaces: clean area, buffer zone, quarantine area, and the passenger sitting area—all of them separated by disposable curtains. The principles for governing the cabin separation are: the clean area will be in the front half of the first class (and/or business class) cabin and will be dedicated exclusively for the use of crew members; the buffer zone will be formed in the rear half of first class; the quarantine area will be formed in the last three rows of the airplane and designated

for use in an emergency, and the passenger seating area will be formed by the remaining seats of the cabin [31].

Airlines and airports have adopted several approaches in response to the current pandemic: passengers assigned to the back seats board first (implemented by Delta Air Lines [32] and by the “Henri Coandă” Airport [33]); passengers assigned to the seats in the front rows (one row at a time) board first while entering an airplane from the rear door (implemented by GoAir [34]), and boarding is based on passengers’ seat numbers (trialed by EasyJet and Gatwick Airport [35]); blocking middle-seats (mooted by Alaska Airlines, Wizz Air, and later by EasyJet [36]).

As a part of COVID-19 restrictions, Delta Air Lines boards passengers in a back-to-front sequence by row, first boarding those passengers seated closest to the rear of the airplane to reduce the chance of boarding passengers passing other (seated) passengers in the process of finding their seats [37,38]. That is, for an airplane with 30 rows, passengers seated in row 30 are the first called to board, followed by row 29 and continuing in this manner until row 1 is reached. Additionally, Delta leaves middle seats empty in the main cabin and for first-class passengers, and on airplanes without middle seats, Delta Air Lines blocks the aisle or the window seats to preserve social distance [39,40]. The wearing of a face mask or a face covering is mandatory for all Delta travelers [39].

Southwest Airlines has announced changes to its usual boarding process to ensure social distancing during the COVID-19 pandemic, such as boarding their airplanes in groups of ten passengers, and the passengers are only lined up on one side of the Southwest’s boarding poles while wearing masks [41]. This airline asks their passengers to eat before boarding, since drinks and snacks are no longer served to all passengers on board [41]. The only beverage offered by the company is canned water, which is provided upon request [42].

American Airlines follows the same “no snacks, no food” policy to all passengers, including first-class, and “no middle seat” for economy-class passengers [42].

As for United Airlines, the rules have changed only slightly for the food policy, as the company continues to offer snacks to its passengers but with no refill of beverages [42]. Even in the case of this airline company, the middle seat is blocked [42].

It is important to recognize that such policies are fluid. As with the rest of the world, airlines are continually re-evaluating their boarding practices as scientists continue to learn more about COVID-19 and everybody learns more about people’s behavioral changes in response to changing knowledge about COVID-19 and the dictates imposed by governments.

All of the discussed safety practices come with advantages and disadvantages. For example, blocking out the middle seat on an Airbus 320 or a Boeing 737 airplane, which are often configured to pack as many passengers in the limited space as possible, results in a maximum load of 66.7% capacity [36], which is below the average global load factor of 84%, reported by the IATA 2019 report [43]. Furthermore, as an empty middle seat keeps the passengers at an average 45 cm distance from each other, the 2 m recommended distance is not met [36]. To follow 2 m distancing among passengers, there should be, at most, two persons seated in each row. Furthermore, considering the passengers in adjacent rows, with a row having a width of 75–80 cm, and taking into account the 2 m recommendation, there should be at least two empty rows between any other pairs of rows containing the maximum of two passengers.

In this context, this paper tests the classical boarding methods used by airlines worldwide for boarding their passengers under the same initial conditions and discusses their efficiency both in terms of costs (determined by the time needed to complete the boarding) and in terms of passenger health (determined by the risk for an infected passenger to spread the virus to another passenger). We consider new norms related to social distancing. In particular, we leave the middle seat empty on each side of the aisle. Furthermore, as passengers walk down the aisle toward their seats we assume that there is a minimum distance between each pair of adjacent walking/standing passengers of 1 m, 1.5 m, or 2 m (aisle distancing), according to the scenario tested to preserve social distancing.

The remainder of the paper is organized as follows: Section 2 presents a short literature review of the classical airplane boarding methods that have been used by the airlines. Section 3 discusses the scenarios and assumptions tested, as well as the metrics used for evaluating the performances of the methods under those scenarios. These scenarios could be implemented by the airlines during the COVID-19 outbreak, considering social distancing and passenger health. Section 4 presents the agent-based model used for the simulations and underlines the primary moving assumptions for the agents. Section 5 provides and analyzes a series of simulations for the different scenarios presented in Section 3. The paper closes with a section on concluding remarks and further research directions. A series of videos presenting simulations made using the agent-based model accompanies the paper.

2. Literature Review

According to the research literature on airplane boarding methods, there are more than 20 methods that have been created and tested under different assumptions [44]. The boarding methods can be characterized as random, by group or by seat. Within the “random” category, the entire group of passengers is called to board as a single group. In the “by group” methods, the degree of granularity is increased, and the passengers are divided into different groups based on a certain set of rules, with each group called to board in turn. The “by seat” methods increase granularity further and consider each individual passenger to be boarded as a one-person group.

All the new boarding methods are in the categories of either “by group” or “by seat” methods. Among the most well-known “by group” methods, one can name: outside-in (also known as “WilMA” or the window–middle–aisle boarding method), back-to-front, reverse pyramid, modified optimal method, and the rotating zone [5,10,45,46]. From the “by seat” methods, the most well-known is the method developed by Steffen [2]. The rules accompanying some of these methods are highlighted as follows.

According to the WilMA method, the passengers are divided into three boarding groups based on the positions of their assigned seats in the airplane. The first group to board is composed of the passengers having seats near the window, the second boarding group includes the passengers assigned to middle seats, and the third group comprises the passengers with seats adjacent to the aisle. At the time boarding begins, all passengers of the first group are called to board in a random sequence within the group. Once the last passenger belonging to the first group has proceeded to board, the second group is called for boarding. Similar to the previous group, the passengers belonging to this group board in a random sequence within the group. Lastly, the third group to board contains all the passengers assigned to aisle seats [2,5,21,47]. With all of the “by group” methods, the sequence of passengers boarding within a particular group is assumed to be random.

The back-to-front by group boarding method divides passengers into a specified number of groups (often five groups with each boarding group containing passengers seated in 1/5 of the rows). The boarding process begins with passengers who have seats in the rear rows of the airplane and continues through to the final boarding group of those passengers who have seats in the front rows of an airplane [44].

In the case of the reverse pyramid boarding method, the passengers are divided into several groups (for example, five groups) which load diagonally starting with a first boarding group comprising 2/3 of the seats located near the windows in the middle–rear side of the airplane and ending with a group formed by the passengers with aisle seats located in the middle–front part of the airplane [4,13,48].

The modified optimal method features four groups. Passengers are assigned to the groups based on their seat locations in odd or even rows, on one side or the other side of the airplane’s aisle [9].

The rotating zone method considers the existence of five groups determined by dividing the airplane into five zones. The first boarding group includes the passengers assigned to seats in the front rows of the airplane, the second group comprises passengers with seats located in the rear rows of the airplane. The third and the fourth groups include passengers assigned to seats located in the rows in the middle–front and middle–rear part of the airplane [49].

The “by seat” method, developed by Steffen [2], implies the call of the passengers one-by-one to board an airplane. The first passenger to board is the one that has the seat in the rear of the airplane near the window. The second passenger to board is the one that has a seat two rows in front of the first passenger, also near the window. The last passenger to board is the one with a seat in the first row of the airplane near the aisle [2].

As presented above, we observe that the rules apply consistently in all the boarding methods to seats on both sides of the aisle, preserving a symmetry with respect to the aisle.

Considering the methods used in practice, we note that a series of European companies, such as Air France, EasyJet, KLM, Lufthansa, Ryanair, Tarom, and WizzAir, have embraced the random, with assigned seat boarding methods that allows the passengers to line up in no particular order to board an airplane and to proceed to their seats once they arrive inside the cabin [27], while Southwest Airlines, an American airline company, uses the random boarding method without assigned seats. This method, also known as the open seating method, allows every passenger to select (determine) their seat upon arriving inside the cabin [50]. Other companies, such as United Airlines, Air Canada, Air China, Alaska, American Airlines, Delta, British Airways, Frontier, Japan Airlines, Korean Air, Spirit, Virgin Atlantic, and JetBlue, favor “by group” boarding methods: WilMA, back-to-front by group, back-to-front by row, and modified reverse pyramid half zone.

One “by seat” method was tested on selected flights by KLM in 2013 [50]. Another “by seat” method was tested by EasyJet for a two-month trial at Gatwick Airport [51–53]. The latter method is similar to the Steffen method, except with passengers boarding back-to-front by column in every row rather than the Steffen approach of every other row. To the best of our knowledge, no “by seat” method has been adopted in practice aside from the KLM and EasyJet tests.

Apart from the elements mentioned in the Introduction related to the conditions considered over time for proposing or simulating different boarding methods, the approaches used for the evaluation of these methods have varied in the scientific literature. Over time, the following approaches have been used: cellular Discrete-Event System Specification (Cell-DEVS) modeling [54], cell-based computer simulation [21], computer simulation [3,8,47,48,55], Markov Chain Monte Carlo optimization algorithm and computer simulation [2], Discrete-Event simulation [3], linear programming [24,48,56], genetic algorithm [4], grid-based simulation model [57], stochastic modeling [58–60], agent-based modelling [11,44,61], empirical tests of the performance of the considered boarding methods [22], and simulated annealing [15].

Various factors have been considered, related but not limited to: the number of rows or airplane type [1,4,21,22,62], airplane occupancy [1,3,22,25,46,47,63], seat selection [21,49], using one or both airplane doors for boarding [1–5,8–10,13,17,24,45,56,63,64], passenger movement [2,49], passengers’ personal characteristics [46,62,63], the presence of carry-on hand luggage [1,2,17,56,63], seat and aisle interferences [20,65,66], and group behavior [16–19].

In this paper, we use a single-door Airbus A320 configuration with one aisle, thirty rows, and three seats on each side of the aisle, as suggested by [14,67] and depicted in Figure 1. All seats are considered economy class.

Figure 1. Airplane configuration used in this paper.

3. Scenarios of Passenger Boarding Methods and Metrics for Their Evaluation

The scenarios to be simulated and the metrics used for their evaluation are discussed in the following subsections.

3.1. Scenarios of Passenger Boarding Methods

The proposed scenarios implemented and simulated in the agent-based model include the mooted rule that the middle seat should be empty, along with some additional rules related to the minimum distance between boarding passengers while they advance through the aisle (called “aisle distancing”, which can be either 1 m, 1.5 m, or 2 m—depending on the scenario) and parameters related to the number and size of hand luggage brought inside the airplane, as shown in Table 1. We assume that the passengers will follow the aisle distancing rule as they advance down the aisle towards their seats.

Table 1. Volume of luggage scenarios used in the numerical simulation experiments.

Scenario	Passenger Luggage Frequencies Expressed in Percentages of Passengers Carrying Them				
	None	1 Small	2 Small	1 Large	1 Large and 1 Small
S1	10%	10%	0%	10%	70%
S2	15%	20%	5%	10%	50%
S3	25%	20%	10%	15%	30%
S4	35%	25%	10%	15%	15%
S5	60%	10%	10%	10%	10%
S6	80%	5%	5%	5%	5%
S7	100%	0%	0%	0%	0%

The luggage scenarios are numbered from S1 to S7, based on the percentage of bags carried by the passengers and within each scenario [11]. In the S1 scenario, 90% of the passengers are carrying hand luggage inside the aircraft; this can be either a small bag, a large bag, or both a small and a large bag. The quantity of the carried luggage decreases as the number of scenarios increases, so, in the S7 scenario, none of the passengers bring hand-luggage inside the aircraft, as shown in Table 1. The modified version of the original boarding method is simulated in three situations of aisle distancing (1 m, 1.5 m, and 2 m).

The methods used for testing are from the most common boarding methods all over the world: random without assigned seats, random with assigned seats, WilMA, back-to-front by group, back-to-front by row, and modified reverse pyramid half zone. Some of the major airlines using these methods are listed in Table 2.

Table 2. Boarding methods and airlines that use them [4,13,27,45].

Boarding Method	Airline
Random without assigned seats/Open seating method	Southwest
Random with assigned seats	Air France; EasyJet; KLM; Lufthansa; Ryanair; Tarom; WizzAir
Outside-in/WilMA	United Airlines
Back-to-front by group	Air Canada; Air China; Alaska; American Airlines; British Airways; Cathay Pacific; Eva Air; Frontier; Japan Airlines; Korean Air; Spirit; Virgin Atlantic
Back-to-front by row	Delta
Modified reverse pyramid half zone	JetBlue

The rules for all the considered boarding methods are adapted to fit the social distancing requirements in the case of COVID-19, which implies that the middle seats, located in columns B or E on the airplane, will be kept empty of passengers, as illustrated in Figure 2.

Figure 2. Airplane configuration in COVID-19 situation tested.

In the case of the random with assigned seats boarding method, the passengers enter the airplane in a random sequence and walk down the aisle until their assigned seat. In the case of the random without assigned seat method, the passengers enter the airplane and select an available seat based on their preferences for the front/middle/rear part of the airplane and their preferences for window or aisle seats.

The (adapted) WilMA method has only two boarding groups: the first group entering the airplane contains passengers with seats adjacent to the windows, while the second group contains aisle seat passengers, as shown in Figure 3.

Figure 3. WilMA in COVID-19 situation.

The back-to-front by group method implies the passengers are divided into five equal sized groups, as shown in Figure 4. With the (adapted) back-to-front by row method, the four passengers in row 30 board the airplane first, followed by the four passengers in row 29, and so forth, with the final set of four passengers to board being those with seats in the first row of the airplane, as shown in Figure 5.

Figure 4. Back-to-front by group in COVID-19 situation.

The (adapted) modified reverse pyramid half zone has three boarding groups: the first one consisting of the window seat passengers in the rear of the airplane, the second group formed by passengers assigned to the window seats in the front rows of the airplane and with aisle seats in the rear of the airplane, and the third group—the remaining passengers—including the aisle seat passengers in the front of the airplane, as shown in Figure 6.

Figure 5. Back-to-front by row in COVID-19 situation.

Figure 6. Modified reverse pyramid half zone in COVID-19 situation.

3.2. Metrics Used to Evaluate Passenger Boarding Methods

Following the COVID-19 restrictions, with social distancing playing a key role in passenger health, we evaluate the six boarding methods in terms of five metrics. These metrics are the time to complete boarding of the airplane and four metrics that indicate health risks for the passengers. The health risks stem from increased interactions between passengers due to COVID-19 droplets spreading through the air and spreading to surfaces that are subsequently touched by passengers who may later touch their noses or mouths. The health risk of an interaction is greater when its duration is longer. We explain each of the four boarding health risks in turn, followed by its metric.

According to the literature, there are four types of seat interferences that can be encountered by a passenger whose path to his/her seat is blocked by another passenger or passengers sitting in the same row and side of the airplane where the passenger's seat is located [65]. These four types of seat interferences are depicted in Figure 7. In the case of COVID-19 restrictions related to the constraint of leaving the middle seat empty, the only situation of seat interference that might arise is type 3, in which the passenger with a window seat arrives at his/her row after a previously boarding passenger has sat down in the aisle seat in the same row and side of the airplane. When the aisle seat passenger rises to clear space to enable the later boarding passenger to sit, the aisle seat passenger may touch the headrest of the seat in front or may touch an armrest. The later boarding passenger may touch either surface and, thus, increase the risk of infection spreading. Furthermore, when the aisle seat passenger rises to clear space for the later boarding passenger, this may cause either passenger—if infected—to spread COVID-19 droplets through the air to the other passenger or to other nearby passengers who may be affected by their movements. Consequently, for our first health metric, we measured the number of seat interferences resulting from each tested boarding method under the scenarios.

The second health metric pertains to the risk of a passenger being exposed to the virus from touching luggage in the overhead bin stored by a previously boarding passenger who may be infected. We estimated this risk by calculating the time it takes a particular passenger to store luggage (given any previously stored luggage existing in the overhead bin) minus the time for the passenger to store luggage in an empty overhead bin. This calculated time indicates the added risk of touching the other

passengers' luggage or part of the overhead bin that may have been touched by the previous passenger. This extra luggage time is summed over all passengers to create the second health metric: total extra luggage storage time.

Figure 7. Types of seat interferences.

The third and fourth health-related metrics pertain to the health risks to seated passengers who are passed by other (potentially infected) passengers who are walking towards their seats or standing in the aisle where it intersects the seated passengers' rows. A (potentially infected) passenger may be walking or may be standing in the seated passengers' row due to waiting in a queue for a down-aisle passenger clear the aisle. The longer the (potentially infected) passenger is in the row, the greater this health risk. We defined and calculated the third metric for aisle seat passengers as:

$$\text{RiskAisleSeats} = \sum_p \sum_{r \leq \text{RowSit}_p} \left(\text{RowTime}_{pr} * \sum_{p' < p} \text{AisleSeat}_{p'r} \right)$$

where:

RiskAisleSeats = the total duration of aisle seat risks

p = passenger advancing towards his/her seat

r = row index

RowSit_p = row in which passenger p has a seat

RowTime_{pr} = time that passenger p spends in row r

(this duration begins when passenger p begins to enter row r

and concludes when passenger p begins to leave row r;

this convention is chosen because a passenger's nose and mouth are at the front of the passenger)

p' = passenger boarding before passenger p

AisleSeat_{p'r} = 1 if passenger p' has an aisle seat in row r

= 0 otherwise

The fourth (and final) health metric is similar to the third metric, except that the fourth metric calculates the risk to previously seated passengers who have window seats:

$$\text{RiskWindowSeats} = \sum_p \sum_{r \leq \text{RowSit}_p} \left(\text{RowTime}_{pr} * \sum_{p' < p} \text{WindowSeat}_{p'r} \right)$$

where:

RiskWindowSeats = the total duration of window seat risks

WindowSeat_{p'r} = 1 if passenger p' has a window seat in row r

= 0 otherwise

4. Agent-Based Model Implementation

In the following section, we discuss the agent-based model implemented to simulate the passenger boarding process in terms of agents and their interactions. Compared to other modeling techniques, the agent-based model provides the needed basis for imitating the details of a mechanism or a real process without involving too much statistical or mathematical modeling. As Manzo [68] noticed, the “enormous flexibility made possible by agent-based simulation” represents “its originality in comparison to other methods of computer simulation conceived as a support for statistical and mathematical analysis” (Manzo [68], p. 435). Glen et al. [69] have shown in recent research that the agent-based models are “unique in their ability to integrate combinations of heterogeneous processes and investigate their respective dynamics, especially in the context of spatial phenomena” (Glen et al. [69], p. 1), while Currie et al. [70] mention in a recent paper that agent-based modeling is appropriate for incorporating variability in human behavior into the model and for observing to which extent some small changes in the analyzed situation and interactions among agents can influence different levels of the outputs.

We chose the NetLogo platform for creating the agent-based model due to the advantages it offers over other agent-based modeling platforms, such as: a visual interface, fast access to documentation, easy installation, integrated graphics, real-time user access on an agent’s state, execution speed, free use of the platform, and the existence of a community which supports the development of models in various economic areas [44,71–74].

To present the inside of the airplane cabin, the “patches” agents were used, each of them possessing different characteristics in accordance with their purpose, either to represent the aisle, seats, or the spaces between the seat rows. The “patches” are small square pieces of ground, each of them measuring 0.4 m × 0.4 m, as suggested by [14,75]. A series of properties were assigned to each patch, as stated in [9].

The boarding passengers were represented using the “turtles” agents, each of them having its own speed, which can range between 0–1 patch/tick (the “tick” is the time moment in NetLogo and it corresponds to 1.2 s [9]), based on their individual properties, which might depend on various factors, such as age, weight, and mobility. The turtle agent can carry different pieces of luggage inside the aircraft (one small bag, 2 small bags, one large bag, one large and one small bag, or no bag—as detailed in Table 1) which reduces its speed between 0.6–0.9 patch/tick. Additionally, to store the luggage in the overhead compartment, each agent needs a luggage storage time, which is determined based on the formula suggested by [76] and used in [1,9,11,19,24]:

$$T_{store} = ((N_{binLarge} + 0.5 N_{binSmall} + N_{passengerLarge} + 0.5 N_{passengerSmall}) \\ * (N_{passengerLarge} + 0.5 N_{passengerSmall}) / 2) * T_{row}$$

where:

T_{store} is the time to store the luggage

$N_{binLarge}$ is the number of large bags in the bin prior to the passenger’s arrival

$N_{binSmall}$ is the number of small bags in the bin prior to the passenger’s arrival

$N_{passengerLarge}$ is the number of large bags carried by the passenger

$N_{passengerSmall}$ is the number of small bags carried by the passenger

T_{row} is the time for a passenger to walk from one row to the next (when not delayed by another passenger in front)

At time zero, the first agent enters the cabin using the front door of the airplane and proceeds to its assigned seat. Depending on the selected boarding method, agents having seats in different parts of the airplane are called for boarding with respect to the selected boarding method rules. In the case of random without assigned seats, the passenger’s preference for a particular part of the airplane (front/middle/aisle) or a particular type of seat (near window/aisle) was determined through a fitness

function, which considers all these aspects. The fitness function is based on the results gathered through a questionnaire in a previous study [27].

Upon entering the cabin, the agents advance down the aisle to their assigned seats, keeping the imposed distance from another passenger in the aisle (1 m, 1.5 m, or 2 m). When it arrives near its assigned seat, if an agent has one or two pieces of luggage, it needs to first store the luggage, blocking the aisle for any passengers behind it—those other passengers will wait for the agent to store the luggage, while preserving the social aisle distance imposed (1 m, 1.5 m, or 2 m). After the luggage is stored, the agent proceeds to its seat. If the seat is near the window and the aisle seat located in the same row is already occupied by another agent, the agent faces a type 3 seat interference and waits for the agent seated in the aisle seat to free its path and then proceeds to its assigned seat. In the time during which the seat interference takes place, none of the passengers located in the aisle behind the passenger engaged in the seat interference can overpass the agent; they can only advance in the aisle within the limits permitted by the aisle distancing, namely keeping an imposed distance of 1 m, 1.5 m, or 2 m. According to the literature, the time associated with a type 3 interference is 10 s, with a range of 9–13 s, as determined in the field trial conducted by Schultz [14]. The simulation ends when all of the agents have taken their assigned seats.

The agent-based model graphical user interface (GUI) is presented in Figure 8.

Figure 8. The GUI for the agent-based model in NetLogo. (View in the case of the back-to-front by row boarding method).

5. Numerical Simulation Results

We used the BehaviourSpace [72] tool provided by NetLogo to run 10,000 simulations for each of the considered scenarios. Below, we present the average values for each scenario. Sections 5.1–5.3 present the average performance metrics with (social) aisle distancing of 1 m, 1.5 m, and 2 m, respectively, while Section 5.4 discusses the results across all of the aisle distancing scenarios.

5.1. Simulation Results for Aisle Distancing of 1 m

Considering an aisle distancing of 1 m, the average times to complete boarding are shown in Table 3. The method providing the fastest boarding time was the modified reverse pyramid half zone, with an average boarding time ranging between 8 min 38 s and 15 min 3 s, depending on the types and quantities of passengers' carry-on luggage. The second-fastest boarding method was WilMA, ranging between 9 min 8 s and 15 min 52 s. Random without assigned seats and random with assigned seats yielded comparable results, while the method with the largest boarding time was back-to-front by row, which offered a boarding time between 12 min 59 s and 23 min 52 s. For the S1 luggage situation, the back-to-front by row method resulted in a boarding time that was 58.58% longer than that resulting from the modified reverse pyramid half zone method.

Table 3. Average boarding times with blocked middle seats and 1 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	1004	952	910	865	808	725	573
Random with assigned seats	1059	1016	975	931	870	786	657
Outside-in/WilMA	952	913	871	833	768	693	548
Back-to-front by group	1169	1090	1023	970	900	821	685
Back-to-front by row	1432	1309	1201	1101	1013	916	779
Modified reverse pyramid half zone	903	867	829	795	742	669	518

The number of type 3 seat interferences is depicted in Table 4. We observed that two of the methods, namely WilMA and the modified reverse pyramid half zone, had zero for this metric. This result was expected, because with these two methods, the passengers with window seats were the ones taking their assigned seats first, followed by the passengers with aisle seats. A reduced value for this criterion was obtained in the case of random without assigned seats as, considering the passengers' preferences presented in [27], we observed that the window seats are preferred to the aisle seats. As for the remaining methods—random with assigned seats, back-to-front by group, and back-to-front by row—the average number of seat interferences was essentially the same and ranged between 29 and 31 interferences, as shown in Table 4. Tiny differences in numerical results can stem from the random variability inherent in stochastic simulation models.

Table 4. Average total number of seat interferences with blocked middle seats and 1 m aisle distancing.

Boarding Method	Aisle Distancing: 1 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	6	5	6	6	6	6	6
Random with assigned seats	30	31	30	30	30	30	30
Outside-in/WilMA	0	0	0	0	0	0	0
Back-to-front by group	30	30	30	30	30	30	30
Back-to-front by row	30	30	29	30	31	30	31
Modified reverse pyramid half zone	0	0	0	0	0	0	0

The average total extra luggage storage duration for each of the considered scenarios showed no significant difference among the six considered boarding methods, as presented in Table 5. This is not

surprising because the rules for each of the methods ignore passenger safety during luggage storage in the overhead compartment. As a result, no boarding method tested was superior with respect to this metric.

Table 5. Average total extra luggage storage duration with blocked middle seats and 1 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	471	351	246	152	98	44	0
Random with assigned seats	472	351	246	152	97	45	0
Outside-in/WilMA	471	351	246	153	97	45	0
Back-to-front by group	471	350	246	153	98	44	0
Back-to-front by row	470	351	245	151	96	44	0
Modified reverse pyramid half zone	472	351	244	152	98	45	0

Table 6 shows the aisle seat risks of the six methods. This pertains to the risk of aisle seated passengers becoming infected by later boarding passengers traversing their row. The best performing method according to this type of risk was back-to-front by row, with a total duration of 984 s for S1 luggage situation, 757 s less than the second-best method based on this metric—modified reverse pyramid half zone. In considering the boarding rules of the back-to-front by row method, we observed that this risk was generated in the row in which the boarding passenger sits, as all the other rows traversed by a boarding passenger were empty. The modified reverse pyramid half zone method produced the second-smallest values for this risk on all the luggage situations as the boarding was done on two halves of the airplane with respect to the number of rows, which reduced the passengers' aisle seat risk for half of the aisles at a time. The worst performing method for this metric was the random with assigned seats boarding method, with durations of up to 986.76% times higher than the best performing method—back-to-front by row.

Table 6. Average aisle seats risk duration with blocked middle seats and 1 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	5514	5299	5015	4800	4530	4033	3312
Random with assigned seats	8015	7816	7290	7154	6631	5927	5392
Outside-in/WilMA	3462	3252	3118	3023	2759	2534	2087
Back-to-front by group	2369	2189	2022	1880	1721	1600	1513
Back-to-front by row	984	900	786	725	682	625	602
Modified reverse pyramid half zone	1741	1655	1537	1440	1336	1196	1034

For the window seat risk, the back-to-front by row method continued to have the smallest duration, with a value of 714 s for S1 luggage situation, as shown in Table 7. The second-best method was back-to-front by group with durations up to 32.23% higher than the best-performing method—back-to-front by row. As both WilMA and random without assigned seats favor the occupancy of the window seats first, these methods had high values for this metric. The highest values were recorded by random without assigned seats, which were up to 2377.98% higher than those obtained for the best performing method, according to this criterion, as shown in Table 7.

Table 7. Average window seats risk duration with blocked middle seats and 1 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	10,950	10,586	10,092	9506	8836	7990	6672
Random with assigned seats	7808	7465	7099	6817	6431	5712	5092
Outside-in/WilMA	10,595	10,152	9658	9203	8472	7668	6460
Back-to-front by group	2083	1868	1744	1596	1447	1292	1234
Back-to-front by row	714	602	511	426	382	336	307
Modified reverse pyramid half zone	7232	6808	6473	6055	5562	5009	4268

5.2. Simulation Results for Aisle Distancing of 1.5 m

We conducted a series of simulations for the S1–S7 luggage scenarios, while imposing an aisle distance for the passengers of 1.5 m.

With respect to the average boarding time, we observed that the boarding methods relative performance hierarchy established for 1m aisle distancing was the same in this case, as shown in Table 8. The method with the smallest boarding time was, again, the modified reverse pyramid half zone. The boarding times for this method ranged between 11 min 26 s and 19 min and 34 s.

Table 8. Average boarding time with blocked middle seats and 1.5 m aisle distancing (in seconds).

Boarding Method	AisleDistancing: 1.5 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	1263	1211	1152	1100	1022	914	743
Random with assigned seats	1327	1280	1227	1173	1095	994	837
Outside-in/WilMA	1211	1162	1109	1062	982	881	714
Back-to-front by group	1483	1408	1315	1245	1156	1051	883
Back-to-front by row	1663	1541	1432	1323	1229	1118	956
Modified reverse pyramid half zone	1174	1125	1078	1034	959	867	686

The average total numbers of seat interferences for 1.5 m aisle distance, as shown in Table 9 were essentially the same as those resulting from the 1 m aisle distancing, presented in Table 4. The tiny differences of this magnitude stem from the variability of stochastic simulation.

Table 9. Average total number of seat interferences for full flight, middle seat empty, 1.5 m aisle distancing.

Boarding Method	Aisle Distancing: 1.5 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	6	6	6	6	5	6	6
Random with assigned seats	30	30	30	30	30	30	30
Outside-in/WilMA	0	0	0	0	0	0	0
Back-to-front by group	30	30	30	29	31	29	30
Back-to-front by row	30	30	30	30	30	30	30
Modified reverse pyramid half zone	0	0	0	0	0	0	0

Furthermore, the average total extra luggage storage duration did not change significantly across the boarding methods, as shown in Table 10. When compared to the 1m aisle distance situation, as shown in Table 5, the absolute difference was less than two seconds.

The aisle seats risk determined for the 1.5 m aisle distancing, as shown in Table 11, provided the same hierarchy (relative performance results) for the boarding methods, as determined for 1 m

aisle distancing, as shown in Table 6. The best performing method (back-to-front by row) provided a duration that was 9.76 times smaller than the worst performing method (random with assigned seats).

Table 10. Average total extra luggage storage duration with blocked middle seats and 1.5 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1.5 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	470	352	244	151	97	45	0
Random with assigned seats	471	350	246	151	97	45	0
Outside-in/WilMA	472	351	246	152	96	45	0
Back-to-front by group	469	350	245	152	97	44	0
Back-to-front by row	470	351	245	151	97	45	0
Modified reverse pyramid half zone	471	350	245	152	98	44	0

Table 11. Average aisle seats risk duration with blocked middle seats and 1.5 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1.5 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	5462	5219	5016	4716	4396	3887	3325
Random with assigned seats	7928	7556	7307	7067	6419	5899	5311
Outside-in/WilMA	3413	3276	3092	3029	2752	2449	2105
Back-to-front by group	2285	2064	1943	1778	1691	1520	1454
Back-to-front by row	1007	886	810	724	667	622	600
Modified reverse pyramid half zone	1720	1636	1507	1438	1324	1188	1045

The window seats risk calculated for the 1.5 m aisle distancing situation, as shown in Table 12, did not provide any new information in terms of the boarding methods performance hierarchy when compared to the 1 m aisle distancing, provided in Table 7. The best performing method according to this metric was back-to-front by row, which resulted in a duration up to 706 s, as shown in Table 12.

Table 12. Average window seats risk duration with blocked middle seats and 1.5 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 1.5 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	10,730	10,298	9881	9365	8747	7834	6618
Random with assigned seats	7556	7265	7058	6679	6110	5658	4968
Outside-in/WilMA	10,444	9928	9514	9060	8365	7499	6418
Back-to-front by group	1968	1789	1688	1525	1380	1267	1178
Back-to-front by row	706	607	518	431	378	335	301
Modified reverse pyramid half zone	7075	6745	6341	6014	5485	4952	4244

If one compares the values for the window seats risk, recorded for both 1 m and 1.5 m aisle distancing, as shown in Tables 7 and 12, we observe that the increase in aisle distancing by 0.5 m contributes to a decrease in risk for five of the six methods, with a decrease of up to 252 s. The only exception is the back-to-front by row method, where the values for this risk had almost the same values (within a 7–8 s variation range), regardless of aisle distancing.

5.3. Simulation Results for Aisle Distancing of 2 m

The 2 m aisle distance resulted in higher boarding times for all the boarding methods, as shown in Table 13. Depending on the quantity of luggage, the average boarding time took up to 31 min 31 s in

the case of back-to-front by row. Again, in this case, the best-performing method was the modified reverse pyramid half zone, with an average boarding time of up to 23 min 36 s.

Table 13. Average boarding time with blocked middle seats and 2 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 2 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	1506	1456	1389	1324	1224	1105	915
Random with assigned seats	1566	1518	1458	1400	1295	1184	1013
Outside-in/WilMA	1445	1401	1338	1288	1183	1063	880
Back-to-front by group	1741	1651	1569	1483	1368	1248	1060
Back-to-front by row	1891	1769	1653	1548	1436	1299	1120
Modified reverse pyramid half zone	1416	1367	1312	1260	1168	1052	853

In terms of the number of total seat interferences, no meaningful changes were observed comparing the 2 m aisle distancing, as shown in Table 14, with those of the 1 m and 1.5 m aisle distancing.

Table 14. Average total number of seat interferences with blocked middle seats and 2 m aisle distancing.

Boarding Method	Aisle Distancing: 2 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	6	6	6	6	6	6	6
Random with assigned seats	30	31	30	30	30	29	30
Outside-in/WilMA	0	0	0	0	0	0	0
Back-to-front by group	30	31	30	30	30	30	30
Back-to-front by row	30	30	30	30	30	30	31
Modified reverse pyramid half zone	0	0	0	0	0	0	0

Furthermore, the average total extra luggage storage durations were, again, consistent across the boarding methods with respect to the imposed aisle distancing, as shown in Table 15.

Table 15. Average total extra luggage storage duration with blocked middle seats and 2 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 2 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	471	352	245	152	98	44	0
Random with assigned seats	471	350	245	153	97	45	0
Outside-in/WilMA	470	351	245	152	97	44	0
Back-to-front by group	472	352	245	152	97	44	0
Back-to-front by row	472	352	245	151	97	44	0
Modified reverse pyramid half zone	470	352	246	153	97	45	0

Again, in this case, the aisle seats risk was lower for the back-to-front by row method when compared to the other considered boarding methods, as shown in Table 16. We further observed that the increasement of 0.5 m aisle distancing (from 1.5 m to 2 m) produced a reduction of up to 288 s in the duration associated with this risk for five of the six boarding methods.

The window seats risk in the case of 2 m aisle distancing, as shown in Table 17, provided the same hierarchy for the boarding methods, as established for 1m and 1m aisle distancing, as shown in Tables 7 and 12).

As for the duration of the window seats risk, when compared to the duration of the same risk in the case of 1.5 aisle distancing, the duration was reduced by up to 271 s. Furthermore, when compared to the 1m aisle distancing situation, the reduction in duration was up to 424 s, illustrating once more

that increasing aisle distancing can reduce the window seats risk. This reduction was highly visible for the boarding methods which did not perform well for the window seats risk metric, such as: random without assigned seats, WilMA, and even random with assigned seats. For the best performing method, back-to-front by row, the value of aisle distancing did not make a meaningful difference in the window seats risk.

Table 16. Average aisle seats risk duration with blocked middle seats and 2 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 2 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	5362	5219	4858	4657	4252	3889	3340
Random with assigned seats	7706	7501	7019	6845	6272	5791	5202
Outside-in/WilMA	3388	3254	3056	2954	2711	2486	2126
Back-to-front by group	2197	2090	1910	1745	1619	1530	1416
Back-to-front by row	996	894	799	724	667	613	599
Modified reverse pyramid half zone	1679	1584	1505	1400	1294	1153	1045

Table 17. Average window seats risk duration with blocked middle seats and 2 m aisle distancing (in seconds).

Boarding Method	Aisle Distancing: 2 m						
	S1	S2	S3	S4	S5	S6	S7
Random without assigned seats	10,663	10,172	9767	9311	8527	7672	6647
Random with assigned seats	7409	7055	6796	6408	6007	5594	4942
Outside-in/WilMA	10,270	9925	9383	8988	8215	7444	6434
Back-to-front by group	1932	1746	1608	1462	1321	1242	1146
Back-to-front by row	712	600	509	425	380	335	300
Modified reverse pyramid half zone	6959	6652	6266	5906	5435	4904	4283

5.4. Simulation Results Summarized across All Aisle Distancing 1 m, 1.5 m, and 2 m

It is interesting to analyze the influence of (social) aisle seat distancing on aisle seat risk and window seat risk. For the back-to-seat by row method, there was no influence other than insignificant differences that arose due to the randomness of stochastic simulation. For the other five boarding methods, the greater the value of aisle distancing, the smaller the resulting aisle and seat risks. We observe those relationships from the close examination of the differences in aisle seat risks from Table 6, Table 11, and Table 16, as the aisle distancing changed from 1 m to 1.5 m to 2 m, and from Table 7, Table 12, and Table 17, examining the analogous impact on window seat risks from the aisle distancing changing from 1 m to 1.5 m to 2 m. However, the clearest way to see the relationships is to examine Table 18, which contains the total seat risk durations (summing over both aisle seat risk and window seat risk), with 1 m aisle distancing minus the total seat risk durations with 2 m aisle distancing.

It is important to recall that the seat risk durations stem from passengers advancing towards the row of their seat and (if infected) spreading the virus to previously boarding passengers already seated in the rows the advancing passenger enters. For the back-to-front by row method, this risk is only generated in the row in which the passenger sits, because all the other rows ahead of a boarding passenger are empty. Consequently, we would expect no meaningful change in the total seat risk duration of the back-to-front row method as aisle distancing changes from 1 m to 2 m. This is consistent with the results illustrated in Table 18.

For the other five methods, consider what happened when aisle distancing changed from 1 m to 2 m. Suppose passenger X follows passenger Y down the aisle. Suppose further that Y hinders

the progress of X. This could be because Y is walking at a slower speed than X. More commonly, X would be delayed while Y stores luggage into an overhead bin and sits in a row prior to the row where X will sit. Once Y has left the aisle, X may walk without interference for at least 1 m (with 1 m aisle distancing) and for at least 2 m (with 2 m aisle distancing). In the latter case, X may proceed for the next 2 m at a faster speed on average (because of no interference) than in the former case (because of potential interference in the second of those two meters). We see the ramifications in Table 18, where for five of the methods the average total seat risk duration was consistently less with 2 m aisle distancing than with 1 m aisle distancing for all but the S7 (no luggage) scenario. Consequently, even though aisle distancing was designed, as illustrated in the example, to reduce the risk of virus spread between passengers X and Y, an additional benefit is that increased aisle distancing reduces the health risk to previously boarded passengers sitting in rows that X passes.

Table 18. Amount by which the average total (aisle and window) seat risk durations with 1 m aisle distancing exceeds that with 2 m aisle distancing (in seconds).

Boarding Method	Difference							Average Difference across All Luggage Scenarios
	S1	S2	S3	S4	S5	S6	S7	
Random without assigned seats	439	494	482	338	587	462	−3	400
Random with assigned seats	708	725	574	718	783	254	340	586
Outside-in/WilMA	399	225	337	284	305	272	−13	258
Back-to-front by group	323	221	248	269	228	120	185	228
Back-to-front by row	−10	8	−11	2	17	13	10	4
Modified reverse pyramid half zone	335	227	239	189	169	148	−26	183

It is important to recall that the seat risk durations stem from passengers advancing towards the row of their seat and (if infected) spreading the virus to previously boarding passengers already seated in the rows the advancing passenger enters. For the back-to-front by row method, this risk is only generated in the row in which the passenger sits, because all the other rows ahead of a boarding passenger are empty. Consequently, we would expect no meaningful change in the total seat risk duration of the back-to-front row method as aisle distancing changes from 1 m to 2 m. This is consistent with the results illustrated in Table 18.

For the other five methods, consider what happened when aisle distancing changed from 1 m to 2 m. Suppose passenger X follows passenger Y down the aisle. Suppose further that Y hinders the progress of X. This could be because Y is walking at a slower speed than X. More commonly, X would be delayed while Y stores luggage into an overhead bin and sits in a row prior to the row where X will sit. Once Y has left the aisle, X may walk without interference for at least 1 m (with 1 m aisle distancing) and for at least 2 m (with 2 m aisle distancing). In the latter case, X may proceed for the next 2 m at a faster speed on average (because of no interference) than in the former case (because of potential interference in the second of those two meters). We see the ramifications in Table 18, where for five of the methods the average total seat risk duration was consistently less with 2 m aisle distancing than with 1 m aisle distancing for all but the S7 (no luggage) scenario. Consequently, even though aisle distancing was designed, as illustrated in the example, to reduce the risk of virus spread between passengers X and Y, an additional benefit is that increased aisle distancing reduces the health risk to previously boarded passengers sitting in rows that X passes.

Looking at all the performance metrics in Table 19 (where the methods performing better according to a specific criterion are highlighted using dark grey, while the methods performing worse are highlighted using light grey), we see the relative performances of the six boarding methods that apply to all of the conditions of aisle distancing (1 m, 1.5 m, and 2 m). We observed that the modified reverse pyramid half zone is the best method for both the boarding time and total number of seat interferences metrics, while back-to-front by row performs the worst, based on those two metrics.

Table 19. Boarding methods hierarchy (best to worst by metric).

Metric	Hierarchy
Boarding time	1. Modified reverse pyramid half zone
	2. Outside-in/WilMA
	3. Random without assigned seats
	4. Random with assigned seats
	5. Back-to-front by group
	6. Back-to-front by row
Total number of seat interferences	1. Modified reverse pyramid half zone
	2. Outside-in/WilMA
	3. Random without assigned seats
	4. Random with assigned seats
Total extra luggage storage duration	
No hierarchy can be established	
Aisle seats risk	1. Back-to-front by row
	2. Modified reverse pyramid half zone
	3. Back-to-front by group
	4. Outside-in/WilMA
	5. Random without assigned seats
	6. Random with assigned seats
Window seats risk	1. Back-to-front by row
	2. Back-to-front by group
	3. Modified reverse pyramid half zone
	4. Random with assigned seats
	5. Outside-in/WilMA
	6. Random without assigned seats

For the health metric related to total extra luggage storage duration, no hierarchy is established as all of the six boarding methods have results in similar values.

As for the aisle and window seats risks metrics, the best performing method was back-to-front by row, followed by either modified reverse pyramid half zone (for the aisle seats risk criterion) or back-to-front by group (for the windows seats risk criterion). WilMA, random with assigned seats, and random without assigned seats ranked lowest in the hierarchy, according to these two risk metrics.

Considering the varying values for the aisle distancing and the S1 luggage situation, in Figure 9 we observe that, when the aisle distancing increased from 1 m to 1.5 m, the average boarding time increased with values between 16.09–29.86%, with an average degradation across all methods of 25.15%.

Figure 9. The average boarding time across the methods, S1 luggage situation.

If the aisle distance doubled, from 1 m to 2 m, the decrement in average boarding time ranged between 32.06% (in the case of back-to-front by row) to 56.63% (in the case of the modified reverse pyramid half zone), with an average of 47.84%. As a result, we observed that each increment in aisle distancing of 0.5 m increased the boarding time by about a quarter.

5.5. Discussions

The new social distancing rules imposed by the occurrence of the COVID-19 coronavirus affect humans' everyday lives, from spare time to work-related activities. In this context, the classical boarding methods used for passengers boarding airplanes have been adjusted to reduce the risk of COVID-19 infections due to social interaction.

In this paper, a series of measures, related to airplane boarding taken or mooted by the airlines in during this pandemic, are evaluated in terms of boarding time and passenger health risk. We used an agent-based model in NetLogo to implement the passenger boarding processes under the new social distancing assumptions and for testing six of the classical boarding methods used in practice by the airlines.

As a result, we observed that the method providing the best boarding time was the modified reverse pyramid half zone, followed by WilMA, and random without assigned seats. The method with the largest boarding time was back-to-front by row. The aisle distance was determined to have an impact on the time to complete the boarding of the airplane. On average, every additional 0.5 m imposed for aisle distance between boarding passengers resulted in an approximate 25% increase in boarding time.

Another metric, one concerning passengers' health, addressed seat interferences. Both the modified reverse pyramid half zone and WilMA boarding methods ensured no interferences among the passengers who had seats in the same row.

As for the extra luggage storage duration—a metric of the duration of time that passengers may be touching the luggage of other passengers, risking exposure due to touching a surface (luggage or otherwise) that may contain COVID-19 droplets—we observed that there was no best method, as all of the considered methods performed the same for this metric. This result was expected, as none of the rules of these boarding methods account for this health risk.

The aisle seats risk and the window seats risk were calculated to evaluate the classical boarding methods based on the health risk of passengers proceeding towards their seats infecting passengers already seated in earlier rows. Combining the results for both of these risk metrics, we observed that the best performing method was back-to-front by row, followed by back-to-front by group, and modified reverse pyramid half zones. We note that that Delta Air Lines boards passengers in a back-to-front by row sequence [37,38] as a part of COVID-19 restrictions for ensuring passenger safety during air transport.

As a result, the six classical boarding methods analyzed in the paper come with advantages and disadvantages in terms of boarding time and passenger safety during the COVID-19 pandemic, and the airlines have the difficult task of making a tradeoff between the economic benefits they from a fast boarding process and the various health impacts of them on their passengers.

6. Concluding Remarks

A key lesson from the paper arises from the observation that increasing the distance between passengers walking and standing in the aisle protects, not only those passengers in the aisle, but also reduces the health risk to seated passengers who are passed by those in the aisle. With increased aisle social distancing, the passengers wait less in the aisle and, thus, transmit fewer COVID-19 droplets onto the seated passengers they pass. This observation can be generalized to other contexts that have nothing to do with airplanes. When a walking person is impeded by the progress of a person in front, policies that increase the social distance between two such people will reduce the health risk of nearby

people they pass. This relationship should be considered in designing and assessing operational processes and policies in many contexts during this pandemic and perhaps beyond.

In the future, we plan to adjust the rules for the classical boarding methods to reduce the extra luggage storage duration and the risks generated by prolonged contact with the luggage of other passengers, while continuing to account for minimizing the aisle seats and window seats risks. We leave to infectious disease scientists the research opportunity to develop the relationships between the health metrics identified in this paper to the probabilities of infection.

The paper is accompanied by videos made for 1 m and 2 m aisle distancing, featuring all six of the classical boarding methods considered in the paper for the S1 luggage situation (Videos S1–S12). The videos can also be accessed at the following link: <https://github.com/liviucotfas/symmetry-airplane-boarding-covid-19>.

Supplementary Materials: The following are available online at <https://github.com/liviucotfas/symmetry-airplane-boarding-covid-19>: Video S1: Random without assigned seats simulation for 1 m social distancing; Video S2: Random without assigned seats simulation for 2 m social distancing; Video S3: Random with assigned seats simulation for 1 m social distancing; Video S4: Random with assigned seats simulation for 2 m social distancing; Video S5: Outside-in/WilMA simulation for 1 m social distancing; Video S6: Outside-in/WilMA simulation for 2 m social distancing; Video S7: Back-to-front by group simulation for 1 m social distancing; Video S8: Back-to-front by group simulation for 2 m social distancing; Video S9: Back-to-front by row simulation for 1 m social distancing; Video S10: Back-to-front by row simulation for 2 m social distancing; Video S11: Modified reverse pyramid half zone simulation for 1 m social distancing; Video S12: Modified reverse pyramid half zone simulation for 2 m social distancing.

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