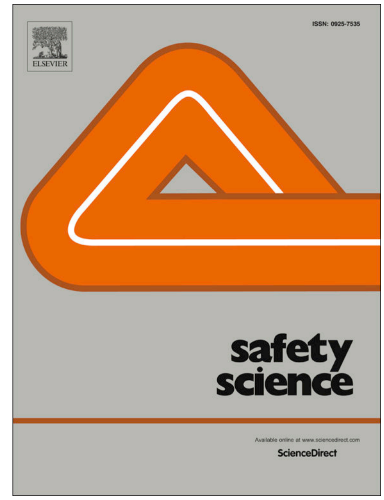
Journal Pre-proofs



Airplane Boarding Methods that Reduce Risk from COVID-19

R. John Milne, Camelia Delcea, Liviu-Adrian Cotfas

PII: S0925-7535(20)30458-6
DOI: https://doi.org/10.1016/j.ssci.2020.105061
Reference: SAFETY 105061

To appear in: *Safety*

Received Date: 9 June 2020
Accepted Date: 20 October 2020

Please cite this article as: John Milne, R., Delcea, C., Cotfas, L-A., Airplane Boarding Methods that Reduce Risk from COVID-19, *Safety* (2020), doi: https://doi.org/10.1016/j.ssci.2020.105061

Airplane Boarding Methods that Reduce Risk from COVID-19

R. John Milne [1], Camelia Delcea [2*], Liviu-Adrian Cotfas [2]

[1]David D. Reh School of Business, Clarkson University, 333 B.H. Snell Hall, Potsdam, NY 13699, USA; jmilne@clarkson.edu
[2]Department of Economic Informatics and Cybernetics, Bucharest University of Economic Studies, Bucharest 010552, Romania; camelia.delcea@csie.ase.ro (CD), liviu.cotfas@ase.ro (LAC)

* Correspondence: camelia.delcea@csie.ase.ro; Tel.: +40-769-652-813

Airplane Boarding Methods that Reduce Risk from COVID-19

Abstract:

Airlines have recently instituted practices to reduce the risk of their passengers becoming infected with the novel coronavirus (SARS-CoV-2). Some airlines block their airplanes' middle seats to preserve social distancing among seated passengers. In this context, we present six new boarding methods and compare their performance with that of the two best boarding methods used to date with social distancing. We evaluate the eight boarding methods using three performance metrics related to passenger health and one operational metric (airplane boarding time) for a one-door airplane. The three health metrics reflect the risks of virus spread by passengers through the air and surfaces (e.g. headrests and seat arms) and consider the amount of aisle social distancing between adjacent boarding passengers walking towards their seats. For an airline that highly values the avoidance of window seat risk, the best method to use is one of the new methods: back-to-front by row – WilMA, though it will result in a longer time to complete boarding of the airplane. Airlines placing greater emphasis on fast boarding times—while still providing favorable values for the health metrics—will be best served by using new methods back-to-front by row – WilMA – offset 2 and – offset 3 when aisle social distancing is 1 m and 2 m respectively.

Keywords: airplane boarding, COVID-19, SARS-CoV-2, social distancing, agent-based modeling

1. Introduction

Airplane boarding time is one of the measures airlines consider in attempting to reduce airplane turn time, which has a direct impact on reducing their costs [1]. Not only can long boarding times lead to costly delays prior to departure, late arrivals at destination airports can cause further delays on subsequent flights and thus yield additional costs [2]. As a result, over the years, a series of boarding methods have been proposed in the scientific literature [3], many of them adopted in practice by the airlines [4].

While reducing boarding times and not causing stress and discomfort to passengers remains a concern for airlines, health considerations and a safe flying environment have emerged as a top concern as a result of the COVID-19 disease caused by the severe respiratory coronavirus 2 (SARS-CoV-2) [5], [6]. Air transport organizations have created a series of recommendations for increasing safety. Airlines and airports have begun implementing some of these recommendation even as the restrictions imposed by national authorities related to air travel have been eased [5].

One of the most discussed measures for reducing the risk of COVID-19 contagion during airplane travelling concerns social distancing [7]–[9]. It would behoove airlines and airports to take actions that reduce interactions between individuals traveling in airplanes and using airport facilities. The International Air Transport Association (IATA) Medical Advisory Group recommends a minimum distance among passengers that can range from 1-2 meters. They recommend ensuring a limited number of passengers passing each other, sequential boarding starting from passengers with seats in the rear of the airplane and window seats, limit carry-on luggage, leaving empty seats in the jump seats region, leaving every second seat empty, or similar [5]. The importance of social distancing in air travel is highlighted by the European Union Aviation Safety Agency (EASA) in a recent report in which they recommend that "airplane operators should ensure, to the extent possible, physical distancing among passengers" [10].

Considering social distancing, Delta Air Lines has recently used a policy of boarding passengers in a back-to-front by row sequence, starting with passengers having seats in the rear row of the airplane [11]. A similar approach is used by GoAir [12] with a difference being that the passengers board from front rows to back rows and enter the airplane using the rear door. EasyJet [13] trialed a boarding procedure based on the passengers' seat numbers, while Alaska Airlines and Wizz Air [14] mooted keeping middle seats unoccupied. Southwest Airlines has announced that its boarding will be made in groups of ten passengers [15].

The IATA Medical Advisory Group believes that a multi-layered approach based on a combination of safety norms can lead to "high-levels of risk reduction" [5]. Social distancing is named as one of the potential measures to be considered.

Due to the new recommendations in view of the COVID-19 pandemic, it has been observed that some of the classical boarding methods succeed in achieving good boarding times, but fail in providing a safe environment for the passengers [16]. In that recent research, Cotfas et al. analyzed the boarding methods used by the airlines while accounting for social distancing among the passengers walking down the aisle and leaving every middle seat empty on each side of the aisle [16]. Like the present paper, they assessed the relative health risks of the classical boarding methods according to the number of seat interferences—which result from aisle seat passengers needing to leave their seats to clear space for later-boarding passengers with window seats in the same row and side of the airplane—and by the durations of aisle and window seat risks—which result from passengers advancing towards their seats while passing previously boarding passengers that are seated in their aisle and window seats respectively. In those simulation experiments, two boarding methods yielded superior performance. The modified reverse pyramid half zone method resulted in the fastest boarding times and tied with the WilMA (Windows Middle Aisle) method for the lowest health risk stemming from seat interferences. On the other hand, the back-to-front by row method provided the lowest health risks for seated passengers that are passed by other (potentially infected) passengers who are walking towards their seats or standing in the aisle [16], namely aisle seat risk and window seat risk. The back-to-front by row method also resulted in the longest time to complete boarding of the airplane.

In the present paper, we propose new boarding methods that take into account the advantages of the above-mentioned boarding methods, while trying to reduce the level of the health risk. We evaluate the methods under various scenarios according to the averages of four metrics: boarding time and three health-related metrics—number of seat interferences and average durations of aisle seat and window seat risks. The best of the new methods are attractive alternatives for airlines to consider depending their relative priorities of the four measured criteria.

The remainder of the paper is organized as it follows: Section 2 provides a brief literature review on airplane boarding methods. Section 3 presents the proposed boarding methods. Section 4 discusses the scenarios to be considered and calculation details on the metrics used to evaluate performance of the methods. Section 5 provides the information needed for creating and understanding the agent-based model used for the stochastic simulation experiments. Section 6 presents the numeric results of the simulation runs and discusses the relative advantages and disadvantages of the best new and existing methods. The paper closes with concluding remarks and future research directions. A series of videos presenting simulations made using the agent-based model accompanies the paper.

2. Literature Review

Methods for airplane boarding can be divided into open seating and assigned seats categories based on the existence or absence of assigned seats. While many airlines (e.g. Air France, EasyJet, KLM, Lufthansa, Ryanair, United Airlines, Air Canada, Air China, Alaska, American Airlines, Delta Airlines, British Airways, Japan Airline, Spirit, Korean Air, etc.) assign passengers to particular seats on the airplane prior to boarding, some airlines (e.g. Southwest Airlines) use an open seating system in which boarding passengers select their seats after arriving in the cabin based on their individual preferences for seat positions within a row (window, middle, or aisle seat) and for sitting in the front, middle, or rear of the airplane [4].

With assigned seating, the most commonly used methods are: random with assigned seats, WilMA, back-to-front by group, back-to-front by row, and modified reverse pyramid half zone, even though the research literature has proposed more than twenty methods for passengers boarding [16]. In the following, we provide the boarding rules that accompany the methods most used in practice and discuss the main criteria the research literature considers when evaluating the proposal of a new boarding method.

According to the random with assigned seats method, the passengers know their seats prior to boarding—either by selecting the seats themselves using the airline's online check-in option or by a seat determination made by the airline—and they proceed to board into the airplane in no particular order, based on the time of their arrival at the boarding gate. Upon arriving inside the cabin, each passenger proceeds to the assigned seat, stores any luggage in an overhead bin, and sits [17].

We describe the other methods assuming a one-door airplane configured with three seats on each side of a single aisle. The WilMA method is so named because passengers with windows seats board the airplane first, followed by middle seat passengers, and then by the third and final group of passengers who will be sitting in aisle seats. As with the other *by group* methods, within a particular group, the passengers board the airplane in a random sequence [18]–[21].

The back-to-front by group method divides the passengers in groups based on their seat positions with respect to the length of the airplane, starting from the rear of the airplane. In most cases, the number of groups is five. The first group to board is formed by the passengers having the seats in the last rows of the airplane (usually, this group comprises 1/5 of the airplane rows). The process continues with one group at a time until the final group, having seats in the first rows of the airplane, has been boarded [22].

Similar to back-to-front by group method, the back-to-front by row method divides the passengers into a number of groups equal to the number of rows in the airplane. The order for boarding these groups is from the rear of the airplane to the front in a random manner inside each group of passengers [3].

The modified reverse pyramid half zone method features a mixture between WilMA and back-to-front by group rules. Four groups of passengers are formed in this case. The first group comprises all the passengers with seats in the rear half of the airplane with seats near the window. The second group is made by all the passengers having seats in the front half of the airplane near the window and in the rear half of the airplane in the middle seats. The third group respects the rules for the second group following the same diagonal scheme, while the fourth group is composed of the passengers in the front half of the airplane having the seats near the aisle [1], [3], [23], [24].

As for methods proposed in the literature, a series of elements have been considered to allow their testing in similar conditions to those encountered practice including: airplane characteristics [1], [20], [25]–[27], airplane occupancy [21], [23], [25], [26], [28]–[30], passengers movement [17], [18], passengers' personal characteristics [27]–[29], number and size of the hand luggage [18], [25], [29], [31], [32], time to store the luggage in the overhead compartment [33], [34], the presence of jet-bridges [35]–[39], the use of apron buses for passengers transport between the airport terminal and the airplane [34], [40]–[43], the occurrence of interferences between passengers either while proceeding down aisle or because of needing to depart a seat to clear space for a later boarding passenger assigned a seat closer to the window [1], [24], [28], [32], [44]. Other studies in the research literature focus on improving boarding methods [1], [18], [23], [25], [31], [32], [36], [44]–[46] and on conducting field trials to estimate data to be used in computer simulations [21], [47], [48].

Following the suggestions made by [35], [48], in our modeling and experiments, we assume a single-door Airbus A320 configuration with one aisle, thirty rows, and three seats on each side of the aisle. Following the most of the literature, we assume the airplane seats are economy class. To consider social distancing among the passengers when seated, we assume that the middle seats will be left unoccupied (empty) as suggested in [16] – Figure 1.

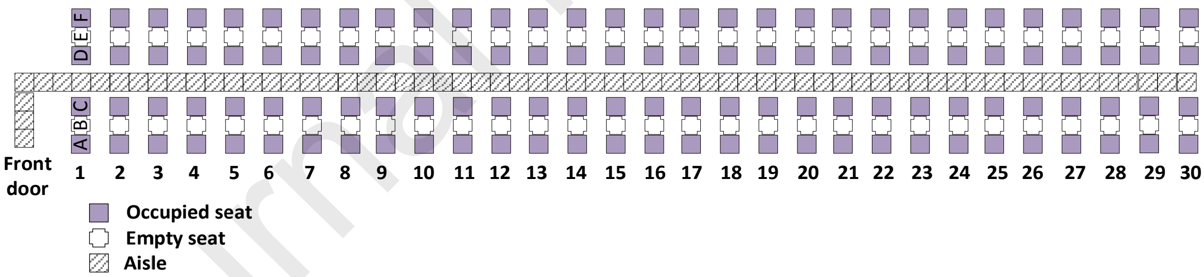


Figure 1 Airplane configuration modeled in this paper

3. Airplane Boarding Methods that Reduce Health Risks

We investigate airplane boarding methods that provide social distancing to mitigate health risks from COVID-19. Two of the methods are baseline methods from prior research with social distancing [16]. The other boarding methods are new.

3.1. Baseline Methods – Modified reverse pyramid half zone and Back-to-seat by rows

A recent study on commonly used airplane boarding methods observed two superior methods when the middle seats are blocked (unoccupied) to preserve social distancing [16]. These methods are back-to-front by row and modified reverse pyramid half zone and are described in the literature review section and illustrated in Figure 2 and Figure 3 respectively.

With middle seat blocking for COVID-19 social distancing, the modified reverse pyramid half zone method resulted in the fastest boarding time and has low health risk from seat interferences. Meanwhile, the back-to-front by row method produced the lowest values of aisle seat risk and window seat risk and had the longest time to complete boarding of the airplane [16]. Thus, we consider these two methods the baseline for comparing with the new methods we propose.

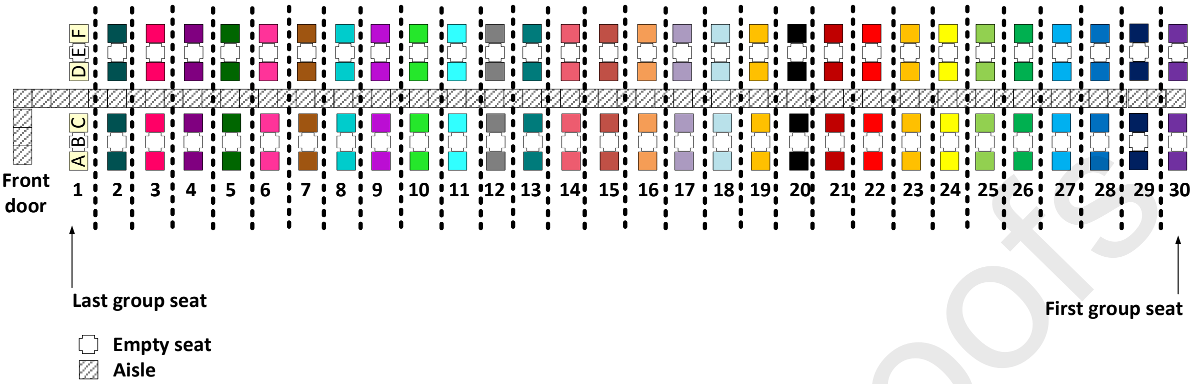


Figure 2 Back-to-front by row considering COVID-19 social distancing

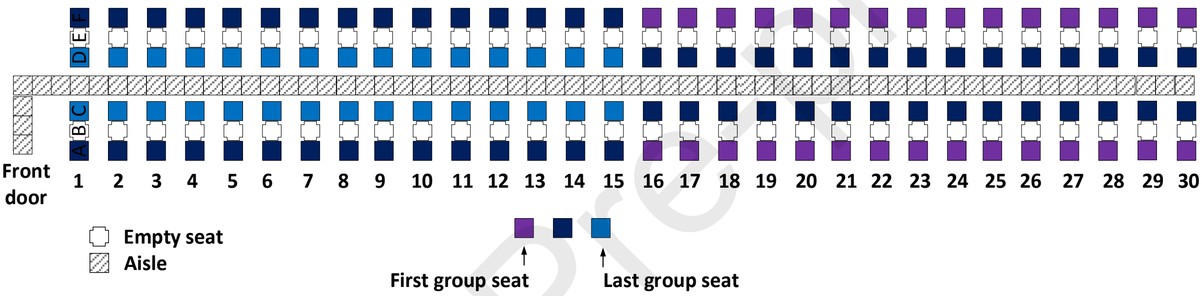


Figure 3 Modified reverse pyramid half zone considering COVID-19 social distancing

As with the previous methods, for our new methods, we assume that the middle seat is blocked and further assume that all window seats and all aisle seats are occupied. The new methods are inspired by the boarding rules of back-to-front by row and WilMA, while trying to reduce the boarding time and provide favorable values for the health-related metrics. In the following, we present the new boarding methods along with their schemes.

3.2. Back-to-front by row - WilMA

The back-to-front by row – WilMA method boards the passengers one row at a time starting from the rear of the airplane. For each row, the two passengers with window seats board first in a random sequence, followed by the two passengers with aisle seats who also board randomly. Figure 4 provides the scheme for this method. The darker shades in each row represent the first two passengers of that row to board and the lighter shades represent the final two passengers in that row to board. This method is designed to have the advantages of the baseline back-to-front by row method but with the additional advantages from having the window seats passengers of a row board before its aisle seat passengers.

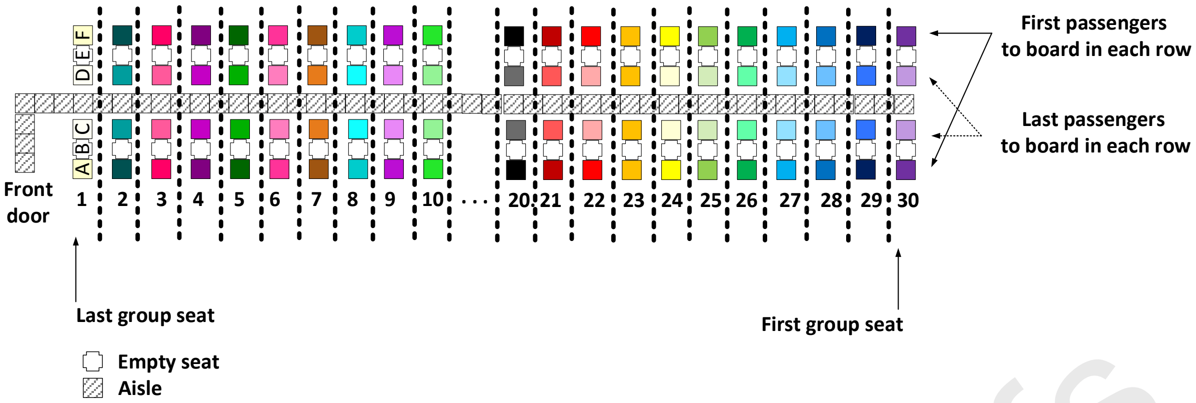


Figure 4 Back-to-front by row – WilMA considering COVID-19 social distancing

3.3. Back-to-front by row – WilMA – offset k

Five new boarding methods are created by adjusting the back-to-front by row – WilMA method so that some of the window seat passengers board earlier. In particular, k rows of window seat passengers will board the airplane before any aisle seat passengers board for the back-to-front by row – WilMA – offset k method. In the five new methods, the value of k ranges between 2 and 6.

When $k = 2$, the first four passengers to board the airplane have window seats in rows 30, 29, 30, and 29 respectively as illustrated by the four rightmost yellow-highlighted seats numbered 1 to 4 in Figure 5. The next four passengers to board have an aisle seat in row 30, a window seat in row 28, an aisle seat in row 30, and a window seat in row 28 respectively. This pattern continues until all window seats have been occupied and only four aisle seat passengers remain to board. These final four passengers to board have the leftmost yellow-highlighted seats numbered 117 to 120 in Figure 5.

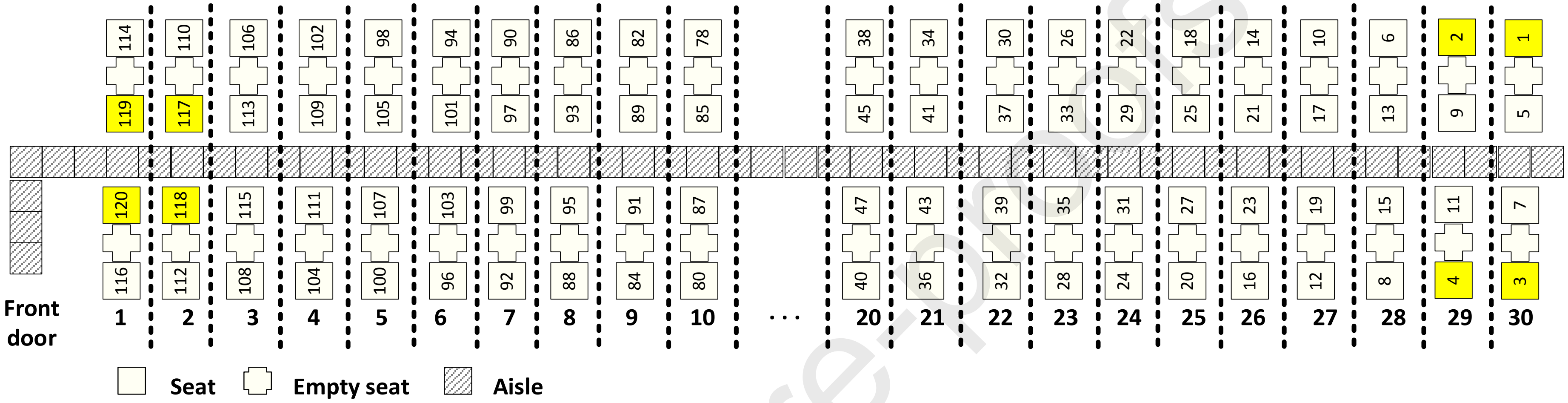


Figure 5 Back-to-front by row – WilMA – offset 2 (for k=2 rows) considering COVID-19 social distancing

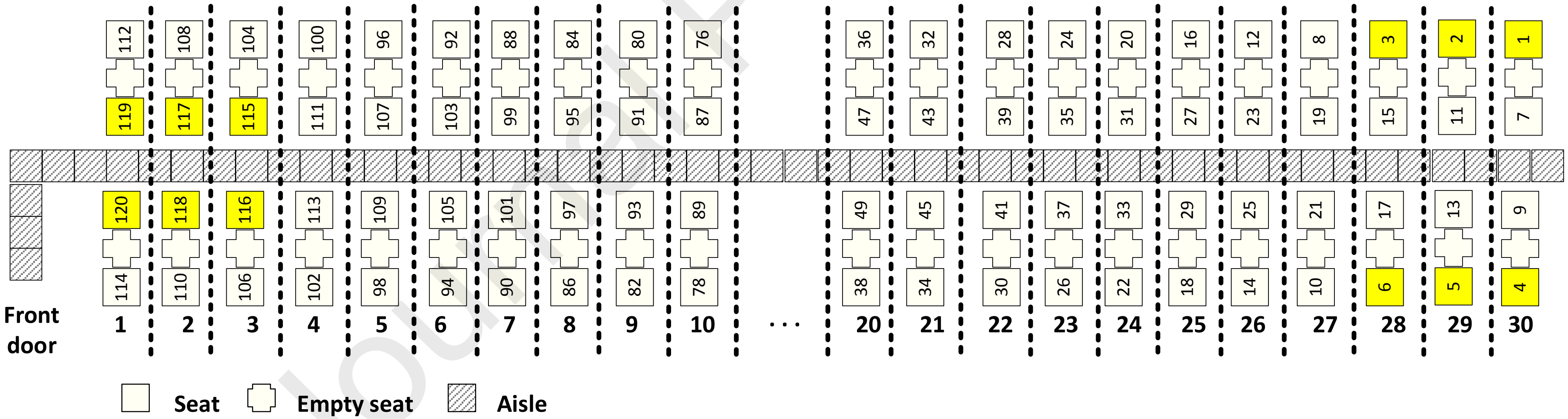


Figure 6 Back-to-front by row – WilMA – offset 3 (for k=3 rows) considering COVID-19 social distancing

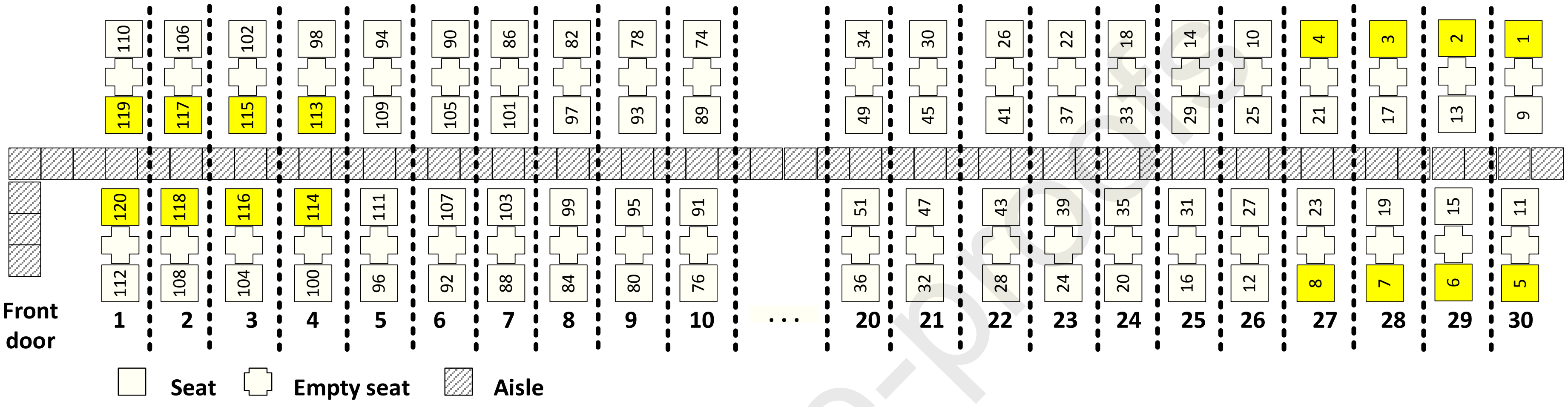


Figure 7 Back-to-front by row – WilMA – offset 4 (for k=4 rows) considering COVID-19 social distancing

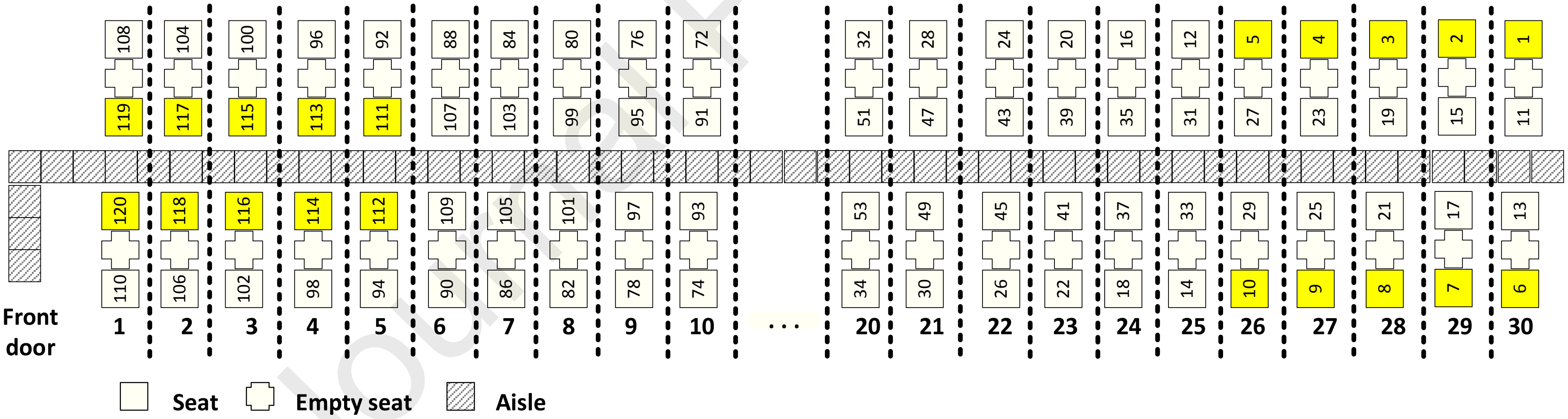


Figure 8 Back-to-front by row – WilMA – offset 5 (for k=5 rows) considering COVID-19 social distancing

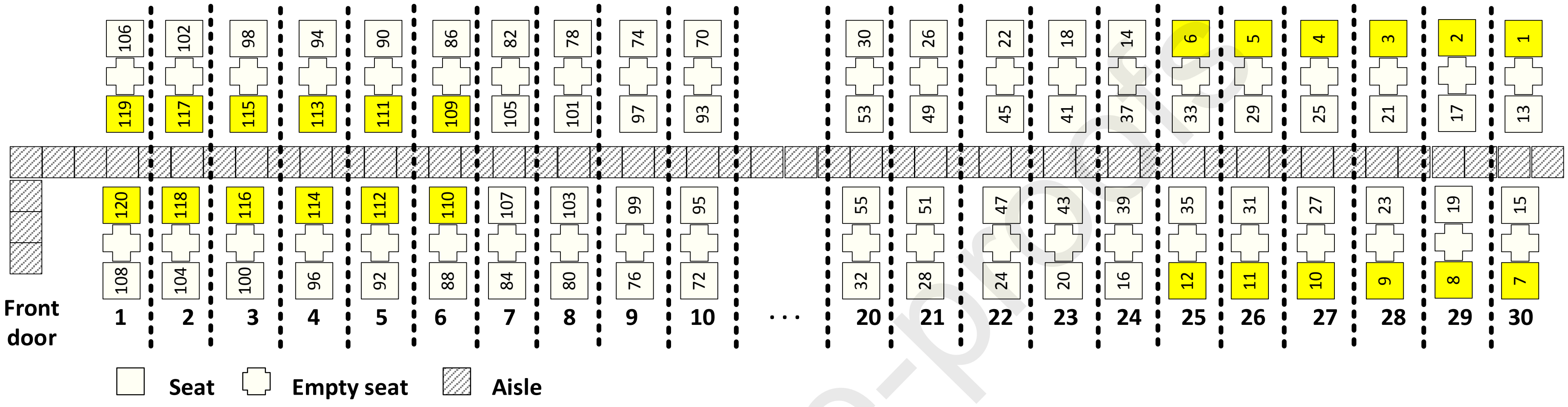


Figure 9 Back-to-front by row – WilMA – offset 6 (for k=6 rows) considering COVID-19 social distancing

The boarding schemes for the five offset methods are presented in Figure 5 - Figure 9 where the value of the offset k ranges from 2 to 6. In each of these methods, the first 2 * k passengers to board have window seats closet to the rear of the airplane and the final 2 * k passengers to board have aisle seats closest to the front of the airplane. Observe that as the value of the offset k increases, the method increasingly resembles the modified reverse pyramid half zone method. The motivation for creating these offset methods is to gain some of the faster boarding time advantage of the modified reverse pyramid half zone method while sacrificing little of the health risk advantages of the back-to-front by row – WilMA method.

4. Metrics and Scenarios for Passenger Boarding Methods Evaluation

Because we will compare the proposed new methods with the classical boarding methods that provide the best results in terms of boarding time, seat interferences, aisle seats risk and window seat risk in a COVID-19 and social distancing context, we will use the evaluation metrics of [16].

4.1. Metrics for Evaluating the Boarding Methods Performance

The time to complete the boarding is measured as the time beginning when the first passenger enters the airplane cabin and when the last passenger has sat down. This metric is measured in seconds.

The total number of seat interferences counts those situations when a passenger having a window seat arrives at their seat's row and is temporarily blocked by a previously boarded passenger that is sitting in that row's aisle seat on the same side of the aisle [49]. In the literature, four types of seat interferences are acknowledged [33]. Due to the COVID-19 restrictions which require leaving the middle seat unoccupied, only one type of seat interference can be encountered, the so-called "type 3 seat interference" depicted in Figure 10. The total number of seat interferences is a health risk metric. That is because when the passenger seated near the aisle rises to clear the path for the passenger with the window seat, either of these two passengers—if infected—may touch and thereby contaminate surfaces (e.g. headrest, armrest) or breath COVID-19 droplets that infect another passenger.

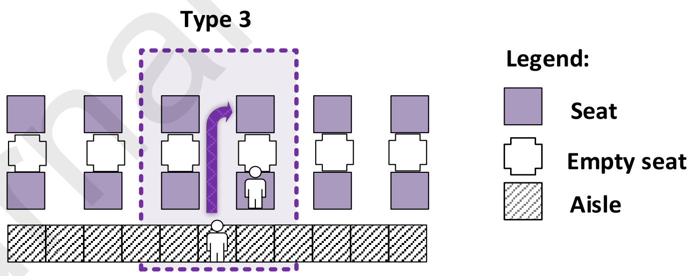


Figure 10 Type 3 seat interference

The second and the third health risk metrics pertain to the possibility of COVID-19 droplets spreading from infected passengers who are moving down the aisle (or standing in the aisle while waiting due to being blocked) to their assigned seats. The aisle seat risk evaluates the occurrence of this risk for the passengers already seated in the aisle seats, while the window seat risk evaluates the occurrence of the risk for passengers already seated in the window seats. More precisely, these two metrics are defined as in [16]:

$$AisleSeatRisk = \sum_{p} \sum_{r \leq RowSit_p} \left(RowTime_{pr} * \sum_{p' < p} AisleSeat_{p'r} \right)$$

where

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

$$WindowSeatRisk = \sum_p \sum_{r \leq RowSit_p} \left(RowTime_{pr} * \sum_{p' < p} WindowSeat_{p'r} \right)$$

where
$WindowSeat_{p'r}$ = 1 if passenger p' has a window seat in row r
= 0 otherwise

4.2. Scenarios for Passenger Boarding

We experiment with scenarios that vary depending on the boarding method, the minimum social distancing between passengers walking or standing in the aisle as they proceed to their assigned seats, and the amount of carry-on luggage they bring inside the airplane. For each scenario, we assume that the minimum social distancing between passengers walking down the aisle (or standing in the aisle) is either 1 m or 2 m. We refer to this minimum social distancing as *aisle distancing*.

Seven luggage scenarios are considered and two types of luggage that can be brought inside the airplane cabin (small bag and large bag) as presented in Table 1 [16], [34].

Table 1 The scenarios considered in the simulation experiments based on the hand luggage carried by the passengers

Scenario	**Percentages of bags carried by the passengers**				
	0 bag	1 small bag	2 small bags	1 large bag	1 large and 1 small bag
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%

5. Agent-based Model Implementation

Agent-based modeling has been a common choice when building models that involve a human component exposed to different economic and social situations [50]–[53] and has proven its applicability in incorporating the variability in human behavior in a model to observe emergent behavior and how small changes in different values of the parameters can lead to various levels of outputs [54]–[56].

NetLogo platform has been selected in this case for simulating the methods related to airplane passengers boarding due to the many advantages offered and to its extensive usage in various models across different research fields [3], [51], [56]–[60]. To build the graphical user interface (GUI, please see Figure 11) and the agent-based model, two types of agents have been used, named "patch/patches" and "turtle/turtles" in NetLogo.

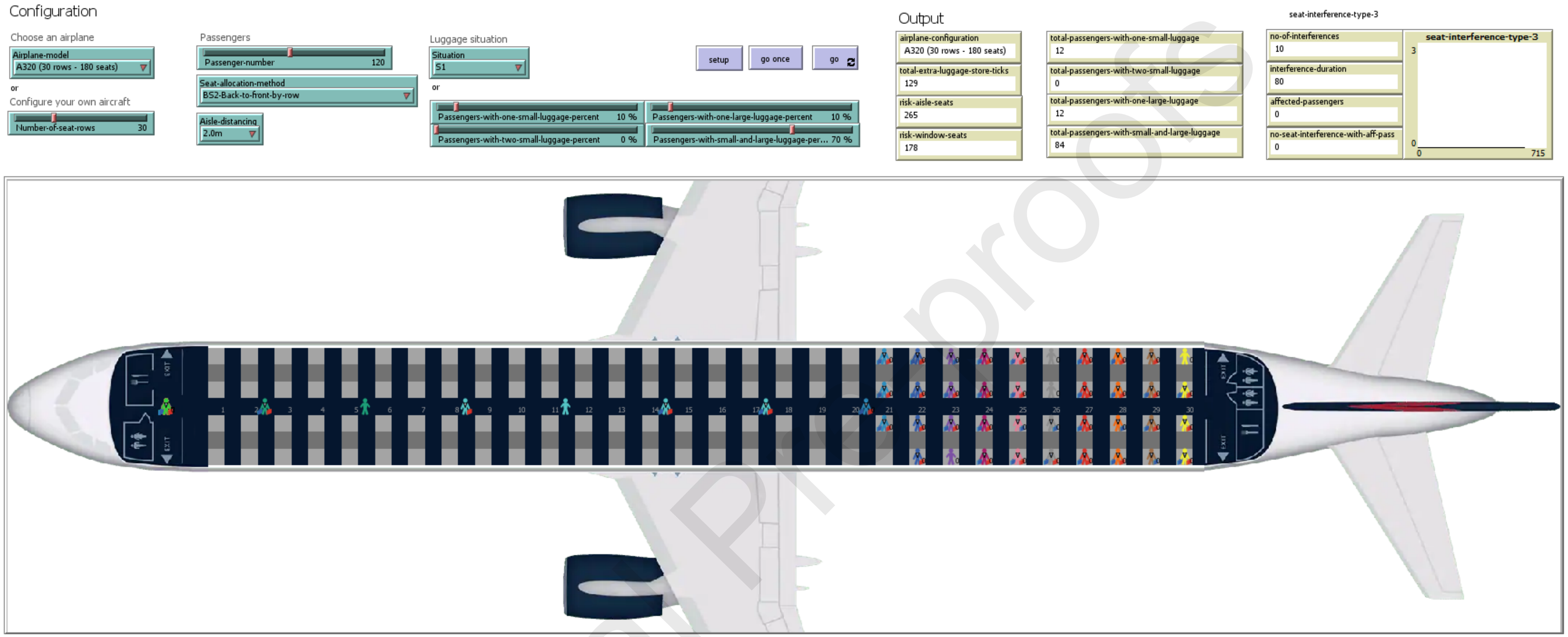


Figure 11 The NetLogo model GUI

No luggage **One small luggage** **Two small luggage** **One large luggage** **One small and one large luggage**

Figure 12 Different representations for the turtle agents depending on their hand luggage

The patch agents represent small pieces of ground and have been used in the model for representing the inside area of the airplane. Their size is associated with 0.4 m by 0.4 m of actual area from the airplane cabin as suggested by [48], [61]. As patches serve for drawing the aisle, the space between consecutive rows of chairs, the empty seats, and the occupied seats, each patch receives characteristics in accordance with its purpose. The characteristics are consistent with [33].

The turtle agents represent the passengers boarding the airplane. These agents have different characteristics in terms of speed to account for different ages, weights, and mobility characteristics, and the different pieces of luggage they might carry aboard the airplane. Based on the types of carry-on luggage, the turtle agents have different speeds while walking down the aisle as reported in [16] and are represented accordingly in the agent-based model (Figure 12). The time to store luggage in the overhead compartment depends on both the size and type of the carried luggage and on the luggage previously stored in the overhead bin above the passenger's seat. The formula for determining this luggage storage time is suggested by [62] and used in [25], [33], [34], [43], [45]:

$$Tstore = ((NbinLarge + 0.5\ NbinSmall + NpassengerLarge + 0.5\ NpassengerSmall) * (NpassengerLarge + 0.5\ NPassengerSmall)/2) * Trow$$

Where:

Tstore is the time to store the luggage

NbinLarge is the number of large bags in the bin prior to the passenger's arrival

NbinSmall is the number of small bags in the bin prior to the passenger's arrival

NpassengerLarge is the number of large bags carried by the passenger

NpassengerSmall is the number of small bags carried by the passenger

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

The flow of passengers (agents) begins when the first agent enters the cabin and ends when the last agent takes its assigned seat. The sequence of the agents is determined by the boarding method. The aisle [social] distancing between the agents in the aisle is either 1 m or 2 m depending on the scenario. Upon arriving inside the cabin, each agent proceeds to its assigned seat moving down the aisle, keeping all the time at least the minimum aisle [social] distance away from any previously boarding agent ahead in the aisle. When an agent arrives near its seat, it stores its luggage in the overhead compartment, blocking the aisle an amount of time equal to the time needed to store the luggage, then takes its seat. If its seat is near the window and an agent with an aisle seat in the same row and side of the aisle has already occupied its seat, the later-boarding agent is engaged in a type 3 seat interference, which makes it stay 9-13 seconds longer in the aisle than otherwise. This time corresponds to the time needed for the agent with the seat near the aisle to clear the path for the agent with the window seat, and it is consistent with the field trials conducted by [48].

6. Numerical Simulation Results and Discussions

Each of the scenarios has been simulated 10,000 times using the BehaviourSpace [56] tool provided by NetLogo. We present the numerical results using the previously described metrics for evaluating the performance of the two baseline boarding methods and the six proposed boarding methods for each of the seven luggage scenarios. First, we present the results when 1 m aisle distancing is the minimum distance separating adjacent passengers walking or standing in the aisle followed by the results with 2 m aisle distancing.

6.1. Numerical results for 1 m aisle distancing

Table 2 shows the average time to completing boarding of the airplane for each of the eight boarding methods and seven luggage scenarios with 1 m aisle distancing. As in the other tables below, we use **bold** font to highlight the best performance of each scenario while recognizing that other methods often result in essentially the same performance. For instance, in Table 2, for the luggage scenario S7, the best performing methods are the five offset methods but the performance of the Back-to-front by row – WilMa method is essentially as good, with the difference between 497 and 498 stemming from the inherent variability from using stochastic simulation for the experiments.

Table 2 indicates that the second baseline method, modified reverse pyramid half zone, results in the shortest time to completing boarding of the airplane for the high volume of luggage scenarios (S1, S2, and S3) and about the best boarding times for the lower volume of luggage scenarios (S4, S5, and S6), except for the no luggage scenario S7 when its time to complete boarding is slightly worse than those of the six proposed methods. The offset methods have boarding times nearly as good (or about as good) as those resulting from the modified reverse pyramid half zone method, except for performing slightly worse for the highest volume of luggage scenario S1. The offset methods' boarding times are better than that of the back-to-front by row – WilMA method for most luggage scenarios but performs only slightly better for the low volume of luggage scenario S6 and essentially the same for the no luggage scenario S7. The baseline back-to-front by row method had the worst (highest) boarding times for each luggage scenario.

Table 2 Average boarding time with blocked middle seats and 1 m aisle distancing (in seconds)

Boarding method	**Aisle distancing: 1 m**						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Baseline 1: Back-to-front by row	1,432	1,309	1,201	1,101	1,013	916	779
Baseline 2: Modified reverse pyramid half zone	**903**	**867**	**829**	795	**742**	**669**	518
Back-to-front by row – WilMA	1,151	1,035	935	850	785	700	498
Back-to-front by row – WilMA – offset 2	914	872	830	792	750	680	**497**
Back-to-front by row – WilMA – offset 3	918	876	832	793	748	676	**497**
Back-to-front by row – WilMA – offset 4	925	878	833	**791**	745	676	**497**
Back-to-front by row – WilMA – offset 5	930	884	836	793	745	676	**497**
Back-to-front by row – WilMA – offset 6	944	887	839	795	747	671	**497**

The total number of seat interferences is the first health metric analyzed, and the results are presented in Table 3. Recall that seat interference occurs when a passenger seated in an aisle seat needs to leave the seat to clear space for a later arriving window seat passenger whose seat is in the same row and on the same side of the airplane. For the baseline method back-to-front by row, because the passengers board in a random sequence within a row, we would expect on average that half of the two aisle seats per row would result in a seat interference. With 30 rows on the airplane, it makes sense that there would be 30 seat interferences on average when using the back-to-front by row method. This is consistent with the results in Table 3 where the tiny differences from 30 stem from the variability due to stochastic simulation.

With the other seven boarding methods, within each row, the window seat passengers board prior to the aisle seat passengers. Consequently, in Table 3, we observe that there are no seat interferences for those seven boarding methods.

Table 3 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**
Baseline 1: Back-to-front by row	30	30	29	30	31	30	31
Baseline 2: Modified reverse pyramid half zone	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 2	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 3	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 4	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 5	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 6	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table 4 shows the average aisle seat risk durations for the eight methods. For this second health metric, the six new methods perform the best, and their results are always about the same for a given luggage scenario. The baseline methods perform much worse according to this metric.

When compared to the best performing of the new methods for each luggage scenario, the baseline back-to-front by row method has 5.2 times as much aisle seat risk for the S1 luggage scenario (984/188=5.2), 16.7 times as much aisle seat risk for the S7 luggage scenario, and multiples that are in between those values and increasing as luggage volumes decrease from S1 to S7. The other baseline method, modified reverse pyramid half zone, has even worse performance with multiples varying from 9.2 for the S1 luggage scenario to 28.7 for the S7 luggage scenario. The latter data can be frightening when viewed from the perspective of an aisle seat passenger when potentially infected later-boarding passengers walk down the adjacent aisle. At the risk of stating the obvious, COVID-19 droplets will fall over time, and the nose and mouth of an infected passenger walking or standing in the aisle will be higher than the nose and mouth of a seated passenger.

Table 4 Average aisle seat 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**
Baseline 1: Back-to-front by row	984	900	786	725	682	625	602
Baseline 2: Modified reverse pyramid half zone	1,741	1,655	1,537	1,440	1,336	1,196	1,034
Back-to-front by row – WilMA	**188**	149	114	**83**	64	48	**36**
Back-to-front by row – WilMA – offset 2	189	**148**	114	84	66	49	**36**
Back-to-front by row – WilMA – offset 3	**188**	150	112	85	64	**47**	**36**
Back-to-front by row – WilMA – offset 4	**188**	145	**111**	**83**	64	48	**36**
Back-to-front by row – WilMA – offset 5	**188**	149	113	84	65	48	**36**
Back-to-front by row – WilMA – offset 6	189	149	113	85	**63**	48	**36**

The third and final health risk metric is the average duration of window seat risk. As indicated in Table 5, for this metric, the baseline back-to-front by row method results in the best window seat risks for the high volume of luggage scenarios (S1, S2, S3) and performs second best for the lower volume of luggage scenarios (S4, S5, S6, S7). Conversely, the back-to-front by row – WilMA method performs best for the lower volume of luggage scenarios (S4, S5, S6, S7) and second best for the higher volume of luggage scenarios (S1, S2, S3).

The back-to-front by row – WilMA – offset k methods have increasing window seat risk as k increases. Recall that with these offset methods, k rows of window seat passengers will board the airplane before any aisle seat passengers board. These are illustrated in Figure 5 - Figure 9 by the 4 to 12 rightmost yellow-highlighted seats for values of k varying from 2 to 6 respectively. Passengers in those window seats will all encounter window seat risk as they will be passed by later boarding aisle seat passenger(s).

When compared to the best performing method for each luggage scenario, the back-to-front by row – WilMA – offset 2 method results in 1.9 to 2.9 times as much window seat risk for luggage scenarios S1 to S7 respectively with the multiple increasing as the volume of luggage decreases. For the back-to-front by row – WilMA – offset 6 method, the multiple varies from 4.1 to 8.7 as the luggage scenarios vary from S1 to S7. The modified reverse pyramid half zone method performs the worst. Its multiples vary from 10.1 to 23.7 as the luggage scenarios vary from S1 to S7.

Table 5 Average window seat 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**
Baseline 1: Back-to-front by row	**714**	**602**	**511**	426	382	336	307
Baseline 2: Modified reverse pyramid half zone	7,232	6,808	6,473	6,055	5,562	5,009	4,268
Back-to-front by row – WilMA	871	691	535	**398**	**315**	**238**	**180**
Back-to-front by row – WilMA – offset 2	1,352	1,162	991	835	716	614	528
Back-to-front by row – WilMA – offset 3	1,746	1,554	1,359	1,181	1,038	905	799
Back-to-front by row – WilMA – offset 4	2,142	1,923	1,717	1,522	1,350	1,202	1,063
Back-to-front by row – WilMA – offset 5	2,530	2,319	2,077	1,873	1,674	1,491	1,320
Back-to-front by row – WilMA – offset 6	2,936	2,692	2,446	2,210	1,982	1,772	1,570

In considering the above results with aisle distancing of 1 m, we observe that the back-to-front by row – WilMA method has shorter boarding times, fewer seat interferences, and less aisle seat risk than the baseline back-to-front method for each luggage scenario. Meanwhile, the baseline back-to-front by row method has less window seat risk for the higher volumes of luggage scenarios.

Figure 13 shows the seat risk durations as a function of luggage scenario for the baseline back-to-front by row method (purple) versus the back-to-front by row – WilMA method (green). Shown in the figure are the window seat risks (circle), aisle seat risks (triangle), and the total of the two risks (square). Observe that the window seat risks of the two methods are closer to each other than are the aisle seat risks. Further observe that for the total of the seat risks, the back-to-front by row – WilMA is the better performer for all luggage scenarios. Because aisle seats are closer to the aisle than the window seats, a COVID-19 droplet from a boarding passenger walking down the aisle is more likely to reach a passenger sitting in the nearby aisle seat than one sitting in a window seat further away. Consequently, one second of aisle seat risk duration from a later-boarding passenger walking down the aisle is worse than one second of window seat risk duration. Thus, we conclude that the practical risk for seated passengers is less when using the back-to-front by row – WilMA method than that from the baseline back-to-front by row method. Given that the back-to-front by row – WilMA method also has better boarding times and fewer seat interferences than the baseline back-to-front by row method, we conclude that the back-to-front by row – WilMA method is superior to the baseline back-to-front by row method—at least for aisle distancing of 1 m (and later below we will see for aisle distancing of 2 m as well).

In considering the four metrics with aisle distancing of 1 m, we see that the back-to-front by row – WilMA – offset 2 method results in less window seat risk than the other offset methods and about the same performance for the other three metrics. Consequently, we conclude that the back-to-front by row – WilMA offset 2 method, the back-to-front by row – WilMA method, and the modified reverse pyramid half zone methods are the best candidates to use with 1 m aisle distancing and blocked middle seats.

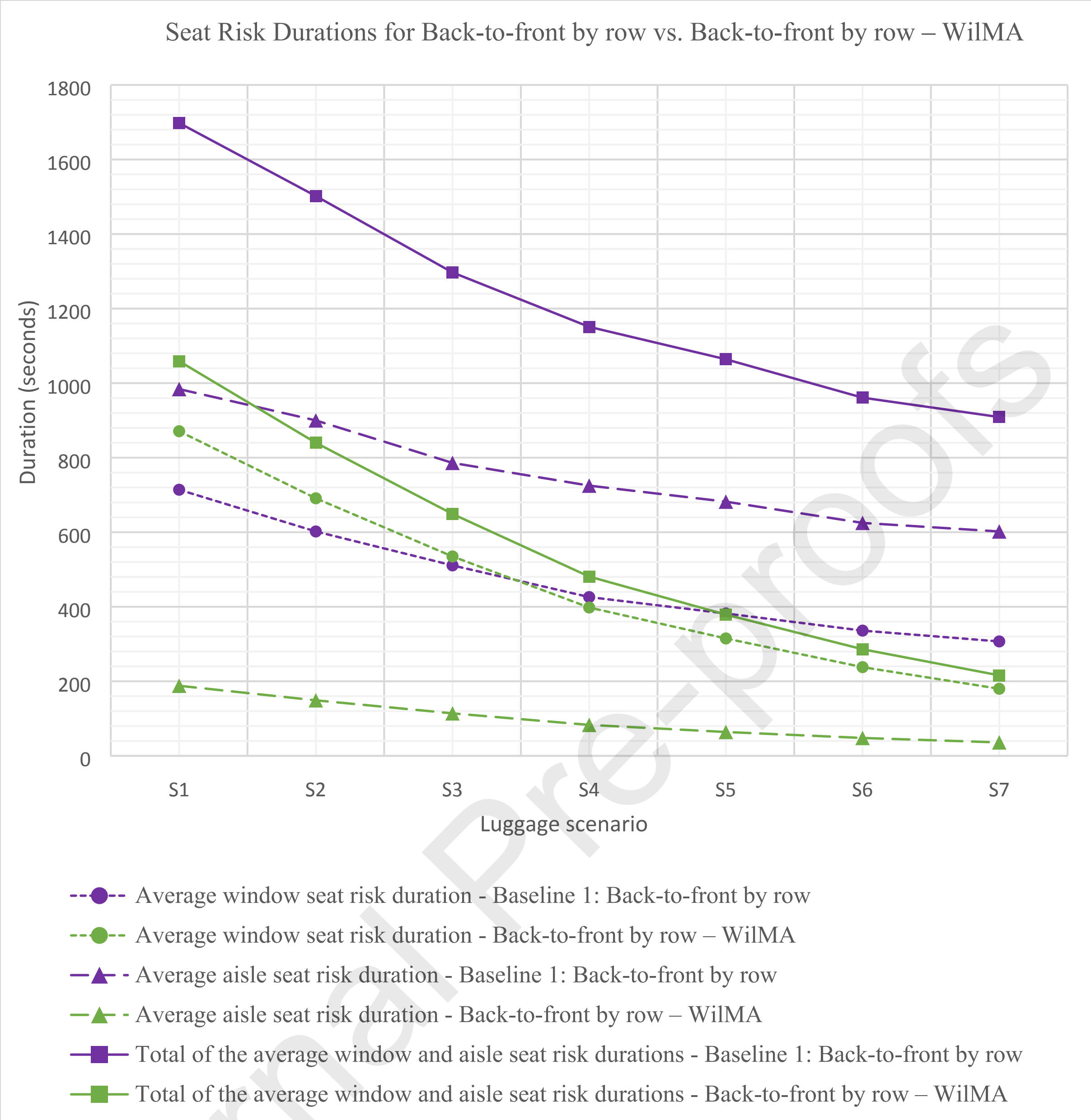


Figure 13 Seat risk comparison between Baseline 1: Back-to-front by row and Back-to-front by row - WilMA

Table 6 summarizes the performances of those three candidate methods against three performance metrics for the highest (S1), median (S4), and lowest (S7) volumes of luggage scenarios. (We don't bother including seat interferences in the table because all three of these methods have zero seat interferences). In examining the table, we see that the back-to-front by row – WilMA method has the worst boarding time except when the volume of luggage is low, and even in the latter case, its boarding time is about the same as that of the back-to-front by row – WilMA – offset 2 method. The modified reverse pyramid half zone method has the worst performance for aisle seat risk and window seat risk. Because that method is worse on the two seat risks and has about the same boarding times as the back-to-front – WilMA offset 2 method, we conclude that it is worse than the latter method.

As for comparing the back-to-front – WilMA method versus the back-to-front – WilMA offset 2 method, we see in Table 6 that the methods are equally good for aisle seat risk. The back-to-front – WilMA – offset 2 method has better boarding times (except for the no luggage S7 scenario where boarding time is the same) and worse window seat risk. Consequently, with 1 m aisle distancing, an airline emphasizing short boarding times should use the back-to-front – WilMA offset 2 method, and one emphasizing the avoidance of window seat risk should use the back-to-front – WilMA method.

Table 6 Selected boarding methods compared for three performance metrics with 1 m aisle distancing

Metric	Luggage scenario	Boarding Method		
		Baseline 2: Modified reverse pyramid half zone	**Back-to-front by row – WilMA – offset 2**	**Back-to-front by row – WilMA**
Boarding time	S1	**903**	914	1,151
	S4	795	**792**	850
	S7	518	**497**	498
Aisle seat risk	S1	1,741	189	**188**
	S4	1,440	84	**83**
	S7	1,034	**36**	**36**
Window seat risk	S1	7,232	1,352	**871**
	S4	6,055	835	**398**
	S7	4,268	528	**180**

6.2. Numerical results for 2 m aisle distancing

For 2 m aisle distancing, the average boarding times for all eight airplane boarding methods are shown in Table 7. The offset methods from k = 3 to 6 produce similar boarding times as the best performing baseline method, modified reverse pyramid half zone. Except for the no luggage scenario S7, the back-to-front by row – WilMA – offset 2 method produces longer boarding times than the other offset methods. The baseline back-to-front by row method results in the longest boarding times.

Table 7 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**
Baseline 1: Back-to-front by row	1,891	1,769	1,653	1,548	1,436	1,299	1,120
Baseline 2: Modified reverse pyramid half zone	1,416	1,367	1,312	**1,260**	**1,168**	**1,052**	853
Back-to-front by row – WilMA	1,608	1,501	1,400	1,314	1,217	1,085	**836**
Back-to-front by row – WilMA – offset 2	1,610	1,504	1,395	1,312	1,218	1,086	**836**
Back-to-front by row – WilMA – offset 3	**1,406**	1,359	1,310	1,262	1,187	1,065	**836**
Back-to-front by row – WilMA – offset 4	1,407	**1,357**	**1,308**	1,264	1,179	1,062	**836**
Back-to-front by row – WilMA – offset 5	1,414	1,372	1,315	1,262	1,182	1,063	**836**
Back-to-front by row – WilMA – offset 6	1,421	1,369	1,316	1,262	1,178	1,060	**836**

After accounting for tiny differences due to the variations within stochastic simulation runs, we see in Table 8, that the average total number of seat interferences for each method and scenario with 2 m aisle distancing is the same as we found in Table 3 with 1 m aisle distancing. This is not surprising.

Table 8 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**
Baseline 1: Back-to-front by row	30	30	30	30	30	30	31
Baseline 2: Modified reverse pyramid half zone	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 2	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 3	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Back-to-front by row – WilMA – offset 4	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 5	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Back-to-front by row – WilMA – offset 6	**0**	**0**	**0**	**0**	**0**	**0**	**0**

The average aisle seat risk durations for the eight methods with 2 m aisle distancing are shown in Table 9. As with the aisle seat risk durations with 1 m aisle distancing (see Table 4), the relative seat risk duration performances in Table 9 indicate that the six new methods perform the best and their results are about the same for each luggage scenario. And, as before, the baseline methods perform much worse according to this metric.

Table 9 Average aisle seat 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**
Baseline 1: Back-to-front by row	996	894	799	724	667	613	599
Baseline 2: Modified reverse pyramid half zone	1,679	1,584	1,505	1,400	1,294	1,153	1,045
Back-to-front by row – WilMA	189	148	115	**83**	65	48	**36**
Back-to-front by row – WilMA – offset 2	**186**	148	**112**	84	**64**	48	**36**
Back-to-front by row – WilMA – offset 3	187	148	115	84	65	48	**36**
Back-to-front by row – WilMA – offset 4	190	148	113	85	**64**	48	**36**
Back-to-front by row – WilMA – offset 5	188	**147**	113	**83**	**64**	**47**	**36**
Back-to-front by row – WilMA – offset 6	187	148	114	85	65	48	**36**

The window seat risk with 2 m aisle seat distancing is shown in Table 10. As with 1 m aisle distancing (see Table 5) , the data in Table 10 indicates that the baseline back-to-front by row method results in the best window seat risks for the high volume of luggage scenarios (S1, S2, S3) and performs second best for the lower volume of luggage scenarios (S4, S5, S6, S7). Conversely, the back-to-front by row – WilMA performs best for the lower volume of luggage scenarios (S4, S5, S6, S7) and second best for the higher volume of luggage scenarios (S1, S2, S3). Also, as with 1 m aisle distancing, with 2 m aisle distancing, the back-to-front by row – WilMA – offset *k* methods have increasing window seat risk durations as *k* increases.

Table 10 Average window seat 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**
Baseline 1: Back-to-front by row	**712**	**600**	**509**	425	380	335	300
Baseline 2: Modified reverse pyramid half zone	6,959	6,652	6,266	5,906	5,435	4,904	4,283
Back-to-front by row – WilMA	871	693	536	**400**	**315**	**238**	**180**
Back-to-front by row – WilMA – offset 2	1,327	1,145	974	825	709	611	528
Back-to-front by row – WilMA – offset 3	1,687	1,501	1,322	1,159	1,023	898	799
Back-to-front by row – WilMA – offset 4	2,064	1,864	1,667	1,495	1,328	1,188	1,063
Back-to-front by row – WilMA – offset 5	2,427	2,220	2,013	1,819	1,626	1,465	1,320
Back-to-front by row – WilMA – offset 6	2,793	2,567	2,351	2,144	1,926	1,735	1,570

Table 11 shows the performance of four best candidates for 2 m aisle distancing. The reason for choosing these candidates is similar to that of identifying the best candidates with 1 m aisle distancing. The primary difference is that the back-to-front by row – WilMA – offset 3 has emerged as a viable candidate with the increase in aisle distancing from 1 m to 2 m.

As indicated in Table 11, the back-to-front by row – WilMA – offset 3 method is superior to the baseline modified reverse pyramid half zone method because its boarding time is about the same and it has less significantly less aisle seat risk and window seat risk. The back-to-front by row – WilMA method has the lowest window seat risk and about the same boarding times and aisle seat risk as the back-to-front by row – WilMA – offset 2 method. Consequently, this leaves the back-to-front by row – WilMA method and the back-to-front by row – WilMA – offset 3 method as the wisest possible methods to use when aisle distancing is 2 m. The preferred method of these two would depend on the airline's relative preference for faster boarding times (for which the back-to-front by row – WilMA – offset 3 method performs best) versus the preference for lower window seat risk (for which the back-to-front by row – WilMA method excels).

Table 11 Selected boarding methods compared compared for three performance metrics with 2 m aisle distancing

Metric	**Luggage scenario**	**Boarding Method**			
		Baseline 2: Modified reverse pyramid half zone	**Back-to-front by row – WilMA – offset 2**	**Back-to-front by row – WilMA – offset 3**	**Back-to-front by row – WilMA**
Boarding time	S1	1,416	1,610	**1,406**	1,608
	S4	**1,260**	1,312	1,262	1,314
	S7	853	**836**	**836**	**836**
Aisle seat risk	S1	1,679	**186**	187	189
	S4	1,400	84	84	**83**
	S7	1,045	**36**	**36**	**36**
Window seat risk	S1	6,959	1,327	1,687	**871**
	S4	5,906	825	1,159	**400**
	S7	4,283	528	799	**180**

7. Concluding Remarks and Further Research Opportunities

Our paper proposes six new airplane boarding methods that consider the advantages of the back-to-front by row and WilMA boarding methods, while trying to reduce the level of the health risk from COVID-19. We compare these new methods and with the literature's two best performing methods that consider the social distancing rules (namely back to front by row and modified reverse pyramid half zone) of blocked middle seats and minimum aisle distancing between adjacent boarding passengers. The methods are evaluated based on four metrics: boarding time and three health-related metrics (number of seat interferences and average durations of aisle seat and window seat risks).

An agent-based model is created using NetLogo. All eight methods have been simulated under the same initial assumptions, in seven luggage scenarios, and two scenarios of aisle distancing between passengers in the aisle (1 m and 2 m).

For an airline that highly values the avoidance of window seat risk, the best method to use is one of the new methods: back-to-front by row – WilMA, though it will result in a longer time to complete boarding of the airplane. Airlines placing greater emphasis on fast boarding times will be best served by using back-to-front by row – WilMA – offset 2 and back-to-front by row – WilMA – offset 3 when aisle social distancing is 1 m and 2 m respectively.

We are not experts in the spread of infectious diseases. Such medical experts should conduct research to map our health-related metrics to the probabilities of infectious disease spread. Additional research should be conducted to test airplane boarding methods considering health metrics under different operational conditions such as: two-door airplanes, varying utilizations of airplane seats, families traveling together, and the use of apron buses.

Our paper is accompanied by videos made for 1 m and 2 m aisle distancing featuring all eight boarding methods considered in the paper for the S1 luggage scenario.

References

[1] M. Soolaki, I. Mahdavi, N. Mahdavi-Amiri, R. Hassanzadeh, and A. Aghajani, “A new linear programming approach and genetic algorithm for solving airline boarding problem,” *Applied Mathematical Modelling*, vol. 36, no. 9, pp. 4060–4072, Sep. 2012, doi: 10.1016/j.apm.2011.11.030.

[2] Eurocontrol, “All-Causes Delay and Cancellations to Air Transport in Europe 2018,” 2019. https://www.eurocontrol.int/sites/default/files/2019-05/coda-digest-annual-2018.pdf.

[3] C. Delcea, L.-A. Cotfas, and R. Paun, “Agent-Based Evaluation of the Airplane Boarding Strategies’ Efficiency and Sustainability,” *Sustainability*, vol. 10, no. 6, p. 1879, Jun. 2018, doi: 10.3390/su10061879.

[4] C. Delcea, L.-A. Cotfas, M. Salari, and R. J. Milne, “Investigating the Random Seat Boarding Method without Seat Assignments with Common Boarding Practices Using an Agent-Based Modeling,” *Sustainability*, vol. 10, no. 12, p. 4623, Dec. 2018, doi: 10.3390/su10124623.

[5] IATA, “Restarting aviation following COVID-19,” 2020. https://www.iata.org/contentassets/f1163430bba94512a583eb6d6b24aa56/covid-medical-evidence-for-strategies-200423.pdf.

[6] WHO, “Advice for public,” 2020. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public (accessed May 31, 2020).

[7] J. De Vos, “The effect of COVID-19 and subsequent social distancing on travel behavior,” *Transportation Research Interdisciplinary Perspectives*, vol. 5, p. 100121, May 2020, doi: 10.1016/j.trip.2020.100121.

[8] S. M. Iacus, F. Natale, C. Santamaria, S. Spyratos, and M. Vespe, “Estimating and projecting air passenger traffic during the COVID-19 coronavirus outbreak and its socio-economic impact,” *Safety Science*, vol. 129, p. 104791, Sep. 2020, doi: 10.1016/j.ssci.2020.104791.

[9] M. Haghani, M. C. J. Bliemer, F. Goerlandt, and J. Li, “The scientific literature on Coronaviruses, COVID-19 and its associated safety-related research dimensions: A scientometric analysis and scoping review,” *Safety Science*, vol. 129, p. 104806, Sep. 2020, doi: 10.1016/j.ssci.2020.104806.

[10] EASA, “COVID-19 Aviation Health Safety Protocol |,” *EASA*, 2020. https://www.easa.europa.eu/document-library/general-publications/covid-19-aviation-health-safety-protocol (accessed May 31, 2020).

[11] E. Writers, “Painful part of flying may be fixed by COVID-19,” *escape.com.au*, Apr. 15, 2020. https://www.escape.com.au/news/positive-effect-of-coronavirus-it-may-change-that-painful-airline-boarding-procedure/news-story/124b6f291580728766c66f03dc86b365 (accessed May 14, 2020).

[12] L. Ash, “What Air Travel Might Look Like Post Covid,” *Simple Flying*, Apr. 16, 2020. https://simpleflying.com/what-air-travel-might-look-like-post-covid/ (accessed May 14, 2020).

[13] Future Travel Experience, “How COVID-19 could change the end-to-end passenger experience forever,” *Future Travel Experience*, Apr. 03, 2020. https://www.futuretravelexperience.com/2020/04/how-covid-19-could-change-end-to-end-passenger-experience/ (accessed May 14, 2020).

[14] J. Walton, “Will empty middle seats help social distancing on planes?,” 2020. https://www.bbc.com/worklife/article/20200422-when-can-we-start-flying-again (accessed May 14, 2020).

[15] J. Harrington, “Southwest changes boarding process: What you need to know.” https://www.mercurynews.com/2020/05/01/southwest-airlines-changes-boarding-process-what-you-need-to-know/ (accessed May 19, 2020).

[16] L.-A. Cotfas, C. Delcea, R. J. Milne, and M. Salari, “Evaluating Classical Airplane Boarding Methods Considering COVID-19 Flying Restrictions,” *paper under journal review*, 2020.

[17] J. H. Steffen, "A statistical mechanics model for free-for-all airplane passenger boarding," *American Journal of Physics*, vol. 76, no. 12, pp. 1114–1119, Nov. 2008, doi: 10.1119/1.2982636.

[18] J. H. Steffen, "Optimal boarding method for airline passengers," *Journal of Air Transport Management*, vol. 14, no. 3, pp. 146–150, May 2008, doi: 10.1016/j.jairtraman.2008.03.003.

[19] E. Bachmat, D. Berend, L. Sapir, S. Skiena, and N. Stolyarov, "Analysis of Airplane Boarding Times," *Operations Research*, vol. 57, no. 2, pp. 499–513, Apr. 2009, doi: 10.1287/opre.1080.0630.

[20] P. Ferrari and K. Nagel, "Robustness of Efficient Passenger Boarding Strategies for Airplanes," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1915, pp. 44–54, Jan. 2005, doi: 10.3141/1915-06.

[21] H. Van Landeghem and A. Beuselinck, "Reducing passenger boarding time in airplanes: A simulation based approach," *European Journal of Operational Research*, vol. 142, no. 2, pp. 294–308, Oct. 2002, doi: 10.1016/S0377-2217(01)00294-6.

[22] E. Bachmat and M. Elkin, "Bounds on the performance of back-to-front airplane boarding policies," *Operations Research Letters*, vol. 36, no. 5, pp. 597–601, Sep. 2008, doi: 10.1016/j.orl.2008.03.008.

[23] M. H. L. van den Briel, J. R. Villalobos, G. L. Hogg, T. Lindemann, and A. V. Mulé, "America West Airlines Develops Efficient Boarding Strategies," *Interfaces*, vol. 35, no. 3, pp. 191–201, Jun. 2005, doi: 10.1287/inte.1050.0135.

[24] M. Bazargan, "A linear programming approach for aircraft boarding strategy," *European Journal of Operational Research*, vol. 183, no. 1, pp. 394–411, Nov. 2007, doi: 10.1016/j.ejor.2006.09.071.

[25] R. J. Milne and A. R. Kelly, "A new method for boarding passengers onto an airplane," *Journal of Air Transport Management*, vol. 34, pp. 93–100, Jan. 2014, doi: 10.1016/j.jairtraman.2013.08.006.

[26] J. H. Steffen and J. Hotchkiss, "Experimental test of airplane boarding methods," *Journal of Air Transport Management*, vol. 18, no. 1, pp. 64–67, Jan. 2012, doi: 10.1016/j.jairtraman.2011.10.003.

[27] L. Hutter, F. Jaehn, and S. Neumann, "Influencing Factors on Airplane Boarding Times," *Omega*, Sep. 2018, doi: 10.1016/j.omega.2018.09.002.

[28] A. Kierzkowski and T. Kisiel, "The Human Factor in the Passenger Boarding Process at the Airport," *Procedia Engineering*, vol. 187, pp. 348–355, 2017, doi: 10.1016/j.proeng.2017.04.385.

[29] S.-J. Qiang, B. Jia, D.-F. Xie, and Z.-Y. Gao, "Reducing airplane boarding time by accounting for passengers' individual properties: A simulation based on cellular automaton," *Journal of Air Transport Management*, vol. 40, no. Supplement C, pp. 42–47, Aug. 2014, doi: 10.1016/j.jairtraman.2014.05.007.

[30] G. Notomista, M. Selvaggio, F. Sbrizzi, G. Di Maio, S. Grazioso, and M. Botsch, "A fast airplane boarding strategy using online seat assignment based on passenger classification," *Journal of Air Transport Management*, vol. 53, pp. 140–149, Jun. 2016, doi: 10.1016/j.jairtraman.2016.02.012.

[31] R. J. Milne, M. Salari, and L. Kattan, "Robust Optimization of Airplane Passenger Seating Assignments," *Aerospace*, vol. 5, no. 3, p. 80, Aug. 2018, doi: 10.3390/aerospace5030080.

[32] T.-Q. Tang, S.-P. Yang, H. Ou, L. Chen, and H.-J. Huang, "An aircraft boarding model with the group behavior and the quantity of luggage," *Transportation Research Part C: Emerging Technologies*, vol. 93, pp. 115–127, Aug. 2018, doi: 10.1016/j.trc.2018.05.029.

[33] C. Delcea, R. J. Milne, L.-A. Cotfas, L. Craciun, and A. G. Molanescu, "Methods for Accelerating the Airplane Boarding Process in the Presence of Apron Buses," *IEEE Access*, vol. 7, pp. 134372–134387, 2019, doi: 10.1109/ACCESS.2019.2941532.

[34] R. J. Milne, C. Delcea, L.-A. Cotfas, and M. Salari, "New methods for two-door airplane boarding using apron buses," *Journal of Air Transport Management*, vol. 80, p. 101705, 2019, doi: 10.1016/j.jairtraman.2019.101705.

[35] M. Schultz, "Implementation and application of a stochastic aircraft boarding model," *Transportation Research Part C: Emerging Technologies*, vol. 90, pp. 334–349, May 2018, doi: 10.1016/j.trc.2018.03.016.

[36] D. C. Nyquist and K. L. McFadden, “A study of the airline boarding problem,” *Journal of Air Transport Management*, vol. 14, no. 4, pp. 197–204, Jul. 2008, doi: 10.1016/j.jairtraman.2008.04.004.
[37] M. Schultz, T. Kunze, and H. Fricke, “Boarding on the critical path of the turnaround,” presented at the 10th USA/Europe Air Traffic Management Research and Development Seminar, 2013, pp. 1–10.
[38] M. Schultz, C. Schulz, and H. Fricke, “Efficiency of Aircraft Boarding Procedures,” in *3rd International Conference on Research in Airport Transportation*, 2008, vol. 371–391.
[39] F. Jaehn and S. Neumann, “Airplane boarding,” *European Journal of Operational Research*, vol. 244, no. 2, pp. 339–359, Jul. 2015, doi: 10.1016/j.ejor.2014.12.008.
[40] L.-A. Cotfas, C. Delcea, R. J. Milne, M. Salari, L. Crăciun, and A. G. Molănescu, “Testing New Methods for Boarding a Partially Occupied Airplane Using Apron Buses,” *Symmetry*, vol. 11, no. 8, p. 1044, Aug. 2019, doi: 10.3390/sym11081044.
[41] C. Delcea, L.-A. Cotfas, N. Chiriță, and I. Nica, “A Two-Door Airplane Boarding Approach When Using Apron Buses,” *Sustainability*, vol. 10, no. 10, p. 3619, Oct. 2018, doi: 10.3390/su10103619.
[42] R. J. Milne, L.-A. Cotfas, C. Delcea, M. Salari, L. Crăciun, and A. G. Molanescu, “Greedy Method for Boarding a Partially Occupied Airplane Using Apron Buses,” *Symmetry*, vol. 11, no. 10, p. 1221, Oct. 2019, doi: 10.3390/sym11101221.
[43] R. J. Milne, L.-A. Cotfas, C. Delcea, M. Salari, L. Craciun, and A. G. Molanescu, “Airplane Boarding Method for Passenger Groups when using Apron Buses,” *IEEE Access*, vol. 8, 2020, doi: 10.1109/ACCESS.2020.2968410.
[44] C.-C. Kuo, “An Improved Zero-One Linear Programming Model for the Plane Boarding Problem,” in *Applications of Management Science*, vol. 17, 0 vols., Emerald Group Publishing Limited, 2015, pp. 53–69.
[45] R. J. Milne and M. Salari, “Optimization of assigning passengers to seats on airplanes based on their carry-on luggage,” *Journal of Air Transport Management*, vol. 54, pp. 104–110, Jul. 2016, doi: 10.1016/j.jairtraman.2016.03.022.
[46] A. Steiner, and M. Philipp, “Speeding up the airplane boarding process by using pre-boarding areas.,” in *Proceedings of Swiss Transport Research Conference*, Ascona, Switzerland, 2009.
[47] S. M. V. Gwynne *et al.*, “Small-scale trials on passenger microbehaviours during aircraft boarding and deplaning procedures,” *J. Air Transp. Manag.*, vol. 67, pp. 115–133, Mar. 2018, doi: 10.1016/j.jairtraman.2017.11.008.
[48] M. Schultz, “Field Trial Measurements to Validate a Stochastic Aircraft Boarding Model,” *Aerospace*, vol. 5, no. 1, p. 27, Mar. 2018, doi: 10.3390/aerospace5010027.
[49] C. Delcea, L.-A. Cotfas, L. Craciun, and A. G. Molanescu, “Are Seat and Aisle Interferences Affecting the Overall Airplane Boarding Time? An Agent-Based Approach,” *Sustainability*, expected 2018.
[50] R.-C. Damaceanu, “An agent-based computational study of wealth distribution in function of resource growth interval using NetLogo,” *Applied Mathematics and Computation*, vol. 201, no. 1–2, pp. 371–377, Jul. 2008, doi: 10.1016/j.amc.2007.12.042.
[51] C. Delcea, L.-A. Cotfas, L. Craciun, and A. G. Molanescu, “An agent-based modeling approach to collaborative classrooms evacuation process,” *Safety Science*, vol. 121, pp. 414–429, Jan. 2020, doi: 10.1016/j.ssci.2019.09.026.
[52] V. Dragotă and C. Delcea, “How Long Does It Last to Systematically Make Bad Decisions? An Agent-Based Application for Dividend Policy,” *Journal of Risk and Financial Management*, vol. 12, no. 4, p. 167, Nov. 2019, doi: 10.3390/jrfm12040167.
[53] R. Dreżewski and K. Doroz, “An Agent-Based Co-Evolutionary Multi-Objective Algorithm for Portfolio Optimization,” *Symmetry*, vol. 9, no. 9, p. 168, Aug. 2017, doi: 10.3390/sym9090168.
[54] C. S. M. Currie *et al.*, “How simulation modelling can help reduce the impact of COVID-19,” *Journal of Simulation*, vol. 1, no. 1, pp. 1–15, Apr. 2020, doi: 10.1080/17477778.2020.1751570.
[55] U. Wilensky, “NetLogo Traffic Basic model.,” 1997. http://ccl.northwestern.edu/netlogo/models/TrafficBasic.
[56] U. Wilensky and W. Rand, *An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo*. Cambridge, Massachusetts: The MIT Press, 2015.

[57] C. Ponsiglione, I. Quinto, and G. Zollo, "Regional Innovation Systems as Complex Adaptive Systems: The Case of Lagging European Regions," *Sustainability*, vol. 10, no. 8, p. 2862, Aug. 2018, doi: 10.3390/su10082862.

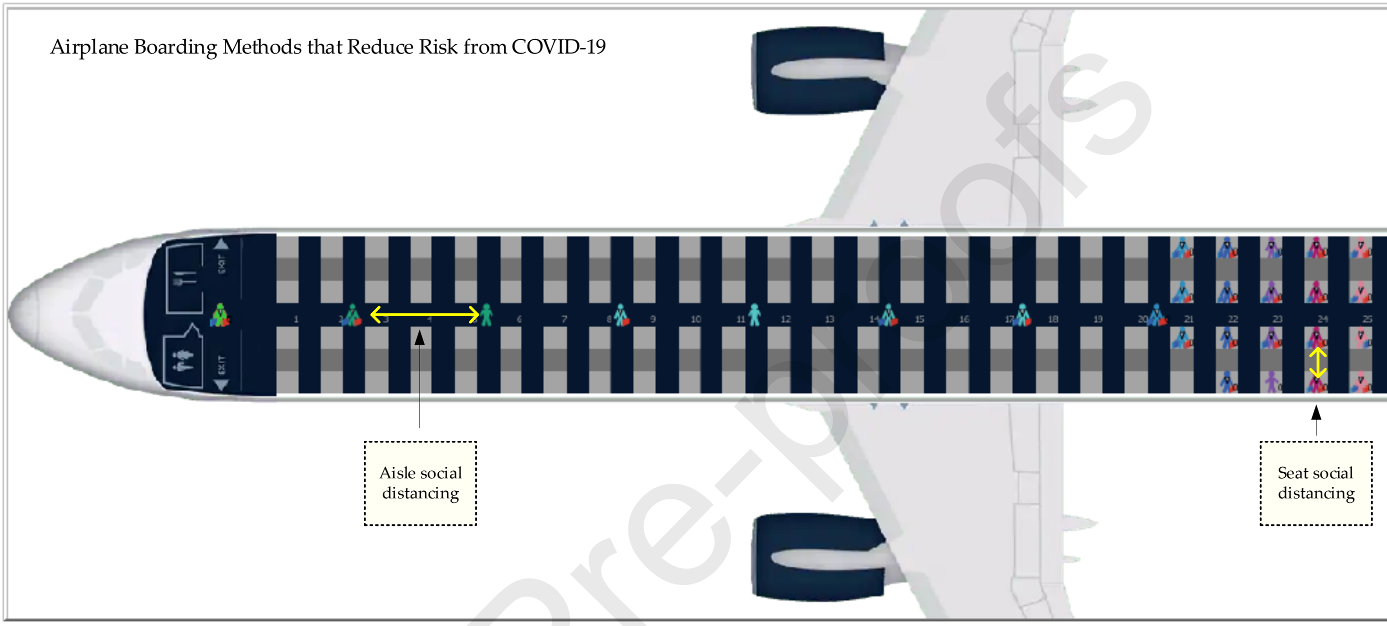
[58] C. Ponsiglione, S. Primario, and G. Zollo, "Does natural language perform better than formal systems? Results from a fuzzy agent-based model," *International Journal of Technology, Policy and Management*, vol. 19, no. 2, pp. 171–175, 2019, doi: 10.1504/IJTPM.2019.100602.

[59] L. R. Izquierdo, D. Olaru, S. S. Izquierdo, S. Purchase, and G. N. Soutar, "Fuzzy Logic for Social Simulation Using NetLogo," *JASSS*, vol. 18, no. 4, p. 1, 2015.

[60] D. Leal Martínez and A. Halme, "MarSim, a Simulation of the MarsuBots Fleet Using NetLogo," in *Distributed Autonomous Robotic Systems*, vol. 112, N.-Y. Chong and Y.-J. Cho, Eds. Tokyo: Springer Japan, 2016, pp. 79–87.

[61] R. Alizadeh, "A dynamic cellular automaton model for evacuation process with obstacles," *Safety Science*, vol. 49, no. 2, pp. 315–323, Feb. 2011, doi: 10.1016/j.ssci.2010.09.006.

[62] J. Audenaert, K. Verbeeck, and G. Berghe, "Multi-agent based simulation for boarding," in *Proceedings of 21st Benelux Conference on Artificial Intelligence*, Eindhoven; Netherlands, 2009, pp. 3–10.


Airplane Boarding Methods that Reduce Risk from COVID-19
Aisle social distancing
Seat social distancing

Highlights:

- 6 new methods for airplane boarding considering social distancing are proposed;
- An agent-based model is created for capturing and simulating the flow of passengers;
- The new methods are tested against two best performing boarding methods used by the airline companies;
- All the new methods reduce the level of the health risk from COVID-19;
- Among the methods, back-to-front by row – WilMA succeed in producing the lowest values for window seat risk;
- Two other methods succeed in providing fast boarding times, while still providing favorable values for the health metrics.