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Methods for Accelerating the Airplane Boarding Process in the Presence of Apron Buses

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ABSTRACT The use of apron buses for transporting passengers from the airport terminal to the airplane has become common practice for a series of airports worldwide. Airline companies have become increasingly aware of this practice and have added information to their boarding passes to suggest the airplane door passengers should use while boarding the airplane. In contrast, many of the literature's methods to reduce boarding time assume the presence of a jet-bridge connecting the airplane to the terminal. These boarding methods are "by seat" and "by group" methods. The use of the apron buses for passengers' transport limits the usage of these methods because, in most cases now, only two apron buses are needed for transporting the passengers. With two apron buses, boarding control is limited to deciding on which passengers to assign to each of the two buses. We propose 15 new methods that we tested against the previously published Back-to-front method adapted for the apron buses case, by considering 7 luggage situations. An agent-based model in NetLogo is created based on field trials and considerations made in the literature, and we used this model for simulations. Experimental results show that the best performing proposed methods combine aspects of the WilMA and Reverse Pyramid boarding methods adapted for apron buses. The best proposed method can reduce boarding time by up to 39.2% when compared to the benchmark Back-to-front method.

INDEX TERMS Airplane boarding, apron buses, agent-based modeling, two-door boarding, boarding strategies, NetLogo.

I. INTRODUCTION

Airplane turn time plays an important role in both the airline companies' costs and passengers' flight satisfaction. The cost associated with time on the ground for an airplane at the airport has been estimated at between \$30 and \$77 per minute by Nyquist and McFadden [1] and Steiner and Philipp [2]. Ferrari and Nagel [3] believe that passenger boarding consumes most of the turn time and thus is more important than the other components of turn time: airplane taxiing, disembarkation of passengers and crew, cabin cleaning, unloading the luggage and goods, airplane refueling, towing the airplane to the start of the runway. Soolaki *et al.* [4] observe that airlines have limited control over passenger behavior. Boarding methods are a way to influence passengers and their impact on boarding time.

According to the Eurocontrol 2019 report [5], the average delay per departing flight in Europe increased by 19% in 2018 compared to 2017, from 12.4 minutes per flight to 14.7 minutes per flight. The percentage of flights delayed at departure by more than 5 minutes increased from 44.4% to 48.4% between 2017 and 2018, reaching the highest level of the last 5 years [5]. In addition to the cost generated by the prolonged waiting time of an airplane at an airport prior to departure, a late departure may lead to a late arrival at the destination airport, causing a late departure on the next flight, generating new costs. These delays may cause passengers to miss connecting flights and add to their stress and discomfort. The time lost in 2018 due to such delays was about 6.7 minutes per flight [5]. Some airports with the most delays in Europe in 2018 are: London Stansted (24.4 minutes of average delay per departure), Cologne-Bonn (23 minutes) and Lisbon (22.8 minutes) [5].

Eurocontrol [6] estimates that the general tendency is for the number of flights in Europe to rise through 2024.

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While there is a need to accommodate higher demand, changes in infrastructure and gate availability are expensive and slow. A relatively inexpensive fix that is gaining in popularity is the apron bus [7] because they consume less space near the terminal than airplanes consume. Presently, many European airports such as Amsterdam Schipol, London Luton, Frankfurt, Pisa, Madrid, Munich, Stuttgart, etc. use the advantages offered by apron buses. In this context, the boarding process can be accelerated by using both the front and rear doors of the airplane. Other advantages are related to technical issues of larger airplanes not being able to park near the smaller gates. Airplanes with wingspans or weights beyond the limits for a gate can still be serviced by buses from the gate. To improve efficiency of boarding, some airline companies now indicate on the boarding pass which door passengers should use. Figure 1 presents an extract from a boarding pass in which a passenger having seat 22A (in row 22) is encouraged to board using the rear door.

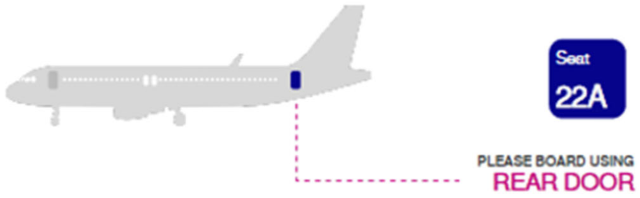


FIGURE 1. Example of a portion of a boarding pass indicating the airplane boarding door the passenger should use.

The literature proposes a number of boarding methods to minimize boarding time when passengers travel through a jet-bridge connecting the airport terminal to the airplane. In this context, passengers may be called board by group (or potentially by seat, that is, by individual passenger). However, when (typically two) apron buses are used, passengers are segregated into only two groups (one group per apron bus). Thus, the "by group" methods—which always involve three or more groups—and the "by seat" methods do not apply with apron buses. Consequently, none of the published boarding methods—assuming jet bridges—are used in practice by airlines using apron buses.

In this context, the aim of this paper is to propose new methods that apply when two apron buses are used (one time each) for passengers boarding with an objective of reducing boarding time—the time to complete boarding of the airplane. The new methods are inspired by the best-performing methods used when the airplane boarding is made through only one door connected to the airport terminal by a jet-bridge. The new methods are tested against the benchmark method Back-to-front for apron buses proposed by [7]. Several luggage situations are considered with respect to the literature. The methods are compared in terms of boarding times.

The remainder of the paper is organized as follows: section 2 provides a literature review, with a focus on those airplane boarding methods that inspired the new proposed methods; also in this section, we discuss the main issues influencing the performance of the boarding methods. Section 3 describes each of the 15 new proposed methods, highlighting the main rules implied by each method. Section 4 focuses on the agent-based model created in NetLogo 6.1.0 and describes the main characteristics of the agents (passengers) and assumptions about their movements, while section 5 uses the model to test the performance of the proposed methods versus the benchmark Back-to-front method, under various conditions. The paper ends with a conclusion section and references. The paper is accompanied by supplementary materials in the form of videos containing simulations of all 15 proposed methods and the benchmark method.

II. LITERATURE REVIEW OF BOARDING METHODS

Over time, methods for accelerating the passengers' boarding process have been created and tested to demonstrate their value. As most of the studies describe methods for airplane boarding through just one airplane door through a jet bridge, in the following, we present a brief literature review of these methods. We focus on those methods that inspired the creation of the new proposed methods for the case in which the apron buses are used.

Considering the boarding rules related to the seat assignment, three main categories of boarding methods are random, by group, and by seat. With the random boarding method, passengers with assigned seats enter the airplane in no particular sequence and proceed to the seats indicated on their boarding passes. The "by group" methods divide the passengers into three or more groups based on the positions of their seats in the airplane and then the passengers from each group are invited to board. As a boarding call is made for an entire group, the passengers within each group board in a random sequence. The vast majority of methods within the literature belong to this category, some of the well-known methods being highlighted in Table 1, along with a short description of the rules they imply [8]–[16].

As for the third category of boarding methods, the "by seat" methods, the passengers are called in one by one for boarding based on the seat they have been assigned in the airplane, following different schemes. Some of the well-known "by seat" boarding methods are: back to front by seating order, in seat descending sequence, the Steffen method, and a variation of the Steffen method [15], [17].

In practice, only a few of the "by group" methods are used, namely WilMA, Back-to-front, and Reverse-pyramid [18]. The "by seat" method was tested in 2013 by the KLM airplane company [19], confirming that it provides shorter boarding times than the other boarding methods used in practice [18].

Other aspects considered in the studies within the field include, but are not limited to: passenger movement [14], [20], seat selection [3], [20], airplane characteristics, [3], [4], [12], [15], [21], airplane occupancy [12], [15], [16], [22]–[25], the presence and type of the carry-on hand luggage [11], [12], [14], [23], [26], boarding interferences—passengers blocked while waiting for other passengers to

TABLE 1. Summary of "by group" boarding methods.

Boarding method	Short description
Back-to-front	The airplane is divided in five equal-sized groups based on the assigned seat-rows. When the boarding process starts, the group located closest to the rear of the airplane is called for boarding. After the last passenger belonging to this group proceeds towards the airplane, the group located in the middle-rear rows of the airplane is called, then the group in the middle and then the one in the middle-front. Last to board is the group of passengers having seats near the front of the airplane.
WilMA	Also known as "window-middle-aisle" or "outside-in" method. According to this method, the passengers are divided into three groups based on their seat location: near the window, middle seat, or near the aisle. At time zero, the passengers having seats near the window (seats marked with letter A or F) are called for boarding and they enter the airplane in a random sequence. Then, the passengers with middle seats are invited to board (letters B and E). The last group to board is the one having the seats near the aisle (letters C and D).
Half-block	The half block method's main idea relies on dividing the passengers into groups not only by starting from the rear to the front but also by considering the left and right sides of the aisle. By proceeding in this way, in most of the half-block methods, ten boarding zones are encountered. The sequence in which the passengers are called for boarding depends on the half-block selected method. For example, in the classical half-block method, the passengers from just one side of aisle are called by following the Back-to-front method rules, then the passengers with seats on the other side of the aisle are called using the same Back-to-front approach. In the half-block mix methods, it might happen that the groups called for boarding load diagonally switching from one side to the other of the aisle or to board the odd groups from one side, followed by the even groups on the other and, then the remaining groups in a Back-to-front sequence.
Rotating zone	In this case, five groups are considered. The first group called is the one located near the front of the airplane, followed by the one near the rear, then the group in the front-middle and then in the rear-middle. Last to board is the group having seats in the middle rows of the airplane.
Reverse pyramid	Variations in this method are possible. The passengers are divided in 5 to 10 groups depending on the reverse pyramid variation. The main idea is that groups board following a diagonal scheme starting from the back of the airplane with a group of passengers seated near the window and concludes a group of passengers seated near the front of the airplane near the aisle.
Modified-optimal	Four boarding groups are considered in this case. The first group consists of passengers with the seats located in odd rows from one side of the aisle. The second group is made from the same odd rows, but from the other side of the aisle. The third and the fourth groups contain passengers from the even rows from one side and from the other side of the aisle. The passengers are called to board according to their group.

move out of their way—[4], [22], [26]–[28], passengers' personal characteristics [21]–[23], group behavior [26], [26], extracting data from the field [29], [30], while other studies focus on improving upon existing boarding methods to reduce the boarding time [1], [2], [4], [11], [12], [14], [16], [26], [28], [31].

A study by Boeing [32] and synthesized in [33] shows that boarding with two doors rather than just one door has the potential of reducing boarding time by almost 5 minutes. Among the methods which can successfully be used with two doors when jet-bridges are available, WilMA provides the shortest boarding time in [1], [34]. Schulz *et al.* [35] underlines that the two-door approach can decrease the boarding time by 25.9%.

In contrast to jetway boarding, with apron buses, passengers may board through two doors of the airplane. Delcea *et al.* [7] proposes using the Back-to-front method, in which the passengers are divided into two groups corresponding to the two apron buses, where those passengers having seats closes to the middle of the airplane board first. When compared to the Random boarding method, this approach has the potential of reducing the boarding time by 8.9%. The scheme for this method is presented in Figure 2 where passengers with seats in rows 8-22 use the first apron bus and thus board the airplane before the passengers in the second apron bus.

Additionally, Milne *et al.* [36] describe new boarding methods, for use with two apron buses, based on Back-to-front, Reverse pyramid and Spread-across-rows rules, which demonstrate a boarding time improvement, in the no luggage case, of up to 36.6% when compared to Back-to-front. While the results obtained in [36] are encouraging from a boarding time perspective, there remain opportunities for improvement. In particular, within the present paper, we consider some of the methods developed in the literature for one-door boarding and leverage their concepts in creating new boarding methods that apply for use with two apron buses. In this investigation, we consider as well combining their concepts in a (successful) attempt to provide boarding times that are faster than using the best methods of Milne *et al.* [36].

III. PROPOSED BOARDING METHODS WITH APRON BUSES

We propose new boarding methods that emphasize concepts and advantages brought by the Back-to-front, WilMA, Reverse pyramid, and Modified-optimal methods, adjusted for the context in which two apron buses (and thus only two boarding groups) are used. To create these methods, we have considered a wider range of methods from the literature associated with boarding through one door of the airplane, as well as combinations of them. We present 15 new methods in the following.

When describing the rules accompanying each method, we provide a scheme using a common airplane model, namely

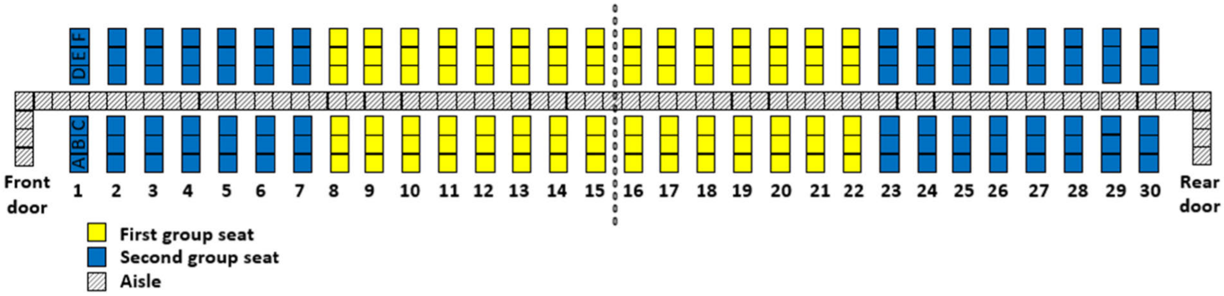


FIGURE 2. Back-to-front boarding for the case of apron buses.

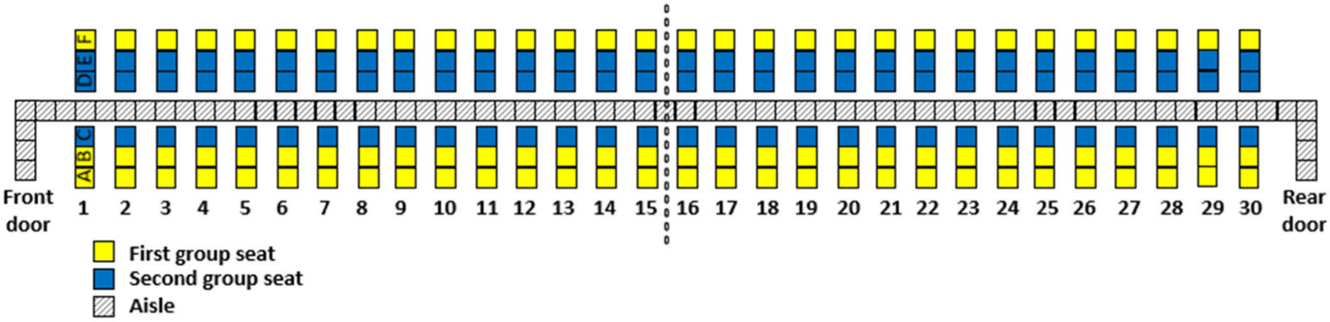


FIGURE 3. Adapted-WilMA.

Airbus A320, having 30 rows and six seats per row, as suggested by [3], [4], [16], [24], [27], [37]. This assumption is based on the fact that many aircrafts with a single aisle have a single cabin for economy passengers (and sometimes for all passengers). We assume that all 180 seats on the airplane are occupied and that there are 90 passengers in each of the two apron buses. Furthermore, we assume that each of the two apron buses delivers exactly one set of passengers from near the terminal to near the airplane (i.e. no return trips for an apron bus).

Each of the new methods divides the passengers into two groups, corresponding to the two apron buses, while trying to keep the airplane boarding scheme symmetrical with respect to the middle of the airplane. We assume that passengers with seats in rows 1-15 of the airplane will board through the airplane's front door while those with seats in rows 16-30 will board through the airplane's rear door.

We describe the proposed methods in this section. All of the new methods leverage concepts from other methods of the literature and many of the proposed methods combine concepts from other methods.

A. ADAPTED-WILMA FOR THE APRON BUSES CASE

In the Adapted-WilMA method, the first group of passengers (those boarding the first apron bus) includes all the passengers having seats near the window of the airplane and those passengers having middle seats on only one side of the aisle. The second group of passengers (those boarding the second apron bus) includes the remaining passengers. Figure 3 presents the general scheme of this method.

B. METHODS BASED ON BACK-TO-FRONT AND WILMA

Three boarding methods are proposed by considering the Back-to-front and WilMA methods' rules. The first boarding method, Mixed-BF-WilMA-A, assigns to the first apron bus those passengers having seats near the window (similar to WilMA) and half of the passengers with middle and aisle seats located in the middle rows of the airplane (half similar to Back-to-front) on one side of the aisle – see Figure 4.

The Mixed-BF-WilMA-B and Mixed-BF-WilMA-C methods are similar to the Mixed-BF-WilMA-A method, except that they are more similar than the latter to the Back-to-front method. These two methods assign more of the passengers with seats closest to the middle of the airplane to the first apron bus than the Mixed-BF-WilMA-A method assigns. Figure 5 and Figure 6 present the schemes for these methods.

C. METHODS BASED ON WILMA AND MODIFIED-OPTIMAL METHOD

Two methods are based on WilMA and Modified-optimal. These are Mixed-WilMA-MO-A and Mixed-WilMA-MO-B. In these methods, the first bus contains all the passengers having seats near the window (similar to WilMA).

In Mixed-WilMA-MO-A, the first bus additionally includes all passengers with middle and aisle seats in the

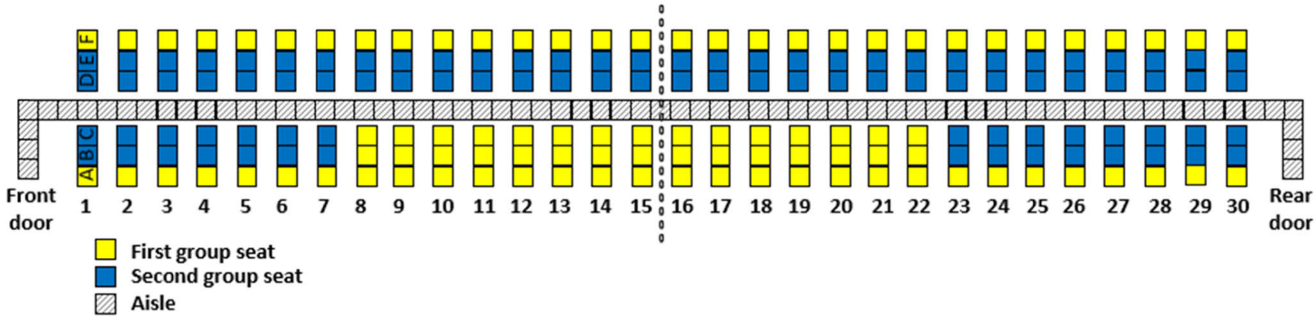


FIGURE 4. Mixed-BF-WilMA-A.

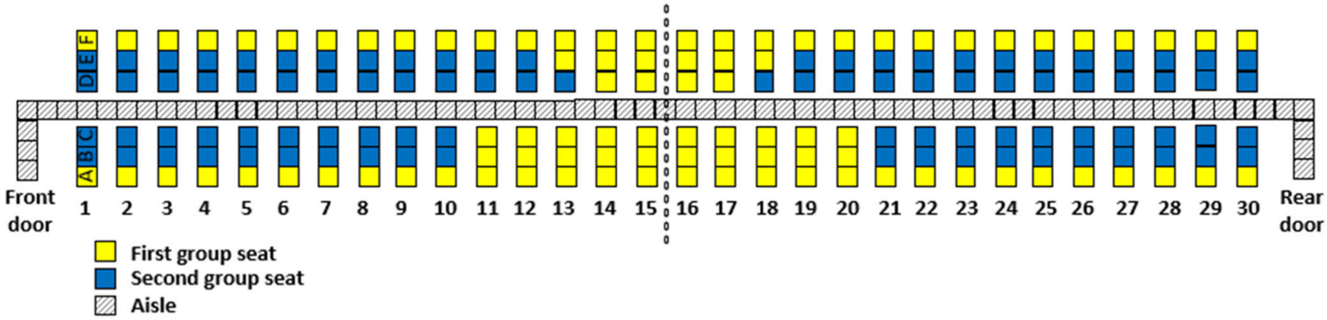


FIGURE 5. Mixed-BF-WilMA-B.

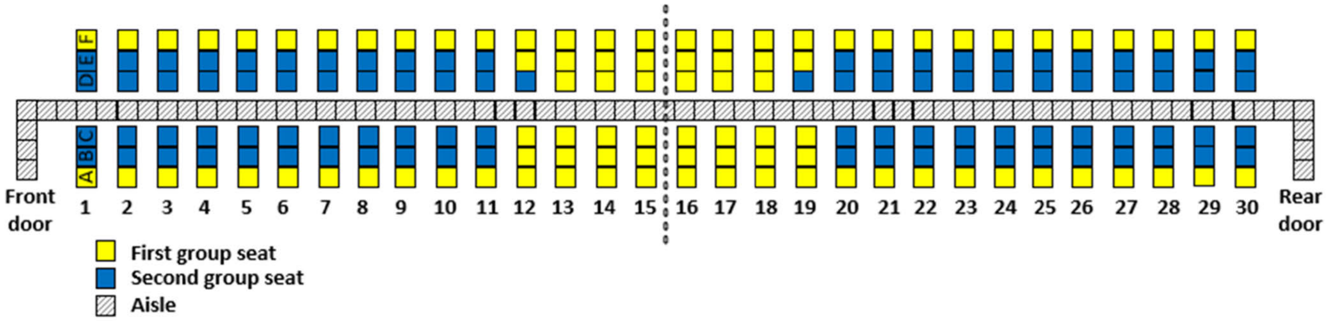


FIGURE 6. Mixed-BF-WilMA-C.

odd rows on one side of the aisle for the passengers entering the airplane using the front door, except for the first row where only the middle seat passenger is additionally selected, while for the passengers entering through the rear door, the passengers with seats on one side of the aisle in the even rows board the first bus, except for the last row, where only the middle seat passenger is additionally selected. Please see Figure 7. In addition to allocating all window seat passengers to the first apron bus, Mixed-WilMA-MO-B also assigns to the first bus some of the passengers with seats on one side of the aisle, alternating every third row between selecting passengers with middle and aisle seats, only middle seats, and neither middle nor aisle seats. Please see Figure 8.

D. METHODS BASED ON WILMA AND REVERSE PYRAMID METHOD

We developed five methods combining concepts from WilMA and Reverse Pyramid: Mixed-WilMA-RP-A to Mixed-WilMA-RP-E, as presented in Figure 9 - Figure 13.

These five methods utilize WilMA concepts in at least three ways. First, every window seat passenger is assigned to the first apron bus. Second, of the aisle seat passengers assigned to the first bus, every one of their adjacent middle seat passengers are assigned to the first bus as well. Third, the number of middle seat passengers assigned to the first bus is higher than the number of aisle seat passengers assigned to the first bus.

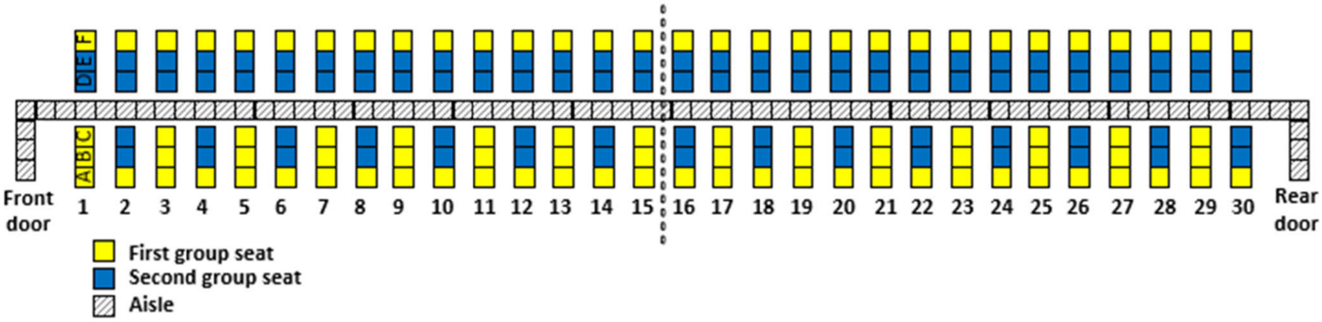


FIGURE 7. Mixed-WilMA-MO-A.

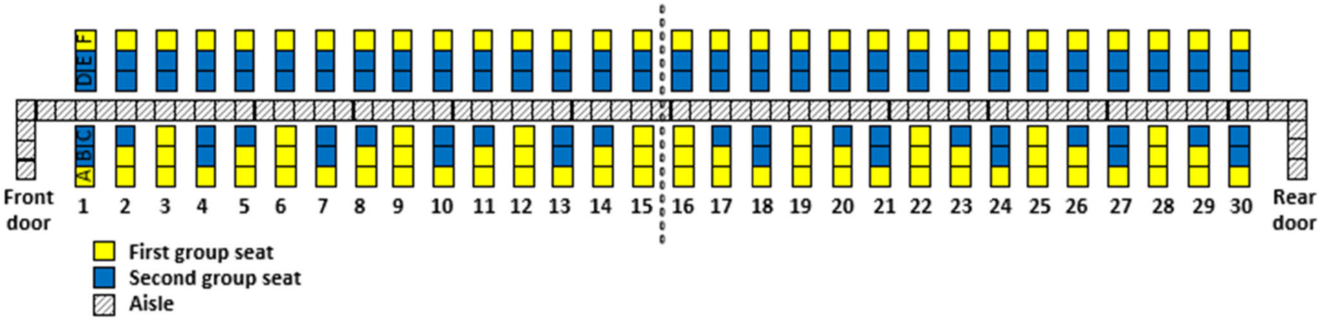


FIGURE 8. Mixed-WilMA-MO-B.

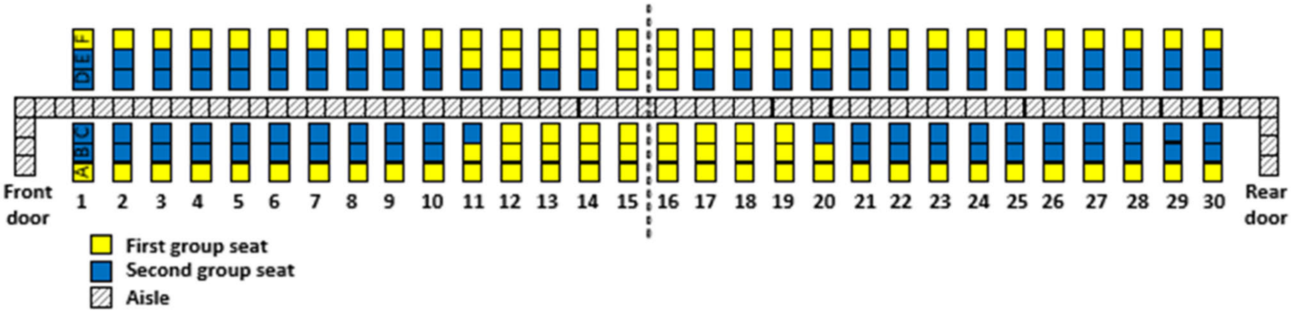


FIGURE 9. Mixed-WilMA-RP-A.

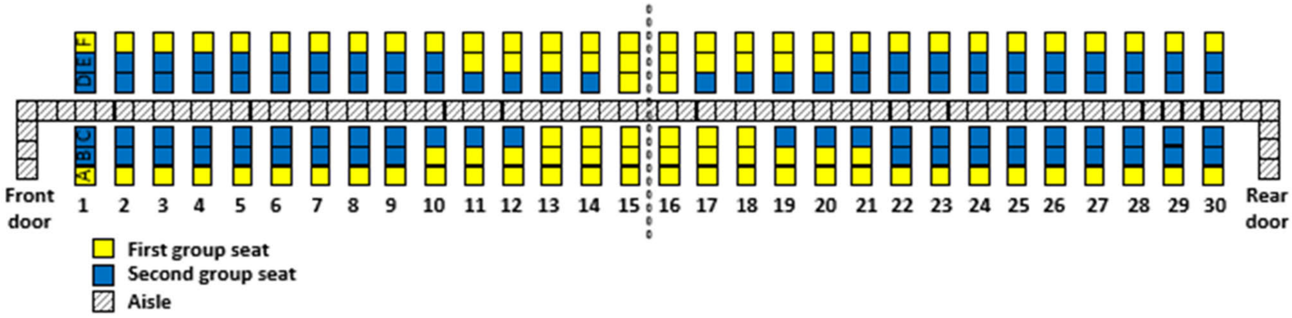


FIGURE 10. Mixed-WilMA-RP-B.

The five methods utilize Reverse Pyramid concepts in the following ways. First, there are more passengers assigned to the first bus who are seated in the middle rows of the airplane than from the rows closest to the front or rear door of the airplane. Second, the increase in the number of first bus passengers per row tends to rise as the passenger seats get

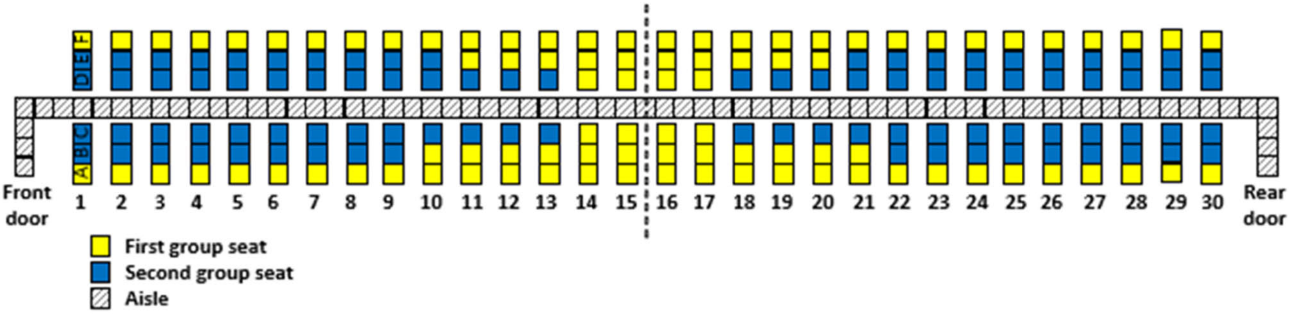


FIGURE 11. Mixed-WilMA-RP-C.

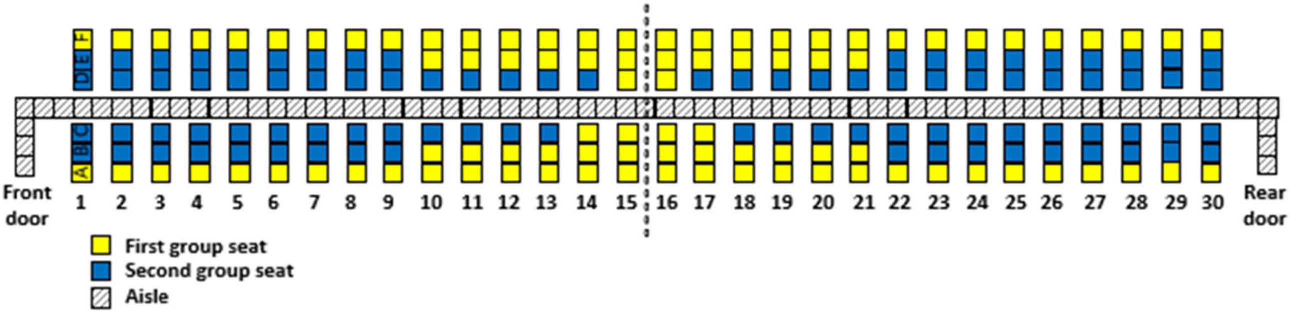


FIGURE 12. Mixed-WilMA-RP-D.

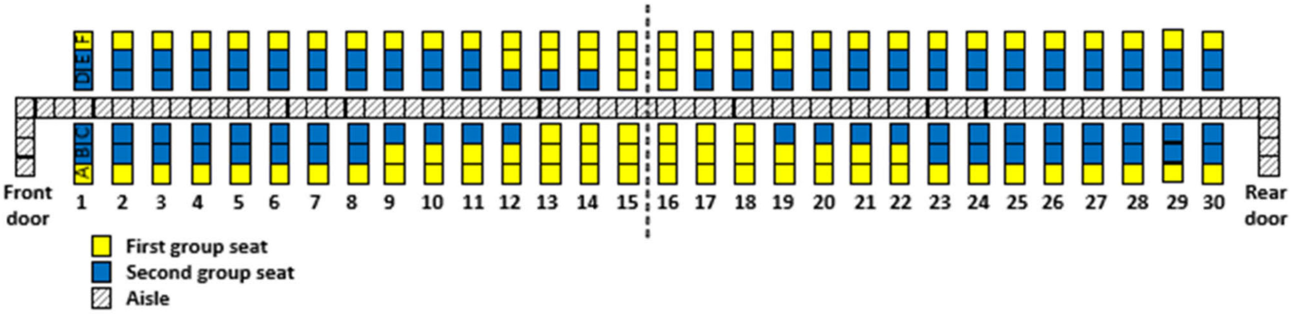


FIGURE 13. Mixed-WilMA-RP-E.

closer to the middle of the airplane in a pyramid fashion. For example, the number of first bus seats per row tends to rise from two to three or four beginning around row 10 (and 21) and again to about five or six for the most middle rows of the airplane (around rows 14-17). The general idea applied from this Reverse Pyramid concept is to favor congestion among first bus passengers in the rows that are closer to the middle of the airplane, and to favor congestion especially in those rows that are very close to the middle of the airplane (around rows 14-17). The five methods that combine WilMA and Reverse Pyramid in this way vary among each other due to different choices of the pyramid's exact shape.

E. OTHER MIXED METHODS

Through blending WilMA, Back-to-front, and Reverse pyramid methods, we tried to retain advantages of these classical methods, while introducing slight variations among the four methods: Mixed-A to Mixed-D, as shown in Figure 14 - Figure 17. We tried some other mixed methods but do not present them because they resulted in longer boarding times than other mixed methods.

IV. AGENT-BASED MODELING OF THE METHODS

We selected agent-based modeling for modeling the passengers' behavior while boarding airplanes as this type of modeling enables the use of different variables which can be associated with various agents, making them as humanized as possible [10], [38].

In particular, we chose NetLogo [39] as the software for modeling the human behavior in this paper and in a series of applications developed in different research fields such as: transportation [40]–[43], evacuation [44]–[49], education [50]–[52], information diffusion and attitude change [53], [54], social sciences [55]–[60], etc.

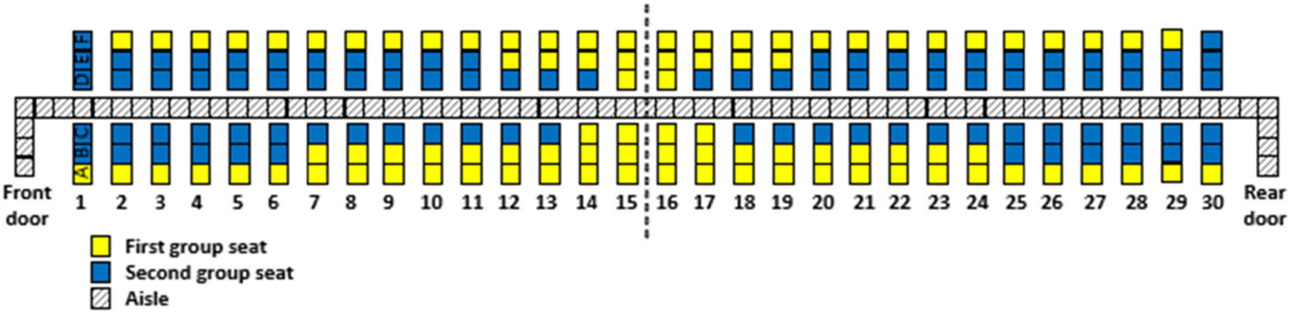


FIGURE 14. Mixed-A.

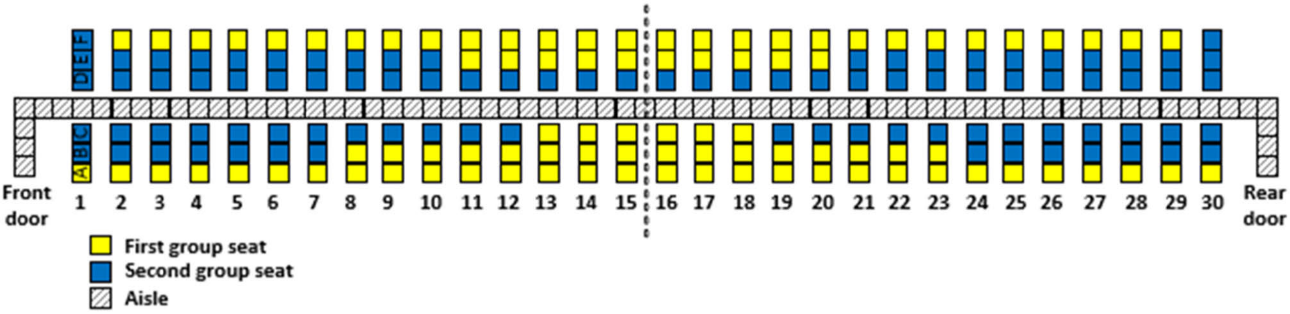


FIGURE 15. Mixed-B.

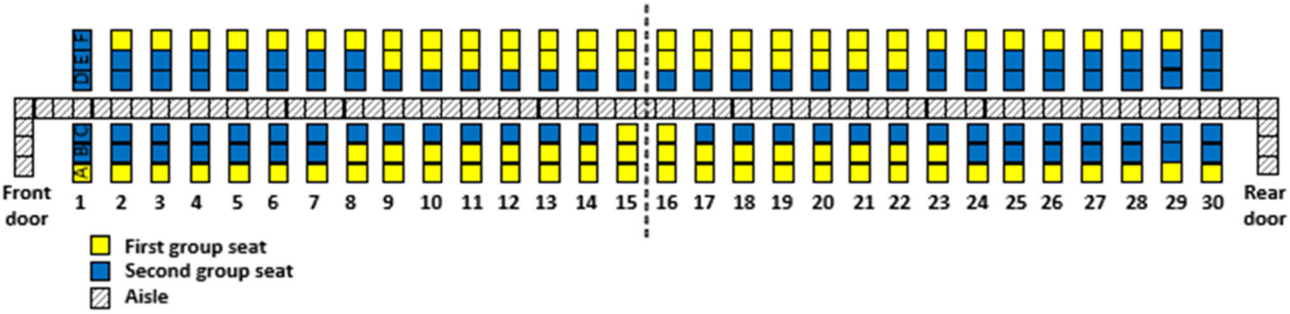


FIGURE 16. Mixed-C.

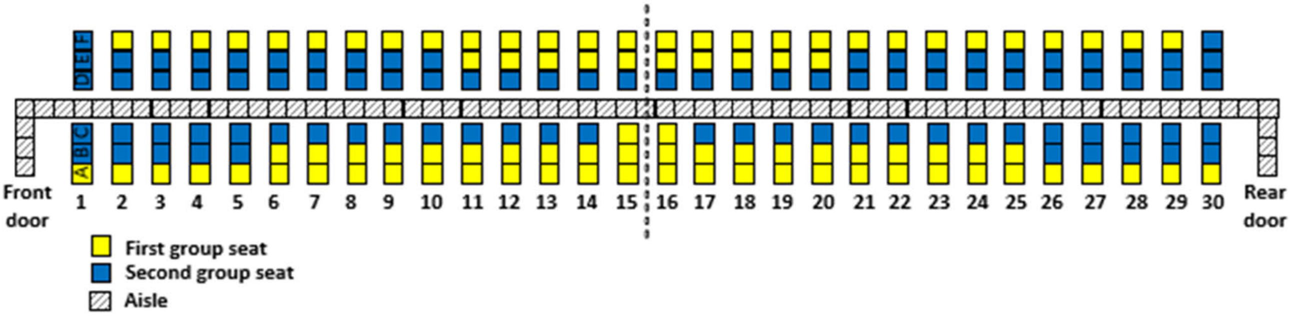


FIGURE 17. Mixed-D.

To model the boarding process of passengers into the airplane using two doors, two types of agents have been used, turtles (representing passengers) and patches, each of them having different properties, according to the modeling purposes.

A. AGENTS CHARACTERISTICS

In NetLogo, the patches are the small pieces of ground which compose the world, where the "action" takes place. In this case, the patches have been used for creating the inside part of the airplane, composed of seats and the aisle, allowing the turtles to move only over the permitted areas. The characteristics of the patches are highlighted in Table 2. The size of a patch is equivalent to 0.4 meters x 0.4 meters as suggested by [30], [61].

TABLE 2. Patches characteristics in the agent-based model.

Agent	Name of variable	Range / Value	Short description
Patch	pcolor	dark blue / grey	Patches in dark blue are used to represent the aisle, while the ones in grey the seats.
	isseat?	true / false	Indicates whether a patch is a seat or a part of the aisle.
	seat-row	a number between 1 and the airplane number of rows	Indicates the row in which a passenger sits.

Turtle agents represent passengers heading towards their assigned seats. To make them act as humans, the agents receive characteristics as presented in Table 3 where a tick is a unit of time (corresponding to 1.2 seconds).

The agent-based model created in NetLogo 6.1.0 is configurable, allowing airplane modeling from a selection of well-known airplane models. If none of these models fits the expectations, one can also build his or her own airplane model by selecting the number of seat-rows. The number of passengers can be also selected from the interface, along with the percentage of passengers carrying no, small, large, and large luggage. The boarding method can be selected using a drop-down menu.

The agent-based model graphical user interface (GUI) is presented in Figure 18.

To compare the relative performance of the boarding methods, the duration of the boarding process is displayed in the output area. Also, a series of plots and monitors are available to display the aisle and seats interferences. The plots are updated in real time as the model runs.

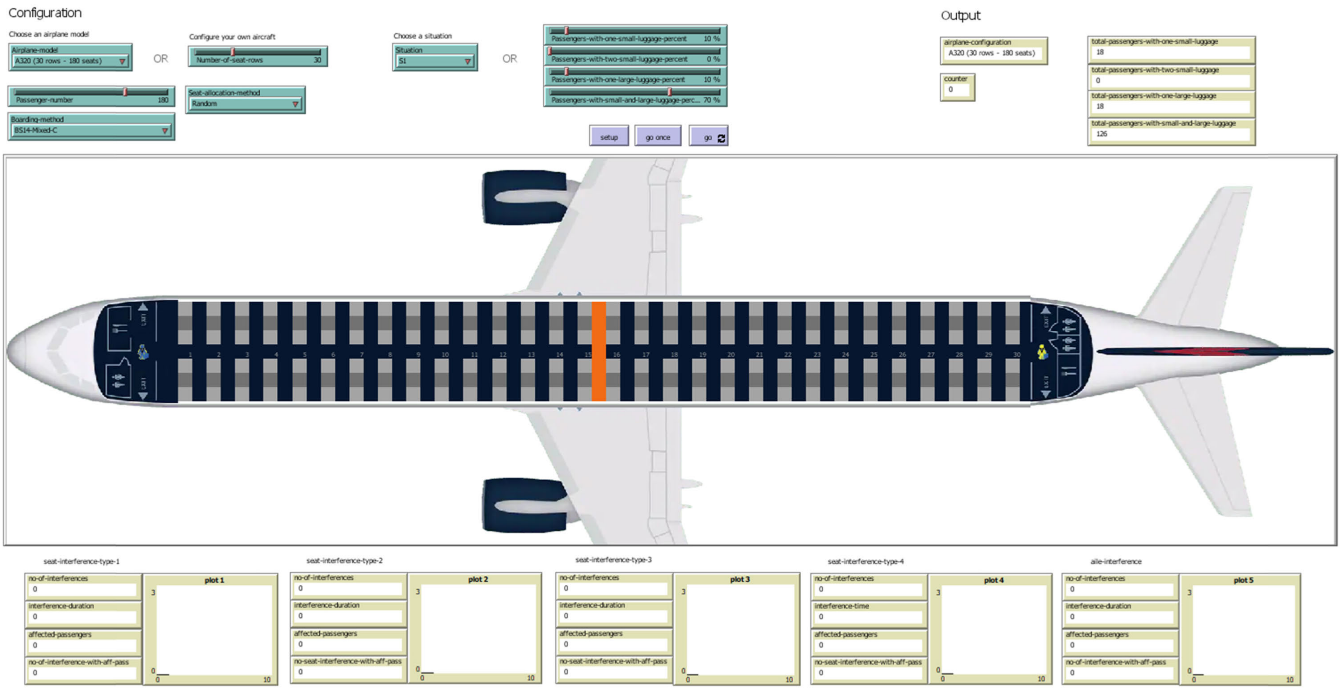
B. ASSUMPTIONS ON RULES OF MOVEMENT

A series of assumptions are made for the passengers boarding, as follows. First, for the passengers' transport between the airport terminal and the airplane, two apron buses are used, each with capacity to hold 90 passengers. Each bus makes only one trip because if more than one trip were made, then that would be conceptually equivalent (from a modeling perspective) to having three apron buses. The passengers' distribution between the two buses is based on one of the embarkment schemes presented above (Figure 2–Figure 17).

To minimize some of the potentially confusing situations related to the bus choice, we assume that on each boarding

TABLE 3. Turtles characteristics in the agent-based model.

Agent	Name of variable	Range / Value	Short description
Turtle	speed	[0, 1]	The maximum speed can be up to 1 patch / tick, representing 0.33 m/s when the turtle agent has no other turtle agent in front of it and it has no luggage, as suggested by [30], [31], [62]. When the agent carries luggage, the speed drops between 0.6 patch / tick and 0.9 patch / tick; when the passenger faces an interference, the passenger's speed drops to zero [7]. The agents possess variations in speed as we account in this way for their individual properties that may depend on factors such as age, weight, and mobility.
	luggage?	true / false	Indicates whether the agent carries inside the cabin any type of luggage.
	large-luggage	0 or 1	Retains the number of large luggage pieces carried by the agent inside of the airplane.
	small-luggage	0 or 1	Retains the number of small luggage pieces carried by the agent inside of the airplane.
	luggage-store-time	[0, 6]	The number of ticks needed for an agent to store the luggage. It is determined based on the formula suggested by [63] and used by [31], assuming both the luggage stored previously by other passengers and an unlimited bin storage space. The formula used for the luggage-store-time is the same as the one used in [36].
	bus	0 or 1	The apron bus to which the passenger is allocated. Zero corresponds to the first bus, while 1 corresponds to the second bus.
	seated?	true / false	Indicates whether the agent is seated or not.
	agent-seat-row	1 until the number of seat-rows	Indicates the seat-row allocated to each agent.
	agent-seat-column	A, B, C, D, E, F	Indicates the position of the seat column: A and F are used for the window seats, B and C for the middle seats and D and E for the aisle seats.
	comfort-distance	1	Equal to 1 patch, needed for assuring a proper personal space between the agents.
	time-to-sit	1	The time needed for a passenger who does not encounter a seat interference to sit, expressed in ticks.



Configuration

Choose an airplane model
Airplane-model: A320 (30 rows - 180 seats)
Passenger-number: 180
Boarding-method: BS14-Mixed-C

OR

Configure your own aircraft
Number-of-seat-rows: 30
Seat-allocation-method: Random

Choose a situation
Situation: S1

OR

Passengers-with-one-small-luggage-percent: 10 %
Passengers-with-two-small-luggage-percent: 0 %
Passengers-with-one-large-luggage-percent: 10 %
Passengers-with-small-and-large-luggage-perc...: 70 %

Output
airplane-configuration: A320 (30 rows - 180 seats)
counter: 0
total-passengers-with-one-small-luggage: 18
total-passengers-with-two-small-luggage: 0
total-passengers-with-one-large-luggage: 18
total-passengers-with-small-and-large-luggage: 126

seat-interference-type-1
no-of-interferences: 0
interference-duration: 0
affected-passengers: 0
no-of-interference-with-aff-pass: 0

seat-interference-type-2
no-of-interferences: 0
interference-duration: 0
affected-passengers: 0
no-seat-interference-with-aff-pass: 0

seat-interference-type-3
no-of-interferences: 0
interference-duration: 0
affected-passengers: 0
no-seat-interference-with-aff-pass: 0

seat-interference-type-4
no-of-interferences: 0
interference-time: 0
affected-passengers: 0
no-seat-interference-with-aff-pass: 0

aile-interference
no-of-interferences: 0
interference-duration: 0
affected-passengers: 0
no-of-interference-with-aff-pass: 0

FIGURE 18. The GUI for the agent-based model in NetLogo 6.1.0.

pass, along with the suggested door for boarding into the airplane, there will be another picture or text suggesting the apron bus the passenger should ride. Thus, we assume that none of the passengers who should board the second bus will choose the first bus by mistake. Also, we assume that all passengers board through their assigned airplane door. We assume that passengers enter and exit their assigned buses in random sequence.

Once the first bus is full, it transports the passengers to near the airplane, where they disembark and proceed to board the airplane through the indicated door. Meanwhile the passengers assigned to the second bus board their bus and follow the same sequence, forming a queue behind the passengers who arrived earlier with the first bus.

We assume that the passengers from the second bus won't take any maneuvers to skip the queue to enter the airplane before the passengers who arrived there with the first bus. As a practical time difference between the two buses exists, it is likely that the last passengers from the first bus will be on the airplane stairs or in the airplane when the second bus arrives, thus making queue skipping impossible.

Nevertheless, it is possible that in some cases there exists a small time difference between the last passenger from the first apron bus and the first passenger from the second bus arriving at the airplane. As this difference does not depend on the boarding method, but is rather associated with the airport's manner of handling the operations, it is not considered in our model. If this difference arises, it would affect all the methods, the boarding time being prolonged in all cases. Similarly, it might happen that in real life, some of the passengers miss the door boarding information and proceed to the wrong door. Again, this situation does not depend on the selected boarding method. Thus, this situation is not considered in the paper.

As for the measured boarding time, it will be determined as the time between when the first passenger enters the airplane cabin, in our case, two passengers—one entering through the front door and the other through the rear door—and the moment the last passenger takes his or her seat, no matter in which part of the airplane this action takes place.

At time zero, the passengers belonging to the first bus enter the airplane in a random sequence using either the front or the rear door, as indicated on their boarding pass, and proceed to the assigned seats. Depending on whether they are carrying or not carrying with them inside of the airplane large and/or small pieces of luggage, they have different values for their walking speed, being normally distributed in 0.6 – 0.9 patches/tick when the passengers have luggage and being equal to 1 patch/tick when they are not carrying any luggage.

Once an agent (passenger) arrives near the assigned seat, the agent blocks the aisle while placing any luggage in the overhead compartment, causing aisle interference as any agent located just behind it cannot pass it and thus needs to wait until the aisle is clear to continue its walk to that agent's assigned seat.

Depending on the type of luggage and on the overhead bin occupancy, the time needed for the agent to store the luggage, retained in the luggage-store-time variable, ranges between zero and 6, zero being the case in which the agent does not carry any hand luggage, while 6 is the case in which it carries

1 large and 1 small piece of luggage and the bin is almost full due to neighboring passengers having brought on board the maximum allowed number of luggage that they already stored in the overhead compartment.

After storing the luggage, depending on the assigned seat, the agent may continue to block the aisle as it might be facing one of the four types of seat interferences – please see Figure 19.

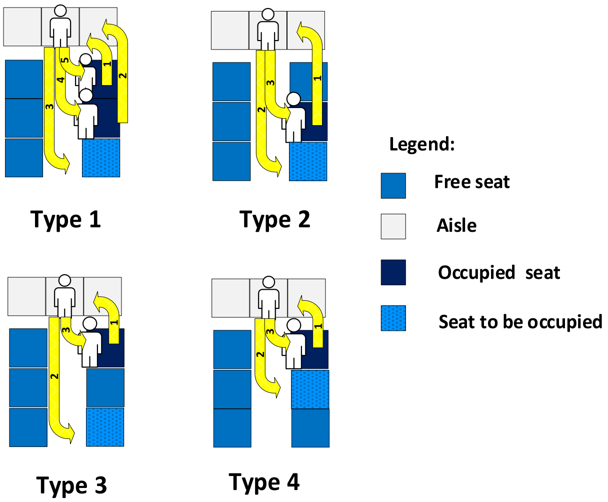


FIGURE 19. Types of seat interferences.

Consistent with the Schultz field trials measurement research [30], the time associated with each type of seat interference is: 22 seconds for type 1, ranging between 20 and 26 seconds, 12 seconds for type 2, between 10 and 13 seconds, 10 seconds for type 3 and type 4, with a range of 9 – 13 seconds. In the model, the times have been translated into ticks (the time unit used by NetLogo) by dividing them by 1.2 seconds and rounding them to the nearest integer.

V. SIMULATIONS AND RESULTS

For running an adequate number of simulations, the BehaviourSpace tool provided by NetLogo has been used [64]. Seven luggage situations have been considered as suggested by [31], [36], as presented in Table 4.

For each considered method in each luggage situation, 10,000 simulation runs have been conducted and the rounded-up average over these simulations has been used to compare the boarding methods. A total of 1,120,000 simulations have been recorded. The results are presented and discussed in the following.

A. SIMULATION - KEY RESULTS

The average times to complete boarding for the 16 methods and 7 luggage situations are shown in Table 5. The Back-to-front method proposed by [7] has been used as the benchmark method. All 15 new methods result in shorter boarding times than the benchmark method for all the 7 considered situations related to the luggage being carrying aboard the airplane.

TABLE 4. The considered luggage situations.

Situation	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%

The method providing the smallest boarding time is Mixed-WilMA-RP-C which combines the advantages provided by the WilMA and Reverse pyramid methods, while applying their rules in a relatively simple manner, and thus is easier than some of the other methods to implement by any airline company, no matter the type of airplane used. The Mixed-WilMA-RP-C method provides the fastest time to board for each of the 7 luggage situations. For the S1 luggage situation, which implies the highest number of luggage among all considered situations, we observe that the best method's time improvement of 120 ticks when compared to Back-to-front, is equivalent to 1 minute and 40 seconds, for a boarding time of 7 minutes and 14 seconds.

When considering the luggage situations which involve a smaller amount of luggage or no luggage at all, the time improvements remain considerable. For example, in the S7 no luggage situation, the Mixed-WilMA-RP-C method brings an average time improvement of 39.2% when compared to Back-to-front.

Table 6 presents the time improvements in percentages for each method when compared to the best-performing published method in the field, Back-to-front. Observe that the improvements range from 14.4 % to 39.2% over the 15 methods and the 7 luggage situations.

The smallest time improvements are brought by the Mixed-WilMA-MO-B and Mixed-WilMA-MO-A methods, both of them mixing the rules for the adapted WilMA and Modified-optimal methods, ranging between 14.4% and 25.7% improvement when compared to Back-to-front. Along with the smallest time improvement made through this methods, by considering their boarding schemes, we observe that their schemes are relatively complicated and thus potentially more difficult to apply in practice, which underscores the preference for the simpler methods with better boarding times, such as the variations in Mixed-WilMA-RP.

B. SIMULATION RESULTS–ANALYSIS OF PASSENGERS' COMFORT AND INTERFERENCES

Considering the passengers' comfort, a seat and aisle interference analysis is provided. The need for this analysis is based

TABLE 5. Average boarding time expressed in ticks.

Boarding method	Luggage Situations:						
	S1	S2	S3	S4	S5	S6	S7
Benchmark: Back-to-front	**434**	**401**	**361**	**343**	**321**	**299**	**268**
Adapted-WilMA	350	317	294	266	246	220	182
Mixed-BF-WilMA-A	341	313	282	264	242	219	185
Mixed-BF-WilMA-B	318	295	268	246	230	204	168
Mixed-BF-WilMA-C	317	294	268	243	225	201	166
Mixed-WilMA-MO-A	366	337	305	281	261	233	201
Mixed-WilMA-MO-B	366	336	309	286	261	234	199
Mixed-WilMA-RP-A	315	289	266	242	220	201	165
Mixed-WilMA-RP-B	315	288	263	241	223	202	164
Mixed-WilMA-RP-C	314	288	263	241	221	199	163
Mixed-WilMA-RP-D	317	290	265	243	221	201	164
Mixed-WilMA-RP-E	316	289	265	241	223	201	165
Mixed-A	320	297	271	250	230	209	172
Mixed-B	327	300	275	252	233	210	174
Mixed-C	330	300	270	254	233	213	176
Mixed-D	329	305	279	257	236	214	178

TABLE 6. Boarding time improvement in % compared to the Back-to-front method.

Boarding method	Luggage Situations:						
	S1	S2	S3	S4	S5	S6	S7
Adapted-WilMA	19.4%	20.9%	18.6%	22.4%	23.4%	26.4%	32.1%
Mixed-BF-WilMA-A	21.4%	21.9%	21.9%	23.0%	24.6%	26.8%	31.0%
Mixed-BF-WilMA-B	26.7%	26.4%	25.8%	28.3%	28.3%	31.8%	37.3%
Mixed-BF-WilMA-C	27.0%	26.7%	25.8%	29.2%	29.9%	32.8%	38.1%
Mixed-WilMA-MO-A	15.7%	16.0%	15.5%	18.1%	18.7%	22.1%	25.0%
Mixed-WilMA-MO-B	15.7%	16.2%	14.4%	16.6%	18.7%	21.7%	25.7%
Mixed-WilMA-RP-A	27.4%	27.9%	26.3%	29.4%	31.5%	32.8%	38.4%
Mixed-WilMA-RP-B	27.4%	28.2%	27.1%	29.7%	30.5%	32.4%	38.8%
Mixed-WilMA-RP-C	27.6%	28.2%	27.1%	29.7%	31.2%	33.4%	39.2%
Mixed-WilMA-RP-D	27.0%	27.7%	26.6%	29.2%	31.2%	32.8%	38.8%
Mixed-WilMA-RP-E	27.2%	27.9%	26.6%	29.7%	30.5%	32.8%	38.4%
Mixed-A	26.3%	25.9%	24.9%	27.1%	28.3%	30.1%	35.8%
Mixed-B	24.7%	25.2%	23.8%	26.5%	27.4%	29.8%	35.1%
Mixed-C	24.0%	25.2%	25.2%	25.9%	27.4%	28.8%	34.3%
Mixed-D	24.2%	23.9%	22.7%	25.1%	26.5%	28.4%	33.6%

on the observation made by Zeineddine [65] who believes that the best methods in the literature do not account for the number of boarding interferences. The purpose of this analysis is to determine whether the methods resulting in a lower (higher) boarding time have more or fewer occurrences of passenger interference. As sometimes it might happen that a passenger produces an aisle or a seat interference, but no passenger is directly behind him to be affected (please see Figure 20), the number of interferences in each category with affected passengers has been extracted for S1 luggage situation (please see Table 7).

The S1 situation has been selected as it is the case in which the passengers are carrying the most luggage aboard the airplane, with only 10% of this situation's passengers carrying no luggage.

Based on the data in Table 7, we observe that the methods producing the best boarding time, namely Mixed-WilMA-RP-C, Mixed-WilMA-RP-B and Mixed-WilMA-RP-D, have the lowest number of type 1 seat interferences, which is the type of interference causing the highest waiting time among the seat interferences. Type 2 seat interferences for these best-performing methods, on average, occur 7 times affecting passengers, placing them somewhere in the middle between the methods having the fewest type 2 seat interferences, e.g. Mixed-BF-WilMA-B and Mixed-BF-WilMA-C with 3 type 2 seat interferences, and the methods having the highest number of type 2 seat interferences, e.g. Adapted-WilMA, Mixed-C, and Mixed-D with 11.

As for the last two types of seat interferences, type 3 and type 4, which produce the same delay time, most of the methods produce a comparable number of interferences with affected passengers. Among all the methods, Adapted-WilMA produces the smallest number of type 4 seat interferences. This method also has zero type 1 and type 3 interferences, which is expected due to the boarding rules associated with this method.

Considering the aisle interferences, the difference among methods are not substantial as the number of these interferences ranges between 96 and 102 in the S1 case.

Additionally, for the aisle interferences, the S2 – S6 luggage situation have been considered and the simulations results presented in Table 8.

TABLE 7. Average number of seat and aisle interferences for S1.

Boarding methods	Average number of aisle interferences*	Average number of seat interferences that block a later boarding passenger*			
		Type 1	Type 2	Type 3	Type 4
Benchmark: Back-to-front	**97**	**14**	**7**	**7**	**20**
Adapted-WilMA	96	0	11	0	10
Mixed-BF-WilMA-A	101	4	3	2	20
Mixed-BF-WilMA-B	100	3	3	2	20
Mixed-BF-WilMA-C	102	3	3	2	19
Mixed-WilMA-MO-A	98	4	3	2	20
Mixed-WilMA-MO-B	97	3	5	2	17
Mixed-WilMA-RP-A	101	2	5	1	18
Mixed-WilMA-RP-B	100	1	7	1	16
Mixed-WilMA-RP-C	100	1	7	1	15
Mixed-WilMA-RP-D	100	1	8	1	15
Mixed-WilMA-RP-E	101	1	7	1	17
Mixed-A	99	1	10	1	14
Mixed-B	100	2	9	1	15
Mixed-C	99	1	11	1	12
Mixed-D	99	1	11	1	11

* the data has been rounded up to the nearest integer

TABLE 8. Average number of aisle interferences for S2–S6.

Boarding methods	Average number of aisle interferences*				
	S2	S3	S4	S5	S6
Benchmark: Back-to-front	**85**	**71**	**55**	**37**	**18**
Adapted-WilMA	88	71	55	37	19
Mixed-BF-WilMA-A	88	74	57	39	19
Mixed-BF-WilMA-B	87	73	56	39	19
Mixed-BF-WilMA-C	87	74	57	38	19
Mixed-WilMA-MO-A	86	72	56	37	19
Mixed-WilMA-MO-B	86	71	55	37	19
Mixed-WilMA-RP-A	88	73	56	38	19
Mixed-WilMA-RP-B	86	73	56	38	20
Mixed-WilMA-RP-C	87	72	55	38	19
Mixed-WilMA-RP-D	87	73	56	38	19
Mixed-WilMA-RP-E	88	73	56	38	19
Mixed-A	87	72	55	38	19
Mixed-B	86	72	56	39	19
Mixed-C	85	72	55	37	19
Mixed-D	85	71	55	38	20

* the data has been rounded up to the nearest integer

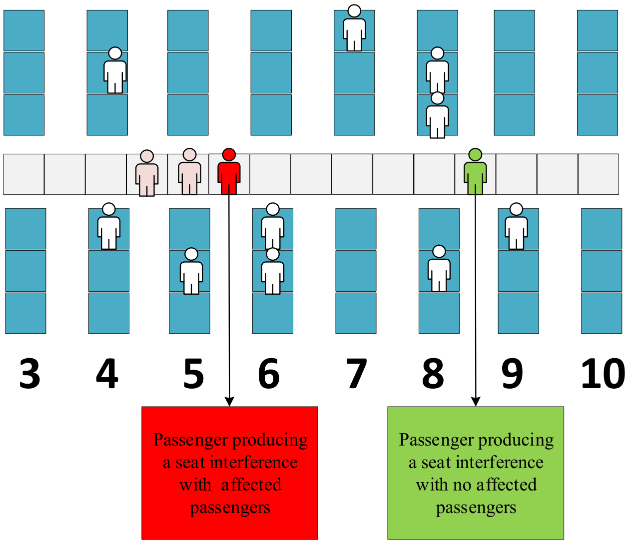


FIGURE 20. Example of seat interferences with and without affected passengers.

As with S1, the average number of aisle interferences for a given luggage scenario varies only a small amount by method, at most by 3 ticks.

The average number of seat interferences for the S2 – S6 situations are the same as for S1 as the number of seat interferences depends on the boarding scheme and not on the quantity and type of luggage.

By summing all the seat and aisle interferences, we observe that the benchmark method has the highest number, 145, while all the other 15 methods have less, resulting in between 117 and 130 interferences with affected passengers. The observation is in line with the research made by Iyigunlu *et al.* [38] who believe that minimizing the total number of seat and aisle interferences is the best way for reducing the boarding time. Furthermore, the literature acknowledges that the more passengers are interfering, the longer the boarding time will be [16], [27], [33], [37]. We add that not only the number of interferences matters, but also the type of interferences. We observe that for the best performing methods, the number of aisle interferences is high in comparison with the other methods, while the number of type 1 seat interferences is low compared with the other methods. The number of type 3 and 4 seat interferences is comparable among the methods, except for Adapted-WilMA which performs relatively poorly compared to the other methods.

Finally, we conjecture that the location of interferences matters. In that regard, we observe from Figure 11 and Figure 19 that for the best performing method (Mixed-WilMA-RP-C), type 1 seat interferences can only occur in rows 14-17 (near the middle of the airplane) and type 2 seat interferences can occur only in rows 10-21 (in the middle rows of the airplane). We suspect that such interferences are less unfavorable in those rows than they would be in rows closer to the front or rear of the airplane. In support of this conjecture, we note that Milne and Salari [31] found, in one context, that interferences in the first two rows (those rows nearest the door) of a one-door airplane can be particularly bad for boarding time performance. Such delays prevent any subsequent passenger from entering the aisle. Conversely, interference in row 15, for instance, can only delay passengers with seats near the middle of the airplane; and when using the Mixed_WilMA-RP-C method, these passengers board the airplane from the first apron bus (earlier than those passengers riding the second apron bus).

As the number of type 1 interferences with affected passengers is low for the best performing methods, Mixed-WilMA-RP-C, Mixed-WilMA-RP-B and Mixed-WilMA-RP-D, we tend to believe that the passengers' comfort while boarding when these methods are used is less affected compared to using the other boarding methods, as these are the most disturbing seat inferences.

Thus, we characterize the boarding methods and rank them by boarding time improvement in Table 9.

TABLE 9. Boarding methods characterized by their boarding time improvement versus the benchmark Back-to-front method.

Hierarchy	Method	Time improvement when compared to Back-to-front. Up to:
Best	Mixed-WilMA-RP-C	39.2%
Good	Mixed-WilMA-RP-B	38.8%
	Mixed-WilMA-RP-D	38.8%
	Mixed-WilMA-RP-A	38.4%
	Mixed-WilMA-RP-E	38.4%
	Mixed-BF-WilMA-C	38.1%
	Mixed-BF-WilMA-B	37.3%
Acceptable	Mixed-A	35.8%
	Mixed-B	35.1%
	Mixed-C	34.3%
	Mixed-D	33.6%
	Adapted-WilMA	32.1%
	Mixed-BF-WilMA-A	31.0%
	Mixed-WilMA-MO-B	25.7%
	Mixed-WilMA-MO-A	25.0%

Additionally, for the S7 luggage case, Mixed-WilMA-RP-C performs at least 4.12% faster than the methods proposed in Milne *et al.* [36]. For the S1 luggage case, the best performing methods proposed in [36] have the same number of aisle interferences with affected passengers as Mixed-WilMA-RP-C and almost the same number of seat interferences. Thus, the boarding time is improved when using Mixed-WilMA-RP-C, while the passengers' comfort is maintained at the same level.

VI. CONCLUDING REMARKS

The practice of using apron buses has become more and more often used in practice as it offers to airports the possibility of handling more flights without making infrastructure investments such as expanding a terminal. Airline companies are aware that apron buses are often used to transfer passengers from the terminal and the airplane. In this case, passengers board into the airplane using both the front door and the rear door of the airplane. In this context, some of the airline companies have added information to their boarding passes to indicate the airplane door each passenger should enter depending on the assigned seat.

In the literature, boarding methods have been proposed for the case of jet-bridges use and boarding using only one door; for two-door boarding when apron buses are used, there is little in the literature regarding methods to employ in this case. Therefore, in this paper, we propose 15 new methods we created based on some of the best-performing methods in terms of boarding time when only one door is used. Using an agent-based model created in NetLogo, the 15 methods are compared to the Back-to-front method adapted for the case in which two apron buses are used, to demonstrate their relative performance in terms of the time to complete boarding of the airplane. Seven luggage situations are considered.

Based on the simulation results, we determine that the best performing method in terms of boarding time is Mixed-WilMA-RP-C, which improves the boarding times obtained by using Back-to-front by up to 39.2%.

Based on an average cost of boarding delay of $53.5 per minute [1], [2] and by considering all the luggage situations, S1 to S7, an average cost reduction of $78.34 per flight is attained when using Mixed-WilMA-RP-C instead of Back-to-front. Depending on the number of luggage, the cost reduction is between $72.81 and $89.17 per flight.

Compared to the other methods, including Back-to-front, Mixed-WilMA-RP-C results in the minimum number of type 1 seat interferences and a comparable number of the other aisle and seat interference, which makes it even more appealing for the passengers as it is less uncomfortable for them than with other methods. Nevertheless, the embarkment rules are relatively simple and can be applied by any airline company.

As for the other methods, each of them decreases the boarding time when compared to Back-to-front for all the luggage situations.

For further research, we plan to examine different utilizations for the apron buses and airplanes and for testing the boarding methods' performance under new assumptions—including different airplane configurations (e.g. double aisle wide-body, two-story boarding, narrower body with fewer seats per row) and potentially different quantities and configurations of apron buses. Another limitation of the present paper is that we consider only individual passengers in the apron bus assignments; future research should consider that groups of passengers traveling together (e.g. families) should be assigned to the same apron bus.

The paper is accompanied by videos made for S1 luggage situation, for all the considered methods, which can be accessed at the following link: https://github.com/liviucotfas/ase-abm-boarding-two-doors-mixed-methods.

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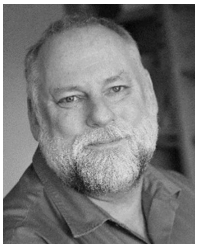

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