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Airplane Boarding Method for Passenger Groups When using Apron Buses

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ABSTRACT This paper proposes a method for reducing the time to complete the boarding of a two-door airplane when its passengers are transported from the airport terminal to the airplane using two apron buses. In contrast to other methods that assign passengers to apron buses, our method considers groups of passengers traveling together (e.g. families). In particular, we propose a mixed integer programming (MIP) model that assigns each group of passengers (including each single-passenger group) to one of the two apron buses based on their seating assignments. We assume that all seats on the apron buses and the two-door airplane are occupied. We conduct stochastic simulation experiments with the proposed MIP-based method and with a baseline method that assigns groups of passengers with seats furthest from one of the airplane doors to the first apron bus and assigns remaining groups to the second apron bus. Numerical results indicate that the proposed MIP-based method reduces the boarding time by up to 27.31% when compared with the baseline approach.

INDEX TERMS Airplane boarding, group boarding, apron buses, agent-based modeling, two-door boarding, mixed integer programming.

I. INTRODUCTION

The airplane boarding process—measured from the moment the first passenger arrives inside the airplane to the moment the final passenger sits in a seat—is a significant part of the airplane turn time and has a meaningful effect on the overall operational costs of airlines [1], [2]. Due to the competitive environment, a series of boarding methods have been proposed in the scientific research literature to reduce the time to complete boarding of airplanes [3].

Many airports use apron buses to transport passengers from the airport terminal to the airplane. Specifically designed for use at airports, apron buses are wider than normal buses and are usually fitted with a reduced number of seats and have large windows and entrances at both ends. Inside these buses, passengers often stand during their journey [4].

Being aware of the airports' practice of using apron buses, some airlines have adapted their boarding passes to suggest to each passenger the appropriate door of the airplane (front or rear door) they should enter after they exit the apron bus [5], [6]. Some airports, e.g. Naples International Airport Capodichino, have attached posters to apron bus doors to indicate the airplane door each passenger should enter based upon their seat on the airplane. These actions support the continuous interest both airlines and airports have for increasing their customers' satisfaction and reducing boarding times.

The recent scientific literature on airplane boarding methods acknowledges the use of the apron buses in practice, and a series of boarding methods for the case in which two apron buses have been proposed and tested [4]–[8]. Like the present paper, this literature assumes that airlines do not control the sequence in which passengers exit an apron bus or enter the airplane. Consequently, in this context, the boarding decision is to determine which passengers to assign to each apron bus. The methods aim to reduce the boarding time, while accounting for the passengers' seating assignments. These prior works do not consider passengers traveling together in groups (e.g. families, friends, business colleagues).

The present paper proposes a method that accounts for groups of passengers traveling together. In our simulation experiments, passengers are assigned to airplane seats so that they sit as close to each other as possible—similar to what is

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likely to happen in real life. Our proposed method uses mixed integer programming to assign each passenger to an apron bus to achieve assignments similar to the targets established by the best performing airplane boarding method for the apron buses case, namely Mixed-WilMA-RP-C [5]. Unlike the prior works, with our proposed method, each group of passengers is assigned to a single bus. Consequently, the passengers travelling together as a group ride the same apron bus from the airport to the airplane. The proposed model is implemented using Python and NetLogo 6.1.0, and the results are tested against a baseline approach. The baseline method resembles Back-to-front boarding [4], [9], [10] in that groups of passengers with seats close to the middle of the airplane (and thus with seats furthest from an airplane door) are assigned to the first apron bus and thus board the airplane prior to the remaining passengers who are assigned to the second apron bus. Simulation experiments show that the proposed method results in faster boarding times than those resulting from the baseline method tested.

The remainder of the paper is organized as follows: Section II provides a literature review, with a focus on airplane boarding methods used in the case of two apron buses; also in this section, we discuss issues analyzed in the literature when group boarding is considered. Section III contains the proposed method's mixed integer programming model formulation. Section IV describes the assignment of groups of passengers to seats on the airplane. Section V 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 VI uses the model to test the performance of the proposed method versus the baseline method, under various conditions. In all conditions, the proposed and baseline methods will be compared using the same passenger seating assignments as determined using the method introduced in Section IV. The paper closes with a concluding section and references. The paper is accompanied by supplementary videos containing simulations for the proposed method and for the baseline method.

II. LITERATURE REVIEW OF BOARDING METHODS

Over time, methods for modeling and improving the airplane boarding process have been created and tested in the research literature with an objective of reducing the time to complete boarding of the airplane. To model the boarding process, researchers have considered a number of factors including: airplane characteristics, [11]–[15], airplane occupancy [2], [9], [11], [12], [16]–[18], passenger movement [19], [20], passengers' personal characteristics [9], [15], [16], group behavior [1], [21]–[23], seat selection [13], [20], the presence and type of the carry-on hand luggage [11], [16], [19], [22], [24], boarding interferences [9], [10], [14], [22], [25]. Some other studies have focused on extracting data from the field [9], [12], [15], [26], [27],so much needed in testing, calibrating and validating the proposed approaches.

Most of the studies have focused on the case in which the airplane is connected directly to the terminal through one or two jet bridges [11], [14], [16], [17], [19], [22], [24], [25], [28]–[32], and only few of the studies are applicable with the presence of two apron buses [4]–[8].

Table 1 highlights some of the methods proposed for the case in which two apron buses are used to transfer passengers from the airplane terminal to the airplane [4]–[7]. We describe these methods under the assumption that these papers (and our present paper) makes that the applicable airplane is an Airbus 320 configured with 30 rows of passengers, each row having six seats (with three seats on each side of the aisle).

Several studies investigate boarding when groups of passengers travel and sit together. Wittman [1] uses simulated annealing to minimize boarding time when four sets of passengers are called to board, with groups of up to three passengers. The author identifies patterns in optimal solutions including that the minimum overall boarding time results when multi-passenger groups are in the first set of passengers to board and the final (i.e. fourth) set of passengers to board are mostly passengers traveling alone.

Zeineddine [23] proposes a method in which boarding occurs in a sequence specified by passenger or by group of passengers. His method has a first priority of boarding windows seat passengers first, followed by middle seat passengers, and lastly aisle seat passengers. The secondary priority favors back to front boarding. Adjustments to those priorities are made so that: all group members board together; if a group's boarding would lead to seat interferences with other passengers in the same row, then the group's boarding is delayed; boarding of subsequent passengers is delayed if their earlier boarding—according to the top two priorities—would result in them being blocked in the aisle by an earlier boarding passenger.

Tang *et al.* [21] acknowledge the importance of considering group behavior in the boarding process. In their proposed model, the authors consider groups having between two and six passengers and use pre-defined seat assignments within a row. For example, if the group has four passengers, their seats can be in either columns ABCD, BCED or CFED (where A and F are window seats, B and E middle seats, and C and D aisle seats). Other assumptions are made by the authors such as that the only passenger handling the luggage in a group is the last passenger in that group, while all the passengers' motion characteristics are homogeneous. Among the results, the authors underline that group behavior can enhance boarding efficiency [21]. In a related work, Tang *et al.* [22] extend the model by considering the quantity of luggage in the boarding process. The authors state that the quantity of luggage may make each passenger's boarding behavior more complex, while the group behavior has positive effects on boarding process. Similar results are obtained by Tang *et al.* [33].

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

Boarding method for the two apron buses case	Short description
Back-to-front	The airplane is divided into four even groups based on the seats' location: front (rows 1-7), middle-front (rows 8-15), middle-rear (rows 16-22) and rear (rows 23-30). The first apron bus accommodates the passengers having seats in the middle-rear and middle front rows of the airplane (rows 8-22) while the second apron bus contains the remaining passengers (rows 1-7 and 23-30). This boarding scheme is presented in Figure 1 [4].
Spread-across-rows	This method is inspired by the WilMA (window-middle-aisle) method and assigns all the passengers with seats near the window and half of the passengers with seats in the middle rows to the first apron bus, while the rest of the passengers are assigned to the second bus. Each row has three passengers assigned to each of the two buses.
Half-spread-across-rows	The method combines the rules of Spread-across-rows method and Back-to-front approach. Passengers with seats near the window are assigned to the first apron bus, along with half of the other passengers with middle and aisle seats, alternating rows, from the second to the third quarter of the airplane. All the remaining passengers are assigned to the second bus.
Reverse-pyramid	This method has six variations (Reverse-pyramid-A to Reverse-pyramid-F) and benefits from the advantages brought by the Reverse-pyramid method used in the case of a single door airplane and the Back-to-front method. For Reverse-pyramid-A, the first bus accommodates the passengers with window seats and all the passengers with middle seats in the middle-front and middle-rear part of the airplane (rows 8-22); the second bus accommodates all the remaining passengers. Subsequent variations (Reverse-pyramid-B to Reverse-pyramid-F) assign increasing numbers of passengers seated close to the middle rows of the airplane to the first apron bus and a corresponding increase in the number of passengers seated near the front or rear door of the airplane to the second bus [7].
Hybrid	Five variations (Hybrid-A to Hybrid-E) of this method are available. The rules of these methods are inspired by the Reverse-pyramid-A and Spread-across-rows methods. The Hybrid-A method is quite similar to Reverse pyramid-A, except with two additional rows (rows 8 and 23) containing three passengers who board the first apron bus.
Adapted-WilMA	This method is based, as its name suggests, on WilMA. The first bus contains the passengers with seats near the window on both sides of the aisle and the passengers with middle seats on just one side of the aisle. The other passengers are assigned to the second apron bus.
Mixed-BF-WilMA	The first bus accommodates all the passengers with seats near the window and some of the passengers with middle and aisle seats located in the middle of the airplane. The variations (Mixed-BF-WilMA-A to Mixed-BF-WilMA-C) are based on which of the middle of the airplane passengers board each bus.
Mixed-WilMA-MO	Two variations (Mixed-WilMA-MO-A and Mixed-WilMA-MO-B) are available. These methods blend concepts of WilMA and the Modified-optimal method for jet bridge boarding proposed by Steffen [19]. The first bus contains all the passengers with window seats on both sides of the aisles and some of the passengers with middle/aisle sears following a pattern inspired by the Modified-optimal method. With variation A, the number of passengers per row assigned to the first apron bus alternate between two and four. With variation B, the number of passengers boarding the first bus alternates between two, three and four.
Mixed-WilMA-RP	This method has five variations (Mixed-WilMA-RP-A to Mixed-WilMA-RP-E). The method considers WilMA for boarding all the passengers with seats near the window in the first apron bus and some of the passengers in the middle of the airplane, loading diagonally. Mixed-WilMA-RP-C provides the best boarding times from all the Mixed-WilMA-RP methods and from all the methods previously tested for boarding a two-door airplane when two apron buses are used. This method can reduce the boarding time by up to 39.2% when compared to the Back-to-front method. This boarding scheme is presented in Figure 2 [5].
Mixed	Four variations (from Mixed-A to Mixed-D) are available. The methods included in this category are inspired by the WilMA, Back-to-front, and Reverse pyramid methods.

III. PROPOSED BOARDING METHOD WITH APRON BUSES AND PASSENGERS GROUPS

We propose a mixed integer programming (MIP) model that assigns each group of passengers and each passenger traveling alone to one of the two apron buses.

A. ASSUMPTIONS

Within the MIP, we assume that the number of passengers within each group and the seat assignment of each passenger is known. Furthermore, we make the following assumptions that apply to the MIP and to the other sections of the paper:

- 30 rows in the single-aisle airplane
- Each row has 6 seats
- 180 passengers have seats (fully loaded airplane)
- There are two apron buses
- An equal number of passengers must be assigned to each bus (with this data, that means 90 passengers per bus). With this assumption, we assume as well that there are

enough passengers traveling alone so that this constraint may be satisfied

- Each passenger seated in rows 1-15 boards through the front door of the airplane and those passengers seated in rows 16-30 board through the rear door
- Groups and individual passengers assigned to a particular apron bus board the airplane in random sequence; however, within a group, passengers board in a smart sequence to avoid unnecessary seat interferences. For example, within a group of three passengers seated in a particular row on one side of the airplane, the window seat passenger of that group will board first, followed by the middle seat passenger of that group, and finally by the aisle seat passenger of that group.

We propose using a MIP to assign each group of passengers to a particular apron bus. A key objective is to assign passengers to the buses—based on their groups' seats—to provide results that are similar to that of the best performing method in the literature (Mixed-WilMA-RP-C), except with the added condition that each group member boards the same apron bus.

B. NOMENCLATURE

Subscripts

$g \in G$	Groups of passengers traveling together in a group or alone;
$b \in B$	The two buses;
$r \in R$	The 30 rows of the airplane.

Parameters

N_g	Number of passengers in group g (some groups will have one passenger);
$\mathrm{W}^{\mathrm{a}}_{gr}$	Number of Window seat passengers in group $g$that are adjacent to a middle seat passenger in row $r$that is not in group g;
$\mathrm{W}^{\mathrm{b}}_{gr}$	Number of Window seat passengers in group $g$that are adjacent to a middle seat passenger in row $r$that is in group g and the latter (middle seat passenger) is adjacent to an aisle seat passenger that is not in group g;
$\mathrm{A}^{\mathrm{a}}_{gr}$	Number of Aisle seat passengers in group g that are adjacent to a middle seat passenger in row $r$that is not in group g;
$\mathrm{A}^{\mathrm{b}}_{gr}$	Number of Aisle seat passengers in group g that are adjacent to a middle seat passenger in row $r$that is in group g and the latter (middle seat passenger) is adjacent to a window seat passenger that is not in group g;
NR_{gr}	Number of passengers from group g sitting in Row r;
TARGET_r	Target for the number of passengers in row r that should be assigned to the first bus; this target is the number of passengers assigned to the first bus in row r by the Mixed-WilMA-RP-C method;
WA_r	Weight to reward occurrences of $\mathrm{W}^{\mathrm{a}}_{gr}$ that are assigned to the first bus;
WB_r	Weight to reward occurrences of $\mathrm{W}^{\mathrm{b}}_{gr}$ that are assigned to the first bus;
AA_r	Weight to reward occurrences of $\mathrm{A}^{\mathrm{a}}_{gr}$ that are assigned to the second bus;
AB_r	Weight to reward occurrences of $\mathrm{A}^{\mathrm{b}}_{gr}$ that are assigned to the second bus;
$\alpha\mathrm{s}_r$	Weight to penalize per passenger first bus assignment shortages from meeting the TARGET_r
$\alpha\mathrm{e}_r$	Weight to penalize per passenger first bus assignment excesses that exceed TARGET_r.

Decision variables

X_{gb}	1 if group g is assigned to bus b; 0 otherwise; X is a binary variable;
S_r	Amount short of TARGET_r for row r of the first apron bus;
E_r	Amount in excess of TARGET_r for row r of the first apron bus;
F	Amount that the number of passengers in the first half of the airplane (rows 1-15) assigned to the first bus is more than the number of passengers in the rear half of the airplane (rows 16-30) that are assigned to the first bus;
Z	Amount that the number of passengers in the first half of the airplane (rows 1-15) assigned to the first bus is less than the number of passengers in the rear half of the airplane (rows 16-30) that are assigned to the first bus;

C. CONSTRAINTS OF THE MIXED INTEGER PROGRAM

Although a MIP is often described beginning with its objective function, for this particular MIP, it is easier to understand its objective function after first understanding its (simpler) constraints:

Constraints

X_{gb} is a binary variable:

$$\mathrm{X}_{gb} \in \{0, 1\} \tag{1}$$

Each group is assigned to a single bus:

$$\mathrm{X}_{g1} + \mathrm{X}_{g2} = 1 \tag{2}$$

The same number of passengers are assigned to each bus:

$$\sum\nolimits_{g\in G} \mathrm{N}_{g*}\mathrm{X}_{g1} = \sum\nolimits_{g\in G} \mathrm{N}_g * \mathrm{X}_{g2} \tag{3}$$

Determine the shortages (S_r) and excesses (E_r) of the number passengers in each row $r$assigned to the first bus ($\sum_{g\in G} \mathrm{NR}_{gr} * \mathrm{X}_{g1}$) when compared with the Mixed-WilMA-RP-C targets (TARGET_r):

$$\sum\nolimits_{g\in G} \mathrm{NR}_{gr} * \mathrm{X}_{g1} = \mathrm{TARGET}_r - \mathrm{S}_r + \mathrm{E}_r \forall r \in R \tag{4}$$

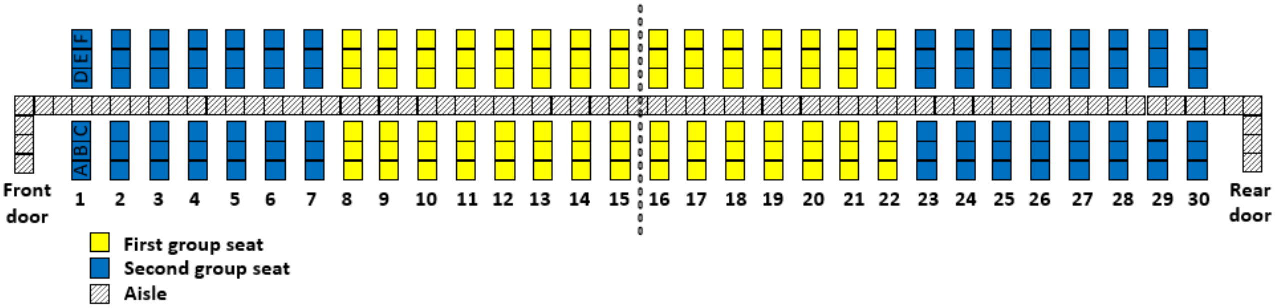


FIGURE 1. Back-to-front for the case of apron buses.

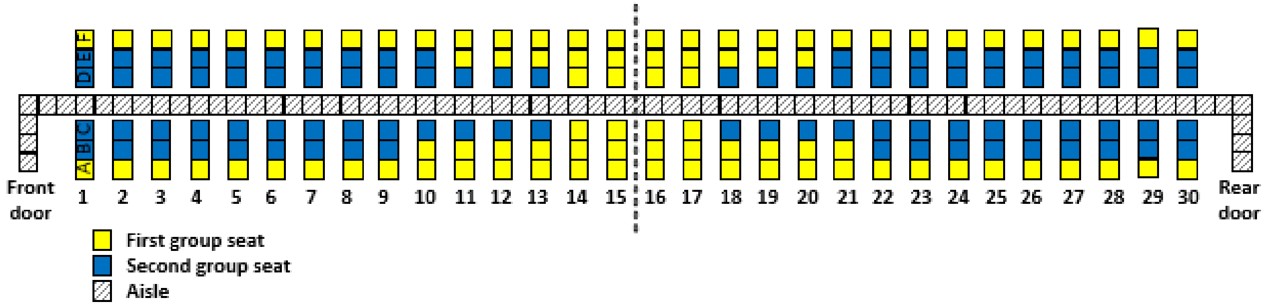


FIGURE 2. Mixed-WilMA-RP-C for the case of apron buses.

Record the imbalance (F+Z) between the number passengers assigned to the front half of the airplane to the first bus and the number of passengers assigned to the rear half of the airplane that are assigned to the first bus. By symmetry, the imbalance for the first bus is the same as the imbalance for the second bus:

$$\sum_{r\in\{1\ldots15\}}\sum_{g\in G}\mathrm{NR}_{gr}*\mathrm{X}_{g1} = (\sum_{r\in\{16\ldots30\}}\sum_{g\in G}\mathrm{NR}_{gr}*\mathrm{X}_{g1})+(F-Z) \quad (5)$$

Non-negativity constraints apply:

$$\mathrm{E}_r >= 0 \ \forall r\in R \quad (6)$$

$$\mathrm{S}_r >= 0 \ \forall r\in R \quad (7)$$

$$\mathrm{F} >= 0 \quad (8)$$

$$\mathrm{Z} >= 0 \quad (9)$$

D. OBJECTIVE FUNCTION OF MIP

The MIP's objective function (10) imbeds several considerations to assign passengers to apron buses to resemble the results of the Mixed-WilMA-RP-C assignment, except to the extent prohibited due to the restriction that all passengers of a group board the same apron bus. As noted above, Mixed-WilMA-RP-C is the best published method on boarding a two-door airplane with two apron buses (when the airplane and both buses are fully occupied); Mixed-WilMA-RP-C does not consider groups of passengers traveling together.

Objective

$$\text{Maximize}(\sum_{r\in R}\sum_{g\in G}(\mathrm{WA}_r*\mathrm{W}^{a}_{gr}+\mathrm{WB}_r*\mathrm{W}^{b}_{gr}) *\mathrm{X}_{g1}+(\mathrm{AA}_r*\mathrm{AA}^{a}_{gr}+\mathrm{AB}_r*\mathrm{A}^{b}_{gr})*\mathrm{X}_{g2}) -((\sum_{r\in R}\alpha s_r*S_r+\alpha e_r*\mathrm{E}_r)+0.05*(F+Z)) \quad (10)$$

Referring to Figure 2, observe that Mixed-WilMA-RP-C assigns the fewest passengers per row (two) to board the first apron bus to rows near the front (rows 1-9) and rear (rows 22-30) doors of the airplane, and the most passengers (six) to the four rows (14-17) nearest the middle of the airplane. These targets (TARGET$_r$) for the MIP of the number of passengers in each row to board the first apron bus are expressed in Table 2. Because of the symmetry of the two-door airplane, the target number of passengers to assign to the first row of the airplane (row 1) is the same as the target number of passengers to assign to the last row of the airplane (row 30). This is due to passengers seated in rows 1-15 entering the front door of the airplane and those seated in rows 16-30 entering the rear door of the airplane. Consequently, the targets and six objective function coefficients in Table 2 are the same for rows 1-15 as they are for the (parenthetical) rows 16-30. With Mixed-WilMA-RP-C, of the passengers boarding the first apron bus, the largest congestion (and thus the most delays from aisle interferences) will be encountered by those with seats in rows closest to the middle of the airplane.

Below we summarize the values in Table 2 of the objective function coefficients, and briefly hint at the thinking

TABLE 2. **The target number of passengers seated in each row to assign to the first bus and objective function coefficients for each row r of the airplane.**

Row $_r$	TARGET$_r$	αs_r	αe_r	WA$_r$	WB$_r$	AA$_r$	AB$_r$
1 (30)	2	0.10	0.60	0.58	0.02	0.74	0.05
2 (29)	2	0.15	0.57	0.61	0.03	0.71	0.06
3 (28)	2	0.20	0.54	0.64	0.04	0.68	0.07
4 (27)	2	0.25	0.51	0.67	0.05	0.65	0.08
5 (26)	2	0.30	0.48	0.70	0.06	0.62	0.09
6 (25)	2	0.35	0.45	0.73	0.07	0.59	0.10
7 (24)	2	0.40	0.42	0.76	0.08	0.56	0.12
8 (23)	2	0.45	0.39	0.79	0.09	0.53	0.15
9 (22)	2	0.50	0.36	0.82	0.10	0.50	0.18
10 (21)	3	0.40	0.40	0.85	0.20	0.40	0.20
11 (20)	4	0.35	0.40	0.88	0.26	0.35	0.15
12 (19)	4	0.40	0.32	0.91	0.27	0.30	0.12
13 (18)	4	0.50	0.25	0.94	0.28	0.20	0.08
14 (17)	6	0.50	1.0	0.97	0.35	0.0	0.0
15 (16)	6	0.70	1.0	1.0	0.40	0.0	0.0

underlying our intuition and conjectures. These values are somewhat arbitrary, but as we demonstrate below in section VI (Simulations and Results), the boarding times resulting from these objective coefficient values are much better than those of the benchmark method.

The values of αs_r and αe_r in Table 2 and in the objective function (10) penalize shortages (S_r) below and excesses (E_r) above the TARGET$_r$ in each row r. For a given value of TARGET$_r$, the penalty per passenger short (αs_r) increases the closer the row r gets to the middle (congested area) of the airplane. Conversely, for a given value of TARGET$_r$, the objective function penalty per passenger of excess (αe_r) decreases the closer the row $r$gets to the middle (congested area) of the airplane. Consider, for instance, that TARGET$_r$ has a value of two for both rows 1 and 9. Yet row 9 is adjacent to row 10, which has TARGET$_r$ of three. Consequently, in setting the values of αs_r and αe_r, we conjecture that shortages below the TARGET$_r$ of two in row 9 (which is close to row 10) should be penalized more severely than in row 1 (which is far from row 10 in which the TARGET$_r$ increases to three) and conversely regarding the penalization of excesses. If the MIP happens to assign three passengers in row 9 to the first apron bus, that seems less harmful than assigning three passengers to row 1.

Mixed-WilMA-RP-C assigns all windows seat passengers to the first bus and (nearly) all aisle seat passengers to the second bus. In the case when all three passengers sitting in the window, middle, and aisle seats of a particular row and side of the airplane are in the same group, there is no explicit incentive in the objective function (beyond the values of αs_r and αe_r) to assign those three passengers to either the first or second bus. However, if a window seat passenger is not sitting next to a member of the same group, then we prefer to assign that window seat passenger to the first bus (consistent with Mixed-WilMA-RP-C) and thus assign a reward weight (in the objective function) of WA$_r$ to the assignment of that passenger to the first bus. If a window seat passenger is sitting next to a middle seat passenger of the same group and the latter's adjacent aisle seat passenger is in a different group, then we assign a reward weight of WB$_r$ ($<$WA$_r$) from assigning that middle and window seat passenger to the first bus. Because Mixed-WilMA-RP-C favors congestion (more passengers from the first apron bus) towards the middle of the airplane, the values of WA$_r$ and WB$_r$ increase in Table 2 as the rows increase from 1 to 15 and decrease from rows 30 to 16.

For aisle seat passengers in rows 1-13 and in rows 18-30 (i.e., the rows that are not near the exact middle of the airplane), Mixed-WilMA-RP-C prefers to assign those passengers to the second apron bus. The values of AA$_r$ in table 2 reward the assignment of aisle seat passengers not sitting next to an adjacent middle seat passenger of the same group to the second bus by an amount that decreases the closer a row gets to the middle (congested) rows of the airplane where their assignment to the first bus would seem less harmful than those passengers closer to either airplane door. As with the other objective function coefficient values of Table 2, the values of AB$_r$ ($<$AA$_r$) are somewhat arbitrary. After we conducted the (time-consuming) simulation experiments, we realized that probably we could have done a better job in setting the values of AB$_r$. Exploring additional settings for the values of all of the objective function coefficients remains an opportunity for future research.

A final objective coefficient of 0.05 was chosen to lightly penalize any imbalance between the numbers of passengers boarding the front and rear halves of the airplane in each bus. We chose a low value for this objective coefficient because intuitively it does not seem as important as the other factors in the objective function.

IV. PASSENGER SEATING ASSIGNMENTS

This section describes how groups of passengers will be assigned to seats on the airplane. The proposed MIP-based and baseline methods will be compared in Section VI when using the same assignment of passengers to seats. Consequently, the intention of section IV is not to provide a novel method for assigning passengers to seats on an airplane. Rather our intention is to approximate a reasonable way in which each group of passengers may select their seats—given that when they select their seats (typically upon ticket purchase), some of the other seats on the airplane are already reserved by other passengers who previously selected their seats.

A. ASSUMPTIONS IN SEAT ASSIGNING

- All seats in the airplane will be occupied
- The next group of passengers (and its group size) to be assigned to a set of seats is selected at random; this mimics the situation of a particular group of passengers buying their airplane tickets and making their seat reservations at the time of ticket purchase
- In pre-emptive priority sequence (most important first):

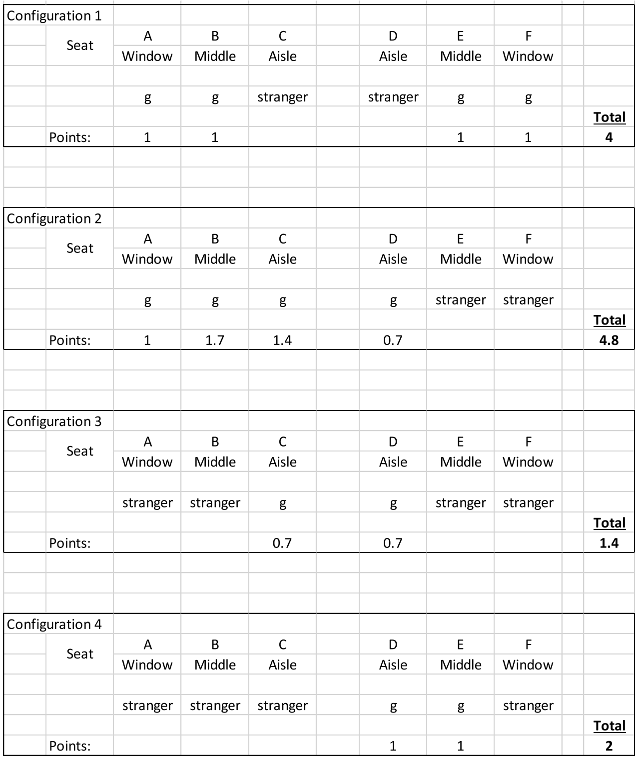
- Each particular group of passengers will have all its members seated among rows 1-15 (and boarding through the front door of the airplane) or all of its members seated among rows 16-30 (and boarding through the rear door of the airplane). This simplifies the boarding experience of the passengers
- Favor the assignment of a group of passengers to as few rows as possible
- Favor assignments in which many of the group's passengers have seats adjacent to other passengers in the group. A composite seating ''score'' is tabulated for possible seat configurations. Points are assigned to reflect the desirability of each passenger having at least one other passenger of the group in an adjacent seat and preferably two passengers of the group in adjacent seats (if the passenger is not in a window seat) and providing more points for adjacent seating on the same side of the aisle. The determination of the seating score is described further in the next subsection entitled, ''Determining scores for seating configurations''
- Favor the assignment of a group's passengers to rows that are close to the front of the airplane
- If there are equally good assignments (according to the above pre-emptive priority scheme), then select one at random

B. DETERMINING SCORES FOR SEATING CONFIGURATIONS

Points are allocated to various seating configurations. The general idea is to assign more points to the more favorable seating configurations. Table 3 provides the details of points allocated to an individual passenger P of a group depending on whether the seat(s) adjacent to him or her are occupied by member(s) of the same group or by stranger(s). One point is allocated to the situation where passenger P has exactly one person of the group sitting in an adjacent seat on the same side of the aisle. If passenger P is in an aisle seat and the only person of the group in a seat adjacent to P is sitting in the aisle seat on the other side of the airplane, then 70% of one point is allocated. One can debate whether 0.7 is the proper weighting for this. The idea is that the value of an adjacent traveling companion on the other side of the aisle is lower than the 1 point value of a traveling companion sitting in an adjacent seat on the same side of the aisle. If passenger P already has one companion sitting in an adjacent seat, then the value of a second companion sitting in an adjacent seat is less than the value of the first companion. As indicated, for example, in Table 3, the point value of a middle seat passenger P having adjacent companions from the same group on both sides of him or her is 70% more than the value of having only one adjacent passenger from the group (for a total of 1.7 points). There are several reasons for putting less emphasis (fewer points) for the second adjacent companion. With at least one companion in an adjacent seat, passenger P has somebody familiar with which to converse. When a group has more than two passengers, those passengers' approach to assigning those seats to individuals within the group is often not random. For instance, consider a four-passenger group consisting of a parent traveling with three children; if they must sit in two separate rows, then the parent may pair the two older children together or pair together the two children who enjoy each other's company the most.

TABLE 3. Seating points of passenger P depending on which adjacent seats are assigned to passengers in the same group as P.

Seat of passenger P	Seats adjacent to passenger P that are occupied by passengers in the same group	Points assigned to passenger P
Window	Middle	1
Middle	window only	1
	aisle only	1
	window & aisle	1.7
Aisle	middle only	1
	aisle only	0.7
	middle & aisle	1.4



Configuration 1

	A	B	C	D	E	F	
Seat	Window	Middle	Aisle	Aisle	Middle	Window	
	g	g	stranger	stranger	g	g	**Total**
Points:	1	1			1	1	**4**

Configuration 2

	A	B	C	D	E	F	
Seat	Window	Middle	Aisle	Aisle	Middle	Window	
	g	g	g	g	stranger	stranger	**Total**
Points:	1	1.7	1.4	0.7			**4.8**

Configuration 3

	A	B	C	D	E	F	
Seat	Window	Middle	Aisle	Aisle	Middle	Window	
	stranger	stranger	g	g	stranger	stranger	**Total**
Points:			0.7	0.7			**1.4**

Configuration 4

	A	B	C	D	E	F	
Seat	Window	Middle	Aisle	Aisle	Middle	Window	
	stranger	stranger	stranger	g	g	stranger	**Total**
Points:				1	1		**2**

FIGURE 3. Sample scores for various seating configurations of passengers in group g.

Figure 3 illustrates sample scores for a few seating configurations. Observe that Configuration 2 has a higher total (composite) score (4.8) than Configuration 1 (4.0) for a group of four passengers and thus is considered preferable. This preference is consistent with the experiences, preferences, and intuitions of the authors based on our personal situations when traveling. Although some travelers may have other

TABLE 4. **Maximum seating score possible as a function of the number of passengers in the group.**

N_g	MaxScorePossible
1	0
2	2 (two passengers adjacent on same side of airplane)
3	3.7 (three passengers adjacent on same side of airplane)
4	4.8 (see configuration 2)
5	6.5 (five passengers adjacent; one window seat available)
6	8.2 (six passengers consume the row)
7	8.5 (combines N_2 and N_5)
8	10.2 (combines N_2 & N_6 or equally good: N_3 & N_5)
9	11.9 (combines N_3 and N_6)
10	13.0 (combines N_4 and N_6)
11	14.7 (combines N_5 and N_6)
12	16.4 (consumes two rows; similar to 2 * N_6)

preferences, from the broader point of interpreting the conclusions of this paper, such subtleties of seating preferences do not appear to be important. For a group of two passengers, Configuration 4 has a higher total score (2) than Configuration 3 (1.4), reflecting the desirability of the two passengers sitting next to each other on the same side of the airplane.

C. METHOD TO DETERMINE SEAT ASSIGNMENTS

The method to determine seat assignments uses the pre-emptive priority sequence and makes the other assumptions as described in the previous section IV.A on Assumptions in Seat Assigning. The inputs and outputs of the method are described as follows.

Inputs:

- $g \in G$ (groups of passengers traveling together and individual passengers traveling alone in groups with the size of one)
- $r \in R$ (rows of the airplane)
- $s \in S$ ($|S| = 6$ representing six seats in each row r)
- N_g = Number of passengers in group g

Outputs

- $\text{Group\_Assigned\_to\_Seat}_{rs}$ = group number (g) of the passenger sitting in row r and in seat s
- Once $\text{Group\_Assigned\_to\_Seat}_{rs}$ has been determined for all rows r and seats s within each row, the following can be determined in a straightforward manner:
    - W_g = number of Window seat passengers in group g
    - A_g = number of Aisle seat passengers in group g
    - NR_{gr} = Number of passengers from group g sitting in Row r

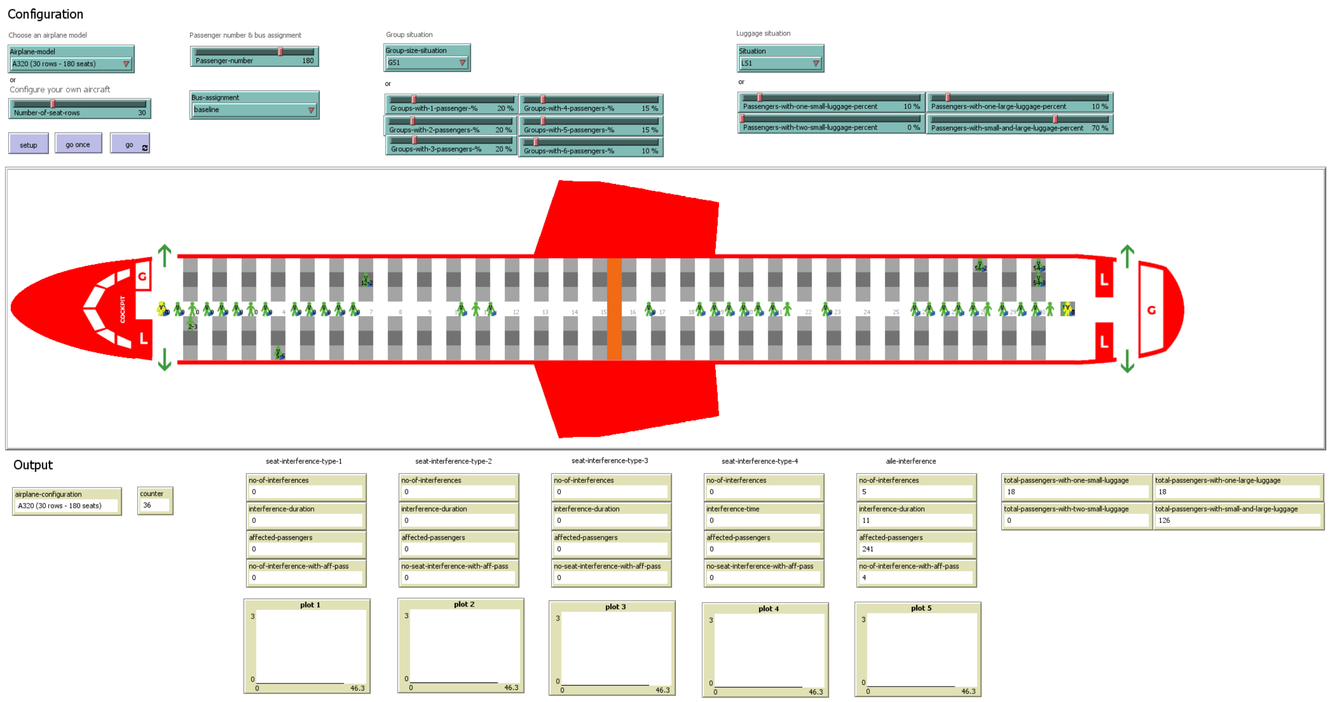
Method To Determine Seat Assignments

```
Until all groups of passengers have been assigned to seats do
    1. Randomly choose a group of passengers g from the list of groups
       containing passengers who have not yet been assigned to seats
    2. Nrows = 0
    3. NpassengersRemaining = $N_g$
    4. for each row r' in descending sequence of their number of unassigned seats until NpassengersRemaining < 1
        4a. Nrows = Nrows + 1
        4b. Reduce NpassengersRemaining by the number of unassigned seats in row r'
    5. end for
    6. Find the MaxScorePossible in Table 4 that corresponds to $N_g$
    7. MaxScoreAchievable = -1
    8. Set $r$ to the lowest numeric row (i.e. closest to the front door)
       that has at least one unassigned seat.
    9. while ($r < 31$) and(MaxScorePossible > MaxScoreAchievable) do
            [9a.] if it is possible to combine unassigned seats from row $r$ with additional seats available from any other combination of (Nrow − 1) rows—in the same half of the airplane as row $r$—to assign all $N_g$ passengers to available seats on those rows
            and if the total seating score of that combination is > MaxScoreAchieveable,
            then set MaxScoreAchievable to that total seating score and record that combination (set of rows) as the best combination of rows found
            end if
        9b. $r = r + 1$
    10. end while
    11. Assign group g's passengers to seat(s) in the best combination
        of rows found and within those rows, so that the highest total seating
        score results
End Until all groups of passengers have been assigned to seats
```

V. AGENT-BASED MODELING OF THE METHODS

The passengers' behavior while boarding into an airplane has been modeled using an agent-based modeling approach in NetLogo[34]. This software has been the choice for various researchers when modeling the human behavior in a series of applications developed in different research fields such as: transportation [35]–[38], education [39]–[41], evacuation [42]–[48], information diffusion and attitude change [49]–[51], social sciences [52]–[57], complexity and organizational learning [58]–[60], etc. Besides the graphical interface, the software offers several types of agents that can be configured to serve the research purposes.

For the airplane passengers' boarding case, in particular, two types of agents have been used in NetLogo: turtles for



Configuration

Choose an airplane model

Airplane-model: A320 (30 rows - 180 seats)

or

Configure your own aircraft

Number-of-seat-rows 30

Passenger number & bus assignment

Passenger-number 180

Bus-assignment: baseline

Group situation

Group-size-situation: GS1

or

Groups-with-1-passenger-% 20 %

Groups-with-2-passengers-% 20 %

Groups-with-3-passengers-% 20 %

Groups-with-4-passengers-% 15 %

Groups-with-5-passengers-% 15 %

Groups-with-6-passengers-% 10 %

Luggage situation

Situation: LS1

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-percent 70 %

Output

airplane-configuration: A320 (30 rows - 180 seats)

counter: 36

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: 5

interference-duration: 11

affected-passengers: 241

no-of-interference-with-aff-pass: 4

total-passengers-with-one-small-luggage: 18

total-passengers-with-one-large-luggage: 18

total-passengers-with-two-small-luggage: 0

total-passengers-with-small-and-large-luggage: 126

FIGURE 4. Graphical user interface while running a simulation step.

representing the passengers boarding and patches for designing the inside of the airplane (seats and aisles). Each type of agent possesses its own characteristics in accordance to the modeling purpose, as presented in the following.

A. AGENTS CHARACTERISTICS

For the patches, the characteristics in Table 5 have been considered [5], each patch having a size equivalent to 0.4 meters x 0.4 meters as suggested by [26], [61].

TABLE 5. Patches characteristics in the agent-based model.

Agent	Name of variable	Range / Value	Short description
Patch	pcolor	white / grey tones	Patches in white represent the aisle, while grey tones indicate 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.

The turtle agents receive the characteristics presented in Table 6. These characteristics and their range/value are the same as the one assumed in Delcea *et al.* [5] for the case of airplane boarding in the presence of two apron buses when no group has been considered. The only new characteristic is the ''group-index'' variable, which can take any value greater or equal to one. When equal to one, the model acts as in the case in which no group is considered and the boarding results are similar to the case in which each passenger boards individually. As before, the tick, namely the time unit in NetLogo, corresponds to 1.2 seconds [5].

The agent-based model created in NetLogo 6.1.0 is configurable, allowing several set-ups directly from the interface. The airplane model can be chosen from a selection of well-known airplane models, the number of passengers to board can be selected, the maximum size of the groups, the number of passengers carrying inside of the airplane, a particular type of luggage (small or large) or a luggage combination, and the number of passengers not carrying luggage inside the airplane. Also, the silhouette of the airplane is configurable if one desires to test a new type of airplane, not included in the airplane gallery.

The agent-based model graphical user interface (GUI) is presented in Figure 4.

In the output area, the duration of the boarding process is displayed using a monitor, allowing real-time performance evaluation. Even more, the number of aisle and seat interferences are provided in the output area and updated in real-time as the model runs.

B. ASSUMPTIONS ON RULES OF MOVEMENT

Regarding the assumptions made related to the rules of movement, it should be stated that the presence of two apron buses, having the capacity of 90 passengers, is considered.

TABLE 6. Turtles characteristics in the agent-based model.

Agent	Name of variable	Range / Value	Short description
Turtle	group-index	1, 2, …,	The group index can take any numerical value greater or equal to 1 and represents the maximum number of passengers that might be on a group. When equal to 1, the situation is similar to the case in which no group is considered.
	speed	[0, 1]	In the case in which the turtle agent has no other turtle agent in front of it and it has no luggage, the maximum speed can be up to 1 patch/tick, equivalent to 0.33 m/s when the turtle agent has no other turtle agent in front of it. This assumption is based on [26], [28], [62]. For the case in which the agent carries luggage, the speed drops between 0.6 patch/tick and 0.9 patch/tick. Also, when the passenger faces an interference, the passenger's speed drops to zero [4].
	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 [28], 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 [7].
	bus	0 or 1	The apron bus to which the passenger is assigned. 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 assigned 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.

TABLE 6. *(Continued.)* Turtles characteristics in the agent-based model.

Once loaded, each bus makes only one trip from the airport terminal to the airplane.

We also assume that the passengers are not confused and that, once arrived near the airplane, they do not miss the selection of the airplane door assigned to them for boarding. For this, we assume that either the airline clearly indicates on the boarding pass the door each passenger should select or that there are signs inside the apron buses that request the passengers select a specific door given their airplane seat's row and the configuration of the airplane they are boarding.

Once arrived near the airplane, we assume that the passengers from the first apron bus proceed to embarkment in a random manner considering the groups they belong too and the location of their seat in the airplane. We also assume that none of the passengers in the second apron bus, which arrives later near the airplane, do not skip the queue or force in any way their entrance in the airplane prior to any of the passengers arrived with the first apron bus.

Regarding the groups, we assume that the passengers belonging to a particular group board into the airplane in a sequence that avoids unnecessary seat interferences within the group. For example, a group of 3 passengers having the seats A, B and C in the same row, will enter the airplane following the ABC order, avoiding the interferences among their group.

The boarding time is measured in accordance with the research literature from the moment the first passenger enters the airplane until the final passenger sits. In our case, passengers enter through the front and rear doors of the airplane.

When the clock starts, at time zero the passengers belonging to the first apron bus proceed to their assigned seats, having their own walking speed depending on the type and number of luggage they carry inside the airplane.

Once an agent (i.e., passenger) arrives near the assigned seat, it is possible the agent will block the aisle to place its luggage, creating an aisle interference as none of the passengers located behind it cannot pass it. Depending on the type and size of luggage and the bin occupancy, the action of storing the luggage can take various amounts of time.

After storing the luggage, an agent can be involved in seat interference if it is in one of the cases presented in Figure 5. The time associated with each type of seat interference is consistent with the measures made in the field trials by Schultz [26]: 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. These values have been transposed in ticks in the agent-based model by dividing them with 1.2 seconds/tick and rounding them up to the nearest integer.

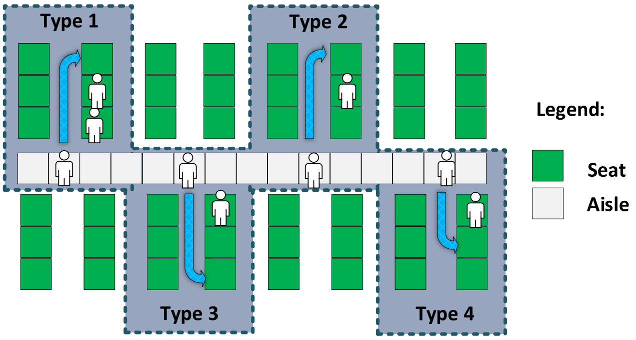


FIGURE 5. Types of seat interfaces.

VI. SIMULATIONS AND RESULTS

We use simulation and the agent-based modeling described above to test the performance of the MIP-based proposed method versus a baseline method.

The baseline method attempts to assign those groups of passengers sitting closest to the middle of the airplane to the first apron bus and the remaining passengers to the second apron bus so that each bus has 90 passengers. The final assignment that results will resemble the Back-to-front assignment of Figure 1. The baseline method begins by assigning to the first bus those passenger groups that have a passenger sitting in row 15 or 16 of the airplane. The method proceeds with a first priority of assigning groups that have an unassigned passenger with a seat in a row that is closest to the middle of the airplane and with a secondary priority of having an unassigned passenger in a window seat (most preferred), followed by middle seat (less preferred), and lastly aisle seat (least preferred). An assignment matching Figure 1 exactly may or may not be possible because: a group may have passengers sitting in multiple rows of the airplane, all passengers of a group are assigned to the same apron bus, and exactly 90 passengers are assigned to each bus. Further details of the baseline method are described in Table 7.

TABLE 7. Baseline method.

```
Baseline method assigning passengers to apron buses
Begin with all groups of passengers (including single-passenger groups) unassigned to apron buses
while the number of passengers assigned to the first bus < 90 do
    Find the set of row(s) containing an unassigned passenger in which the row is closest to the middle of the airplane
    Of those row(s), select an unassigned passenger who has a seat that is closest to the window
    Find the group g of that selected passenger
    if assigning all group g passengers to the first apron bus would result in 90 or fewer passengers in the first apron bus
    then assign all group g passengers to the first bus
    else assign all group g passengers to the second bus
    end if
end while
Assign all remaining unassigned passengers to the second apron bus
```

The determination of the simulation-generated parameters are in line with our previous research [7] and they refer to: passenger walking speed, the time needed to store the luggage, and the seat interferences times. We summarize the generation and calculation of these values below, while a more complete explanation can be found in [7].

Each passenger can be in one of the following situations regarding the hand luggage he or she carries inside the airplane: no hand luggage, 1 small bag, 2 small bags, 1 large bag, 1 small and 1 large bag. The speed of a passenger depends on the amount of luggage carried: the passengers having no luggage walk at a speed of 0.33 m/s as suggested by [26], [28], [62], while for the passengers with luggage, their speed will be randomly generated between 0.2 m/s and 0.3 m/s using the uniform probability distribution [7]. If a passenger closely follows a slower passenger, then the speed of the former passenger will slow to maintain the minimum distance between the passengers for their comfort—a distance equal to half of the row (0.4 m). Passengers cannot pass each other in the aisle.

Each seat interference might produce a boarding time delay depending on whether later-boarding passengers are affected. The average time of seat interferences—generated using a triangular distribution—is in line with Schultz [26], as presented above.

The aisle interferences time depends on the time needed for the passengers to store their luggage in the overhead compartment and has been determined by the following formula, as suggested by [63] and used by [5], [7], [11], [28]:

$$\begin{aligned} Tstore = {} & ((NbinLarge + 0.5\ NbinSmall + NpassengerLarge \\ & +0.5\ NpassengerSmall) * (NpassengerLarge \\ & +0.5\ NPassengerSmall)/2) * Trow \end{aligned}$$

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)

Various situations are tested. Seven different cases have been considered for the percentage of passengers carrying on board the amount of luggage as represented in Table 8 and suggested by [5], [7], [28]. For a given luggage situation, the number of passengers carrying a given combination of luggage is deterministically determined from Table 8; however, the individual passengers carrying the particular amount of luggage is determined randomly.

TABLE 8. **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
LS1	10%	10%	0%	10%	70%
LS2	15%	20%	5%	10%	50%
LS3	25%	20%	10%	15%	30%
LS4	35%	25%	10%	15%	15%
LS5	60%	10%	10%	10%	10%
LS6	80%	5%	5%	5%	5%
LS7	100%	0%	0%	0%	0%

Each of the considered cases in the following sections has been simulated 10,000 times using the BehaviourSearch Tool offered by NetLogo [64]. The results are rounded within the output tables but precise numbers are used in all calculations (including the calculations of percentages).

The comparison between the MIP-based proposed method and the baseline method is made first by considering different group size scenarios (as presented in sub-section A in the following), second by considering variations in the percentage of passengers traveling alone, while keeping the percentage of the remaining groups in equal proportions (as presented in sub-section B), and third by analyzing the number of seat and aisle interferences as provided in sub-section C.

A. ANALYSIS BASED ON DIFFERENT GROUP SCENARIOS

Simulations and analysis are conducted using passenger group sizes and probabilities for the scenarios in Table 9. The group size represents the number of passengers belonging to each of the six considered group sizes.

Based on the simulations, the average time to complete boarding is presented in Table 10 for each of the group size scenarios and luggage situations for both the benchmark baseline method and for the MIP-based proposed method.

TABLE 9. **Group scenarios.**

Scenario	Group size*					
	1	2	3	4	5	6
GS1	20%	20%	20%	15%	15%	10%
GS2	30%	20%	18%	12%	10%	10%
GS3	40%	18%	15%	10%	10%	7%
GS4	50%	16%	12%	8%	8%	6%
GS5	60%	14%	10%	7%	5%	4%
GS6	70%	10%	8%	5%	4%	3%
GS7	80%	6%	6%	4%	2%	2%

*Note: When generating group sizes, the next group of passengers to assign is chosen at random using the above table. However, after nearly 180 passengers have been assigned, the next randomly generated group size may be too high. For example, the next randomly chosen group size may be for 5 passengers when there are only 3 remaining open seats on the airplane. In that example, the method will assign 3 passengers to that final group of passengers.

Among all the considered situations, the longest boarding time results when 90% of the passengers are carrying luggage inside the airplane (luggage situation LS1) and when 80% of the passengers are travelling alone (group scenario GS7). In this case, the average boarding time when the MIP-based proposed method is used is 6 minutes and 39.6 seconds, which is 1 minute and 13.2 seconds shorter than that resulting from the benchmark baseline method.

The smallest boarding time is recorded when no passengers carry luggage (luggage situation LS7) and when the fewest passengers are traveling alone (group scenario GS1). The average boarding time is 2 minutes and 33.6 seconds when the proposed method is used, while by boarding using the benchmark baseline method, the average boarding time is 3 minutes and 3.6 seconds, which is 30 seconds longer than with the proposed method.

Considering all the situations listed in Table 10, we observe that the proposed method provides a reduction in average boarding time between 26.4 seconds (which is for GS1, LS5) and 1 minute and 13.2 seconds when compared to the benchmark baseline method.

Comparing the average boarding times listed in Table 10 based on the luggage situations, we observe that as passengers carry more luggage into the airplane, the longer the boarding takes (as expected).

For the baseline method, the results presented in Table 10 indicate that for each luggage situation, the time to complete boarding increases as more passengers travel alone (i.e. as group scenarios vary from GS1 to GS7). For the proposed method, the relationship between boarding time and group size is not as straightforward. For the proposed method, the fewer luggage carried aboard the airplane, the greater and more consistent is the increase in boarding time as more passengers travel alone. For instance, with no luggage (LS7), each increase in the percentage of passengers traveling alone (from 20% in GS1 to 80% in GS7) results in an increase in boarding time. However, with the most luggage

TABLE 10. Simulation results: average boarding time in seconds.

Scenario	Group boarding method	Luggage Situations						
		LS1	LS2	LS3	LS4	LS5	LS6	LS7
GS1	**Benchmark:** Baseline Method	434.4	379.2	336	296.4	265.2	236.4	183.6
	Proposed Method	396	344.4	303.6	267.6	238.8	208.8	153.6
GS2	**Benchmark:** Baseline Method	442.8	391.2	342	302.4	276	242.4	190.8
	Proposed Method	398.4	351.6	307.2	270	243.6	211.2	160.8
GS3	**Benchmark:** Baseline Method	446.4	394.8	350.4	312	278.4	250.8	200.4
	Proposed Method	399.6	350.4	310.8	270	243.6	217.2	166.8
GS4	**Benchmark:** Baseline Method	454.8	405.6	361.2	324	286.8	262.8	211.2
	Proposed Method	396	352.8	313.2	278.4	242.4	222	172.8
GS5	**Benchmark:** Baseline Method	462	414	370.8	328.8	301.2	273.6	229.2
	Proposed Method	400.8	358.8	320.4	279.6	254.4	226.8	181.2
GS6	**Benchmark:** Baseline Method	464.4	421.2	376.8	340.8	312	280.8	238.8
	Proposed Method	398.4	357.6	319.2	285.6	259.2	228	183.6
GS7	**Benchmark:** Baseline Method	472.8	427.2	391.2	351.6	328.8	298.8	259.2
	Proposed Method	399.6	358.8	320.4	286.8	262.8	235.2	188.4

TABLE 11. % of time improvement of the proposed method compared to the baseline method.

Scenario	Luggage Situations						
	LS1	LS2	LS3	LS4	LS5	LS6	LS7
GS1	8.84%	9.18%	9.64%	9.72%	9.95%	11.68%	16.34%
GS2	10.03%	10.12%	10.18%	10.71%	11.74%	12.87%	15.72%
GS3	10.48%	11.25%	11.30%	13.46%	12.50%	13.40%	16.77%
GS4	12.93%	13.02%	13.29%	14.07%	15.48%	15.53%	18.18%
GS5	13.25%	13.33%	13.59%	14.96%	15.54%	17.11%	20.94%
GS6	14.21%	15.10%	15.29%	16.20%	16.92%	18.80%	23.12%
GS7	15.48%	16.01%	18.10%	18.43%	20.07%	21.29%	27.31%

TABLE 12. Scenarios for variations in travelling alone group.

Scenario	Group size*					
	1	2	3	4	5	6
G1-SG1	20%	16%	16%	16%	16%	16%
G1-SG2	40%	12%	12%	12%	12%	12%
G1-SG3	60%	8%	8%	8%	8%	8%
G1-SG4	80%	4%	4%	4%	4%	4%
G1-SG5	100%	0%	0%	0%	0%	0%

*Note: When generating group sizes, the next group of passengers to assign is chosen at random using the above table. However, nearly 180 passengers have been assigned, the next randomly generated group size may be too high. For example, the next randomly chosen group size may be for 6 passengers when there are only 2 remaining open seats on the airplane. In that example, the method assign 2 passengers to that final group of passengers.

scenario (LS1), increasing the percentage of passengers traveling alone (from GS1 to GS7) results in three increases in boarding time and three decreases in boarding time. These results inspire further investigation of the impact of group size variations on boarding time in the next subsection.

In percentage terms, the average boarding time improvement from using the proposed method versus the baseline method varies from 8.84% (for GS1—20% of passengers traveling alone, LS1—heavy luggage) to 27.31% (for GS7—80% of passengers traveling alone, LS7—no luggage), depending on the combinations of luggage and group situations, as presented in Table 11

B. ANALYSIS OF FURTHER GROUP VARIATIONS

We examine further variations in passenger group sizes and the resulting impact on the time to complete boarding of the airplane. We conduct this analysis for the no luggage situation (LS7) for both the proposed and baseline methods. Table 12 contains five group size scenarios in which the percentage of passengers travelling alone varies from 20% to 100%, while keeping a proportionally equal percentage of passengers for the other five group sizes.

The results of these simulations are in Table 13. We observe an increase in boarding time as more passengers travel alone (varying from G1-SG1 to G1-SG5). Furthermore, by comparing the results in Table 13 with the average boarding times previously listed in Table 10 for the same luggage situation, namely LS7, for the scenarios in which the number of groups with travelling alone passengers are the same, e.g. GS1 vs. G1-SG1, GS3 vs. G1-SG2, GS5 vs. G1-SG3, GS7 vs. G1-SG4, for both the proposed method and the benchmark baseline method, we observe that as the number of groups with more passengers increases, the average boarding time decreases. This relationship may stem from the fact that a series of seat interference situations disappear as the members of a group enter the airplane in the best sequence, namely in a group in which the passengers have all the seats in a seat-row on one side of the aisle, first the passenger

TABLE 13. Average boarding time results for variation in the number of passengers travelling alone.

Group boarding method	Scenario				
	G1-SG1	G1-SG2	G1-SG3	G1-SG4	G1-SG5
Benchmark: Baseline Method	181.2	195.6	219.6	252	303.6
Proposed Method	152.4	159.6	170.4	184.8	196.8

entering in the airplane will be the one with a window seat, followed by the passenger with the middle seat, and last the passenger having the aisle seat. A more detailed analysis in terms of seats and aisles interferences is provided in the next sub-section.

C. ANALYSIS OF SEAT AND AISLE INTERFERENCES

We conduct a seat and aisle interference analysis to provide an overview of the passengers' comfort when the proposed method is used instead of the benchmark baseline method. The motivation for this analysis is stated by Zeineddine [23] and used in Delcea et al. [5] for discussions regarding the best performing method's ability to increase the passengers' comfort while boarding. The luggage situation LS1 is considered along with the group scenarios GS1-GS7.

The average number of seat and aisle interferences with affected passengers are reported in Table 14. The term "affected passengers" refers to later-boarding passengers who are delayed because of an interference; when no later-boarding passenger is delayed, no interference is recorded in Table 14.

From Table 14, we observe that the proposed method results in more aisle interferences, fewer seat interferences of Types 1, 3, and 4, and generally (depending on the test case), more seat interferences of Types 2 than resulting from the baseline method. First we discuss the per-flight seat interferences.

The proposed method has Type 1 seat interferences ranging between 1 and 1.6 interferences per flight, in comparison with the baseline method interferences ranging between 2.9 and 8.4 interferences per flight. We note that Type 1 seat interference is the interference causing the highest passenger waiting time among the four types of seat interferences and also the one causing the highest disturbance to the passengers as two of the passengers located in the aisle and middle seats need to exit their seats to make space for the passenger having the seat near the window to proceed that seat. Thus, a reduction in the number of Type 1 seat interferences produces both a reduction of average boarding time and a more pleasant boarding experience for the passengers.

Regarding Type 2 seat interference, we observe from Table 14 that the number recorded with the proposed method is lower when compared to the baseline method for the GS6 and GS7 scenarios and higher in the GS1-GS5 scenarios. We note that these differences are not as significant as with the Type 1 interferences.

TABLE 14. Average number of seat and aisle interferences for LS1.

Scenario	Boarding methods	Average number of aisle interfer-ences*	Average number of seat interferences that block a later boarding passenger*			
			Type 1	Type 2	Type 3	Type 4
GS1	**Benchmark:** Baseline Method	124.4	2.9	0.2	4.1	2.7
	Proposed Method	125.9	1	0.4	2.8	1.1
GS2	**Benchmark:** Baseline Method	124.2	3.4	0.4	4.4	3.4
	Proposed Method	125.6	1.1	0.9	3.1	1.5
GS3	**Benchmark:** Baseline Method	122.5	4.3	0.8	4.6	4
	Proposed Method	124.4	1.1	1.2	3.6	2.4
GS4	**Benchmark:** Baseline Method	121.9	5.2	1	4.6	4.8
	Proposed Method	122.9	1.2	1.5	3.8	3.4
GS5	**Benchmark:** Baseline Method	118.6	6.1	1.8	5.1	6.6
	Proposed Method	120.1	1.3	2.2	4.2	5.0
GS6	**Benchmark:** Baseline Method	115.6	6.9	2.7	5	7.8
	Proposed Method	117.8	1.5	2.5	3.9	6.7
GS7	**Benchmark:** Baseline Method	111.4	8.4	3.7	5.5	10.5
	Proposed Method	114.1	1.6	3.3	4.0	9.1

*the seat and aisle interferences' numbers refer only to the occurrences in which affected passengers have been delayed by these interferences.

Type 3 and Type 4 seat interferences produce the same waiting time as both of them require that the passenger located in the aisle seat should depart his/her seat to clear the path for a later-arriving passenger having the window or middle seat. Therefore, we will analyze both of them by summing up the values in the last two columns of Table 14. As a result, we observe that in all the cases, the number of Type 3 and Type 4 seat interferences is greater when the baseline method is used, ranging between 6.8 and 16 interferences per flight. For the proposed method, the number of Type 3 and Type 4 seat interferences is reduced by up to 42.65%, ranging between 3.9 and 13.1 interferences per flight.

By analyzing the number of aisle interferences with affected passengers, we observe that more aisle interferences resulting from the proposed method than from the baseline method with a difference of up to 2.7 interferences per flight. We conjecture this increase in aisle interferences may stem from the increased congestion near the middle of the airplane for those passengers boarding the first apron bus when the proposed method is used. Recall that the proposed method uses a MIP with targets of passengers boarding the first apron bus determined by the Mixed-WilMA-RP-C method. With the latter method having six passenger per row in rows 14-17 (the most middle rows), high congestion (and thus aisle interferences) would be expected for passengers boarding the first apron bus who have seats near the middle of the airplane.

Considering all the seat and aisle interferences, we conclude that the proposed method produces less interference delays than the baseline method. As a result, the average boarding time is smaller when using the proposed method than with the baseline method. Also, the passengers' boarding experience is more pleasant with the proposed method due both to the reduced impact of interferences and to the reduced boarding time.

VII. CONCLUDING REMARKS

In this paper, we propose a mixed integer programming (MIP)-based boarding method that can be used when groups of passengers (e.g. families) travel together and transfer from the aiport terminal to the airplane using buses. An agent-based model is created in NetLogo 6.1.0 to test the proposed method against a baseline method that resembles Back-to-front boarding. We assume that the passengers of a particular group board the same apron bus and sit near each other on the airplane. We further assume that the two-door airplane and two apron buses are fully occupied.

Simulations results indicate the proposed method results in an improvement in the overall boarding time of up to 27.31% compared to the benchmark baseline method. Furthermore, in all the considered cases, the proposed method results in faster average boarding times than the baseline method. This time improvement ranges between 26.4 and 73.2 seconds per flight. Considering an average cost of boarding delay of $53.5 per minute [29], [30] and by considering all the luggage and group situations, an average cost reduction of up to $65.27 per flight is attained when the proposed method is used instead of the benchmark method. Given the number of flights in all the world's airports where apron buses are used, and the predictions related to their increasing trend, the value of this potential cost reduction is considerable.

From the passengers' point of view, the proposed method is consistent with them boarding an apron bus with their fellow group members and sitting near each other on the airplane. Passenger satisfaction should increase by the proposed method minimizing the time to complete boarding of the airplane. Furthermore, the reduced number of seat interferences they face when the proposed method is used compared to the benchmark method should have a positive impact on them having a pleasant boarding experience.

One limitation of this paper is that we assume—for both the MIP-based and baseline methods—that all passengers of a group would be sitting in the same half of the airplane (either in rows 1-15 or in rows 16-30). This assumption may not be universal in practice because there may be groups containing passengers who are seated close to each other but in different rows of the airplane (e.g. a group with passengers seated in both row 15 and row 16). Consequently, relaxing this assumption is an opportunity for future research.

Additional research opportunities include investigation of alternative values of the MIP's objective coefficients. In particular, it may be possible to propose function(s) in which some of the objective coefficients may be parameterized by the airplane seating row number and thereby determine their values. Additional investigation could be conducted to extend and adjust the proposed method to work well with partially occupied apron buses and partially occupied airplanes. Alternative airplane configurations provide additional opportunities for future research.

The paper is accompanied by videos made for group scenarios GS1 through GS7 for the no luggage situation (LS7), for the baseline method and proposed MIP method. The videos can also be accessed at the following link: https://github.com/liviucotfas/airplane-group-boarding-apron-mip

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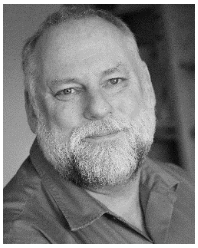

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