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The Impact of Effectiveness of Luggage Arrangement on the Airplane Passengers' Boarding Process

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Abstract

The boarding process is the role activity to maintain the airline's efficiency in the turnaround process on the ground. One of the scenarios to optimize the boarding process is the arrangement of passengers who enter the plane based on the amount of carry-on luggage, adjusted to the selected boarding strategy. This research aims to develop an agent-based simulation model to increase the effectiveness of passengers' boarding process by applying the luggage arrangement method for an airplane with a 180-seat configuration. The simulation results showed that applying the Ascending luggage arrangement method reduced the overall boarding process performance by 6.12%, while the Descending method increased boarding performance by 2.50%, compared to the standard Random method.

Keywords

agent-based simulation, aviation industry, luggage arrangement method, wave strategy, sensitivity analysis

1 Introduction

The aviation industry is crucial to global economic recovery from the impacts and effects of the Covid-19 pandemic. The existence of the aviation industry facilitated tourism, trade, support of millions of jobs, and encouraged sustainable development in various other industrial sectors. Since the first dose of the Covid-19 vaccine was given in late 2020 and shipped to more than 180 countries (Edwards and Orenstein, 2021), it has provided a sign of recovery and hope for a return to some sort of normality in the near future. Through a complete Covid-19 vaccine certificate (full dose) as a travel requirement (Oktari and Adrian, 2021), herd immunity will be reached and the pandemic will ease, so the aviation industry may recover and return stronger. The shift from the new normal to the normal period will bring air traffic volumes that exceed the previous one. Just like before the Covid-19 pandemic, the highest passenger traffic is predicted to be contributed by low-cost airlines, where all seats are set as the economy class (Pan and Truong, 2018; Picardo, 2020; Stalnaker and Usman, 2020).

The profit margins at the aviation industry is appealingly slim even in its best season. The industry provides vital services with a capital-intensive business that requires high operating costs that make the profit scarce. The 'lower possible operating cost' of the airline's business model can be achieved by performing time efficiency in activities related to turnaround and minimizing potential delay. The actual figure of the delay cost may vary between airlines depending on their company's cost structure, with an estimate of €80 for every five-minute delay of an A320 type airplane (Achenbach and Spinler, 2018). Many European airlines achieved a mean delay of 15 minutes during the turnaround (Rosenow and Schultz, 2018). It provides a significant savings impact if the potential delay can be minimized.

Previous research found that the passenger boarding process is the most time-consuming activity that can be account for more than 60% of the total turnaround time (Giitsidis and Sirakoulis, 2016). The boarding process has been a topic of discussion since the late 1970s due to the decreasing average speed of passengers boarding the airplane. This decreasing average boarding speed is mainly contributed by the increasing numbers of passenger carry-on luggage brought to the cabin, inefficient boarding strategy applied by the airlines, and passenger demographic changes related to their composition and behavior (Marelli et al., 1998). Airlines must increase the efficiency of the boarding process since they have limited control over passengers and the entire turnaround

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process (Jafer and Mi, 2017; Soolaki et al., 2012; Steiner and Philipp, 2009). From a business perspective, the faster completion of the boarding process will not only have an impact on the long-term performance of the airlines but also on customer satisfaction and airport management, which can offer more services without the need to invest in new infrastructure (Dorndorf et al., 2012; Jaehn and Neumann, 2015; McGraw, 2017; Schmidt, 2017).

In general, the length of boarding time is influenced by many factors such as passenger load factor, aircraft seat configuration, boarding strategy, queueing order, amount of carry-on luggage, passenger movement velocity, and so on. The airlines should consider efforts to minimize time operations while on the ground. One of the scenarios that optimize the boarding process is the arrangement of passengers who enter the plane based on their amount of carry-on luggage, which is adjusted to the chosen boarding strategy.

The use of simulation provides various alternative improvements compared to real-world experiments in the field. Simulation modeling provides a systematic comparison to conclude the best solution to maintain system efficiency. Scholars have provided various simulation models to design an effective boarding strategy, including discrete event simulation (van den Briel et al., 2005; Zeineddine, 2017), cellular automata (Giitsidis and Sirakoulis, 2016; Qiang et al., 2014; Qiang et al., 2018; Schultz, 2018a; Schultz and Soolaki, 2021), agent-based simulation (Cotfas et al., 2020; Delcea et al., 2018b; Iyigunlu et al., 2014; Nugroho et al., 2021), Monte Carlo simulation (Steffen, 2008), and others. Here, this research aims to develop an agent-based simulation model to measure the effectiveness of passengers' entry sequence with the three luggage arrangement methods, namely Random, Ascending (L1L2L3), and Descending (L3L2L1), adjusted to the selected boarding strategy. None of the studies have considered the boarding situation in which the passengers' entry sequence strategy was combined with these three kinds of luggage arrangement methods. In this way, perhaps the authors could optimize each boarding strategy for achieving their best boarding time and offer airlines the fastest boarding solutions to implement.

2 Research method

2.1 Boarding strategy by considering passenger's carry-on luggage

The main topics of discussion lead to the nine boarding strategies, which have rules as described below:

1. Random (RD) strategy: In this method, passengers enter the plane randomly as passengers will be in the real world. It is the simplest strategy that does not require much cost for implementation (Giitsidis and Sirakoulis, 2016). This model also serves as a basis for capturing the real-world operations in boarding time. In common, most airlines apply a random strategy that does not face any specific issues in the effectiveness of the passenger boarding process.
2. Back-to-front (BF) strategy: This is the most widely used boarding strategy by the airlines. Passengers are grouped into several groups and come to board the plane based on the call order of the group number. In the first call, the group that occupies the seats in the rear of the plane starts the boarding process and this continues to the front seats. This scheme aims to minimize aisle interference by reducing the length of queues to make passengers in accessing their respective seats as quickly as possible. By using a stochastic cellular automaton model, Schultz concluded that BF is the most efficient strategy if two boarding blocks are used (Schultz, 2018b; Schultz et al., 2008).
3. Rotating-zone (RZ) strategy: Passengers are grouped into several and come to the plane based on the call order of the group number. This call is started by the group which occupies the seats in the front, after that the one in the rear, and finally the one in the middle zone (Mas et al., 2013). This scheme will not interfere with the passenger seats in the front and rear zone.
4. Outside-in (OI) strategy: This scheme divides passengers into three groups based on seating position, including the window seat, the middle seat, and the aisle seat. It is also called Window-Middle-Aisle or WILMA (Iyigunlu et al., 2014). This strategy eliminates seat interference and minimizes the waiting time in aisle interference.
5. Reverse-pyramid (RP) strategy: This strategy was introduced by van den Briel et al. (2005) and was designed as a hybrid strategy of OI and BF strategies. The passengers come to the plane following the "V" scheme, starting with the rear windows, middle seats, rear aisle, and finally, front window seats. However, this strategy aims at minimizing seat interference and reducing aisle interference time in a complex model.
6. Steffen Optimal (SF) strategy: This strategy identified that one of the main factors to plane delay time

is the length of time taken by passengers to store the carry-on luggage in the overhead-bin. Steffen (2008) divided passengers into a strictly defined sequence by applying one seat-row spacing between passengers. The model is started with the window seats from the back to the front part and then the middle and finally the aisle seats. This model provides sufficient space for passengers to put their belongings simultaneously, so the duration of boarding time is minimized.

7. Steffen Modified-optimal (MO) strategy: This strategy improves the impracticability of the previous SF method, so it is also known as the Practical Optimal method (Jafer and Mi, 2017). In this model, passengers are broken down into four groups. The groups of which the first queue to enter the plane is the right side with odd-numbered rows, followed by the left side with odd-numbered rows, the right side with even-numbered rows, and finally, the left side with even-numbered rows.
8. Wave-seat (WS) strategy: This is the realization of the 'Wave' strategy through the seat-assignment approach. This strategy was introduced by Nugroho et al. (2021), where passengers enter the plane in a strictly defined sequence and fill the seats starting from the rearmost, followed by others at the front across the aisle with an adaptable seat-row distance that forms a design like 'wave frequency'. The adaptable model is possible to be applied if the number of seat rows is unique. Moreover, this concept is also combined with the order of entry starting from the window, middle, and aisle seats. The WS strategy is designed so that passengers can put their belongings in a sufficient space.
9. Wave-group (WG) strategy: This is the realization of the 'Wave' strategy through the group-assignment approach. This strategy was also introduced by Nugroho et al. (2021), where passengers are broken down into six groups and board the plane based on the call order of the group number. The entering queue is the following: window, middle, and aisle positions. Passengers will fill the seats on the left and right sides of the aisle with alternating rows, which forms a 'wave frequency'. The WG strategy of filling passenger seats on the left and right sides of the aisle forms alternating odd-even configurations.

To the best of the authors' knowledge, most of the literature only discussed the boarding process with luggage arrangement in Random method. None discuss it by comparing it with two other methods, Ascending (L1L2L3) and Descending (L3L2L1).

2.2 Agent-based modelling

This research designs a simulation of airplane passengers' boarding process using agent-based modeling (ABM) which has a computational modelling approach. This approach has the ability to describe agents' behavior to easily develop real-world conditions. The ABM methodology encodes the agent behavior in simple rules; therefore, the agent's interactions are identified. This approach also describes a wide variety of real-world processes and phenomena (Wilensky and Rand, 2015). It is also ideal to be applied in the airplane passengers' boarding process simulation.

NetLogo 6.1.1 is a complete tool for simulations that provides a friendly user interface, visualization of real-time agent interactions, integrated graphics, and fairly good execution speed. The simulation modeling in this research used NetLogo version 6.1.1 software with two-dimension visual approach. With this concept, all parties easily understand and can operate the system, including those who are not experts in the field.

Agents in ABM simulation using NetLogo version 6.1.1 has four categories as follows:

- Turtles, agents who move in the simulation world.
- Patches, grid-shaped agents where turtles can move in a unit area.
- Links as agents that connect between turtles if there is a relationship between them.
- The observer is someone who sets the rules for manipulating all agents in the world.

Here, to obtain the output representing the real-world situation, several formulas have been adapted, with reference to the field experiment test data from the previous studies in the field. This study may represent the real-world problem of the airplane boarding issues, and it is also possible to be applied to achieve the effectiveness of the passenger boarding strategy.

By using ABM simulation in this research, the following advantages are obtained:

- ABM provides cost-effective and time-saving approach for many research models since the software is free and provides an open-source programming language for simulation.
- ABM allows us to see how the passenger boarding model develops over time because the data is generated during the simulation.

- In ABM, the population is represented by a heterogeneous set of agents with their characteristics and rules of action, thus providing the most natural way to describe and simulate models.
- In ABM, emergent phenomena can result from interactions of individual entities that make it difficult to predict, thus making the simulation output fair, acceptable, and close to reality.
- ABM also provides a flexible framework for tuning the complexity of the agents, such as behavior, rules of interactions, degree of rationality, and ability to learn and evolve.

2.3 Parameters of airplane passenger boarding model

The variables and parameters considered for the airplane passengers boarding simulation models are presented as follows.

2.3.1 Passenger load factor (LF) model

The passenger load factor has a role in determining the airline's business performance. To measure the effectiveness of each of the nine boarding strategies mentioned above, this research simulates the passenger boarding process with a load factor (LF) of 70%, 80%, 90%, and 100% using a Random luggage arrangement scenario. The composition of these load factor levels is considered sufficient to represent the volumes that exceed the previous new normal period, which is in the range of 66.7% (Barnett and Fleming, 2020; Nugroho et al., 2021). An airplane with a 100% LF is the benchmark to consider the effectiveness of the boarding strategy. In this case, the acquisition data is also used as a reference in formulating assumptions and the basis for calculations in other situations.

Therefore, if the performance of each boarding strategy shown in four different load factor levels is in a stable sequence, then the resulting simulation output with a load factor of 100% will be used as a baseline data to be compared with two other luggage arrangement scenarios, namely Ascending and Descending methods. Thus, these two other luggage arrangement scenarios will be tested only at a LF of 100% to anticipate the increase in air traffic volume during the transition from the new normal to normal period.

2.3.2 Passenger movement model by considering the amount of carry-on Luggage

In previous studies, Van Landeghem and Beuselinck (2002) and Qiang et al. (2014) achieved 2.4 seconds as modus value when passengers pass through each seat-row using a triangular distribution calculation. In this simulation, A time step will correlate to 2.4 seconds of the absolute boarding time in this simulation. Moreover, for the passenger movement model, each agent is initially set at the left front door and comes to the plane at seven seconds interval. Agents come through the aisle with zero and one patch per tick (unit of time).

In this research, each of the nine boarding strategies, as mentioned earlier, was implemented with passengers' entry setting based on their carry-on luggage. Here, the passenger boarding process is carried out by applying three different luggage arrangement methods: Random, Ascending, and Descending. In the Random luggage arrangement method, the boarding process is carried out without sequential entry rules according to the number of passenger carry-on luggage or in random order. Meanwhile, in the Ascending luggage arrangement method, the passenger boarding process is carried out with sequential entry rules, starting from the passengers with one piece of luggage (L1), followed by those carrying two pieces of luggage (L2), and ending with those carrying three pieces of luggage (L3) so it is called as the L1L2L3 sequence. On the other hand, in the Descending luggage arrangement method, the passenger boarding process is carried out with sequential entry rules, starting from the passengers with three pieces of luggage (L3) followed by those carrying two pieces of luggage (L2), and ending with those carrying one piece of luggage (L1) so it is called as the L3L2L1 sequence.

2.3.3 Bin occupancy model

In the case of airlines where all seats are in economy class only, most passengers will carry-on the luggage into the cabin. It happens because of the implementation of paid baggage policy in the case of several low-cost airlines, the time-consuming baggage picking process at the arrival terminal, and the burglary risk of passenger belongings stored in the baggage, especially for the zippered suitcases model (Musofa et al., 2021). It is assumed that passengers carry belongings with the amount ranging from one to three. The predefined percentage distribution is presented in Table 1. Table 1 is adapted from Qiang et al. (2014)

Table 1 Luggage distribution

Boarding load condition	Distribution		
	1L	2L	3L
High-load condition	20%	60%	20%
Normal-load condition	60%	30%	10%
Low-load condition	80%	10%	10%

and Nugroho et al. (2021), which is considered ideal to be applied, especially for airlines operating in the Southeast Asian region, such as in Indonesia.

Due to the limitations of the simulation in displaying the bin occupancy model, the visualization of the passenger carry-on luggage is illustrated by three different patch-colors on the left and right sides of each seat-row. The distribution view of passenger's carry-on luggage on the overhead-bin is defined and assumed as below:

- 1L (pink): the passengers store a 20-inch suitcase.
- 2L (magenta): the passengers store a 20-inch suitcase and a goodie bag.
- 3L (violet): the passengers store a 20-inch suitcase, a goodie bag, and a laptop bag.

Suppose N_e is the number of luggage stored in the overhead-bin and N_i is the number of luggage that the passengers had carried on; therefore, refer to Qiang et al. (2014), the time of the passengers put their carry-on luggage in the overhead-bin (t_i^{store}) is showed in Eq. (1). It also correlates to the time step in the simulation modeling development.

$$t_i^{\text{store}} = 1.5 + \frac{10N_i}{\left[10-\left(N_e+N_i\right)\right]}, \quad N_i \geq 1 \tag{1}$$

Once the passenger has stored all of their luggage into the overhead-bin, ideally, they pause to take a breath and transition to the next step. Therefore, in this research, we also define a transition time ($t_i^{\text{transition}}$) with a duration of two seconds or one time-step.

2.3.4 Passenger seating model

During the boarding time, delays can appear due to interference condition consisting of aisle and seat interference. Aisle interference is when a passenger blocks the access of other passengers who want to go to their seats due to storing belongings to the overhead-bin. Seat interference is a passenger must wait for other passengers to clear the way to the designated seat. Four possible conditions of seat interference are depicted in Fig. 1.

Referring to the field experiment tested by Schultz (2018b), the type-one is possible to block the aisle for 20–26 seconds, while the type-two for 10–14 seconds. Further, Qiang et al. (2017) found that the time durations were seven seconds for each type-three and type-four seat interferences.

In order to minimize the seat interferences and to set them closer to the output of the literature, this research adapted Qiang et al. (2014, 2018) for determining the time of the passengers moving from the aisle to the respective

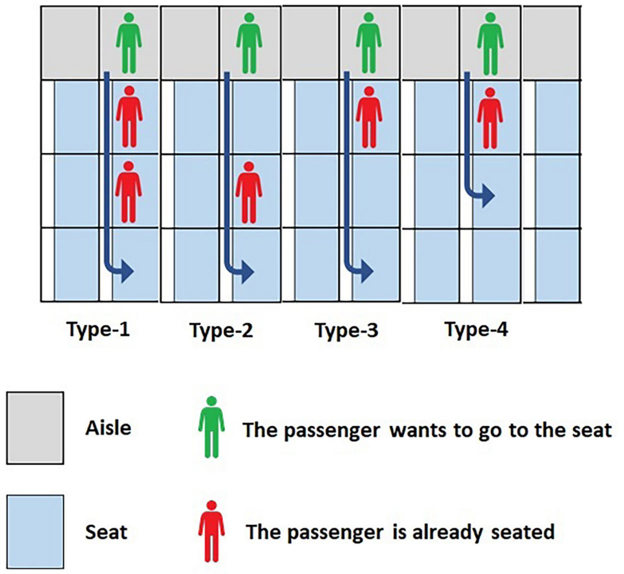


Fig. 1 Seat interference condition; Adapted from: Delcea et al. (2018a)

seats (t_i^{seat}). Suppose that M_i is the number of seat interference in the cabin and t_d is the delay for the passenger to sit in the respective seat (about one time-step), then the time for the passenger to move from the aisle (t_i^{seat}) is shown in Eq. (2). Using Eq. (2), seat interferences (t_i^{seat}) using simulations are shown in Table 2.

$$t_i^{\text{seat}} = 1.5\left(1+2M_i\right)+t_d, \quad M_i \geq 1 \tag{2}$$

In other conditions, the required time to shift from the aisle to the respective seats (t_i^{seat}) without any seat interference follows the steps of the passenger's steps, as shown in Table 3. The output is rounded to the nearest integer.

Thus, the total time required by the passengers to clear the aisle and move to their respective seats ($t_i^{\text{on-row}}$) corresponds to Eq (3).

$$t_i^{\text{on-row}} = t_i^{\text{store}} + t_i^{\text{transition}} + t_i^{\text{seat}} \tag{3}$$

Table 2 Seating time under seat interference

Type of seat interference	Seating time (t_i^{seat})	
	Time-step	Time in second
Type-1	9	22
Type-2	6	14
Type-3	3	7
Type-4	3	7

Table 3 Seating time without seat interference

Passenger's position	Seating time (t_i^{seat})	
	Time-step	Time in second
Near the aisle	1	2
Middle	2	5
Near the window	3	7

where:

- t_i^{store} = Time for passengers to put their carry-on luggage in the overhead-bin.
- $t_i^{transition}$ = Time for passengers to take a breath and make transition from t_i^{store} to t_i^{seat} (about one time-step).
- t_i^{seat} = Time to move from the aisle to the respective seats.

2.3.5 Data acquisition and analysis model

In this research, three different scenarios of passengers' entry settings based on their carry-on luggage were simulated to determine which solution is the best, including the Random method, Ascending method (L1L2L3), and Descending method (L3L2L1). For the boarding process that uses a Random luggage arrangement method, 300 samples were taken from each of the nine boarding strategies under three load conditions, high, normal, and low load, respectively. Since it was applied in four different LF levels, including 70%, 80%, 90%, and 100%, respectively then, a total of 10,800 samples were collected. Suppose the performance of each boarding strategy shown at these four different load factor levels is in a stable sequence. In that case, the resulting simulation output with a LF 100% will be used as baseline data to be compared with two other luggage arrangements scenarios, namely Ascending method (L1L2L3) and Descending method (L3L2L1). In these two luggage arrangement scenarios, 300 samples were also taken from each boarding strategy under three different load conditions, therefore, 5,400 samples were collected.

Furthermore, the collected simulation outputs were processed using descriptive and sensitivity analysis. Descriptive analysis is a statistical technique used to identify patterns and generate insights from a sample data set. A descriptive statistic presents the data using graphs, histograms, and diagrams. The sensitivity analysis is necessary to determine the difference between independent variables that affect the particular dependent variable. This approach is applied within certain limits based on the defined input variables which will affect the overall boarding time such as load factor of the passengers, aircraft seat configuration, selected boarding strategy, queueing order, the number of carry-on luggage, and passenger movement velocity. The effectiveness of luggage arrangement in the boarding process is achieved when the developed boarding strategy has the highest frequency distribution of minimum boarding time of the entire simulation model iterations.

The simulation model is developed with the following limitations:

- It focuses on the airplane with a 180-seat configuration set as economy class only. The airline boarding process for the passengers uses a jet-bridge facility.
- The simulation model does not consider passengers' movement in groups.
- The simulation does not consider boarding priorities for any condition.
- The simulation does not consider passenger profiles and anthropometries such as age, gender, height, and body size.
- The model assumes that all passengers store their luggage in the overhead-bin near their respective seat-row.

2.4 Development of agent-based modelling in NetLogo

Our simulation model was set with a grid world of 49 × 21 torus and 25 patch size, creating an airplane with a 180-seat configuration set for economy class only. The model interface presented in Fig. 2 is complemented with an additional flight deck and tail of the airplane, making it look closer

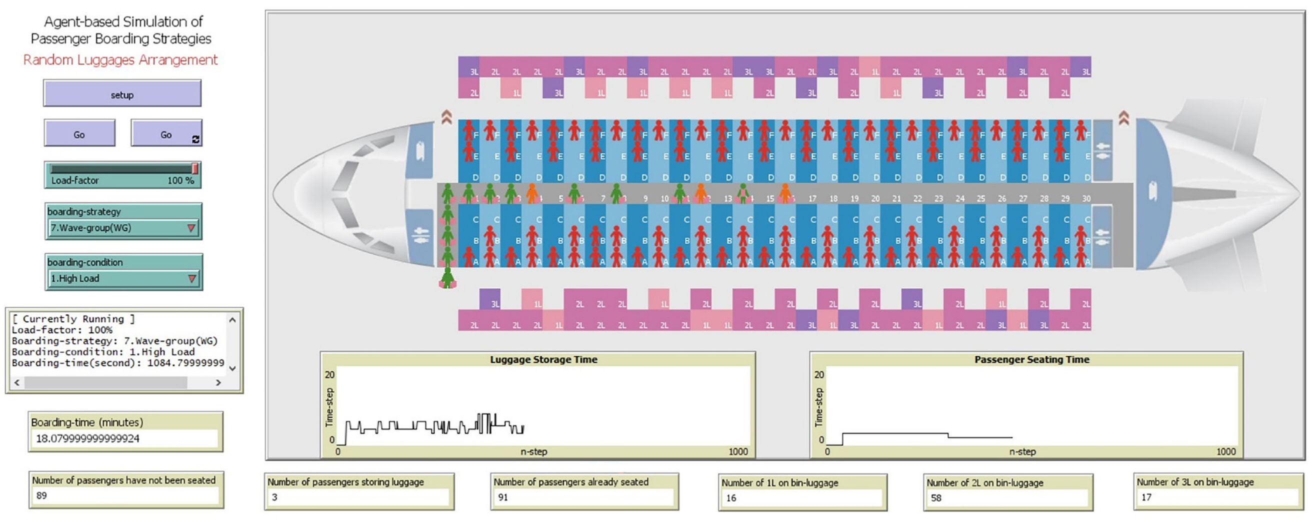


Fig. 2 An illustration of agent-based modelling in NetLogo for airplane passengers' boarding process

to its actual condition. Here, there are two types of agents: turtles represent the passengers, and patches represent areas in the cabin, with variables and values as shown in Table 4.

In our simulation model, passenger load factors, boarding load conditions, and luggage arrangement methods can be configured, working with the selected boarding strategy. Seat coordinates assigned to passengers are determined based on a coding algorithm developed specifically for each of the nine boarding strategy layouts. To make the observation easier, the visualization of bin luggage occupancy is placed on the left side and right side of the passenger seat-row. The left side is allocated for seat

Table 4 Variables in ABM simulation of airplane passengers' boarding process

Agent	Variables	Values	Description
Turtles	Load factor (LF)	(0.7 * 180), (0.8 * 180), (0.9 * 180) and (1.0 * 180)	The composition of LF levels represents the volumes that exceed the new normal period (66.7%). LF 100% level is the benchmark to consider the effectiveness of the boarding strategy.
	Amount of carry-on luggage	1L, 2L, 3L	Passengers with one piece of luggage (1L), two pieces of luggage (2L), and three pieces of luggage (3L).
	Boarding load condition	[(**0.2** 1L + **0.6** 2L + **0.2** 3L) * **LF**]	Boarding in high-load condition.
		[(**0.6** 1L + **0.3** 2L + **0.1** 3L) * **LF**]	Boarding in normal-load condition.
		[(**0.8** 1L + **0.1** 2L + **0.1** 3L) * **LF**]	Boarding in low-load condition.
	Luggage arrangement method	Random	The boarding process is carried out without sequential entry rules to the amount of passenger carry-on luggage (run randomization).
		Ascending	The boarding process is carried out with sequential entry rules, starting from the L1, L2, and L3 (smallest to largest).
		Descending	The boarding process is carried out with sequential entry rules, starting from the L3, L2, and L1 (largest to smallest).
	Passenger's initial position	Coordinate (-12, -4)	Passenger's initial position is set outside the left front door.
	Interval to board the plane	3 ticks (equal to 7 seconds)	The time interval for the passenger to board the plane one by one.
	Passenger movement velocity	0 and 1 patch per tick	A time-step per patch will correlate to 2.4 seconds of the absolute boarding time.
	Luggage storing time	Result of Eq. (1) + transition time	Time for passengers to store their carry-on luggage in the overhead-bin and take two seconds to pause to breath.
	Passenger seating time	Result of Eq. (2), or	Passenger seating time with seat-interference.
		Use the value in Table 3	Passenger seating time without seat-interference.
	Passenger seat allocation	(pxcor, pycor)	Assigned seat-row and seat numbers are defined based on the algorithm code of each boarding strategy.
	Color	Green (55)	Visualization of the passenger when walking on the aisle.
		Orange (25)	Visualization of the passenger when storing luggage and moving to his/her respective seat.
		Red (15)	Visualization of the passenger when sitting.
Patches	Aisle	Coordinate (-12, -3) until (18, 0)	Aisle coordinate, starting from the left front door until the last seat row.
	Seat-row	pxcor: -11 until 18	Indicates the designated seat-row from row 1 until 30.
	Seat-number	pycor: -3, -2, -1, 1, 2, 3	Seat-row letter number (-3 stands for A, -2 for B, -1 for C, 1 for D, 2 for E, and 3 for F).
	Overhead-bin luggage coordinate	Seat position with (xcor, ycor - 3) and (xcor, ycor + 3)	Calculated from passenger seat position with defined coordinate x (y - 3) for seat numbers A, B, C, and x (y + 3) for seat numbers D, E, and F.
	Color	Gray (6)	Visualization of the aisle.
		Sky (95)	Visualization of the odd-number seat.
		Sky (97)	Visualization of the even-number seat.
		Pink (136)	Visualization of bin luggage area when occupied by 1L.
		Magenta (127)	Visualization of bin luggage area when occupied by 2L.
		Violet (116)	Visualization of bin luggage area when occupied by 3L.

numbers A, B, and C. In contrast, the right side is for seat numbers D, E, and F. This visualization is very important for this research to ensure the accuracy of the luggage arrangement layout for each method.

The coding flow mechanism shown in Fig. 3 contains code grouping, which aims to simplify the iteration process and make it easier to trace errors that may occur. Furthermore, we use the BehaviorSpace function embedded in NetLogo 6.1.1 software to automate data acquisition that requires repeated iterative processes.

3 Result and discussion

The boarding time is a critical evaluation criterion for evaluating the effectiveness of passenger boarding strategy in the airline industry. The simulation of several different boarding strategies combined with passengers' entry settings based on their carry-on luggage may produce an effective and faster boarding time. This recommended model in boarding strategy may affect the performance of the respective boarding strategies.

In the simulation, as illustrated in Fig. 4 and Fig. 5, passengers are set to board the airplane according to the developed boarding strategy model. Three models of luggage arrangement methods that will be evaluated, involving Random, Ascending (L1L2L3), and Descending (L3L2L1). Using the initial position outside the left front door, the passengers are lined up and boarded one by one into the plane with a seven-second interval then walk through the aisle at a speed of one patch per tick while carrying their belongings (passengers' illustration in green).

After arriving at their seat-row, it is assumed that each passenger stores all of their carry-on luggage to the overhead-bin with time duration varying according to the calculation results in the simulation using Eq. (1). Meanwhile, other passengers standing behind have to wait until the passenger finishes storing all of the luggage and shifts from the aisle to the designated seat. If there are passengers who come through the seat interference when they want to move to their designated seat, then the time required will use the resulting values from Eq. (2), as

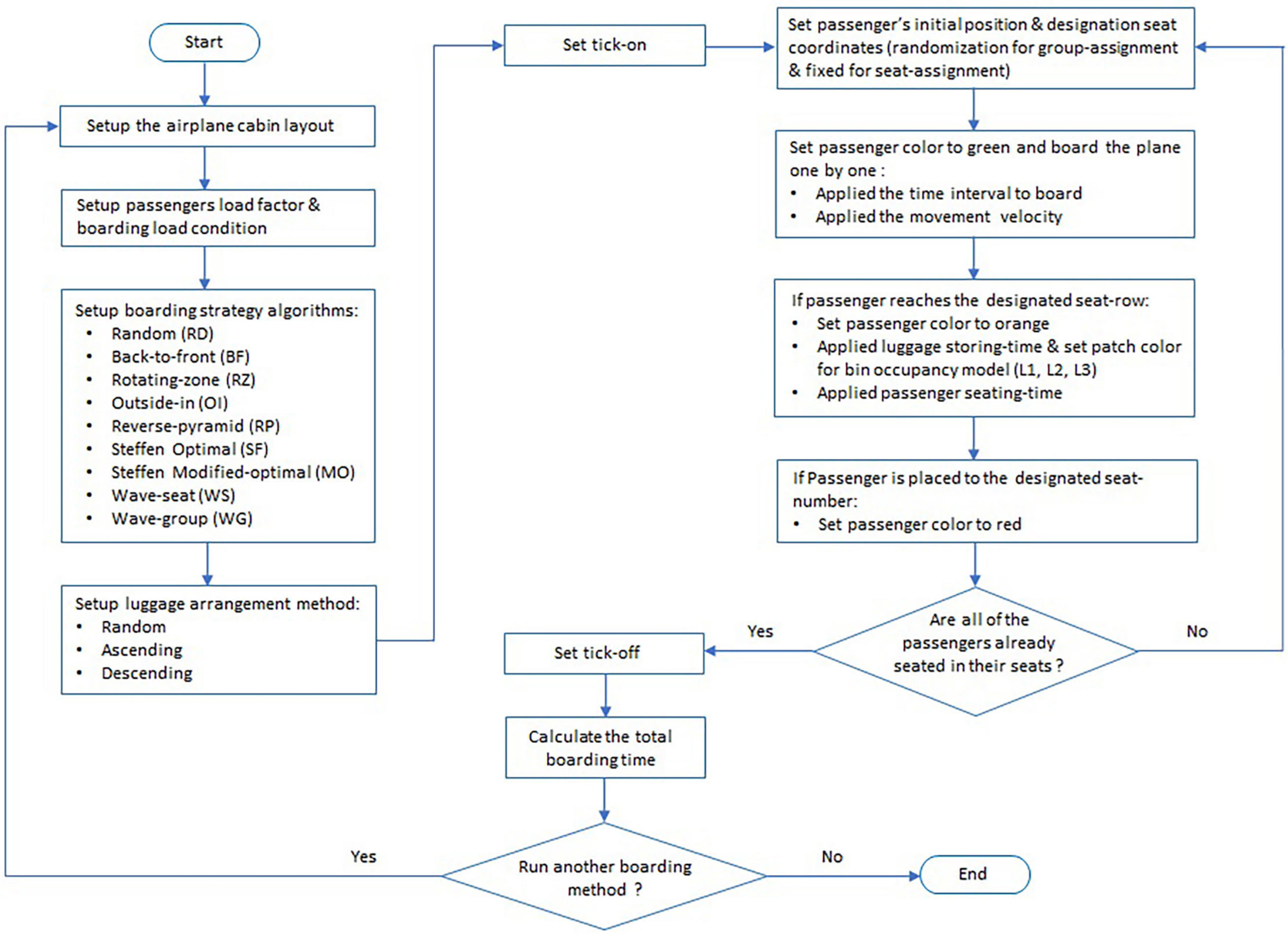


Fig. 3 Coding flow mechanism in ABM simulation of airplane passengers' boarding process

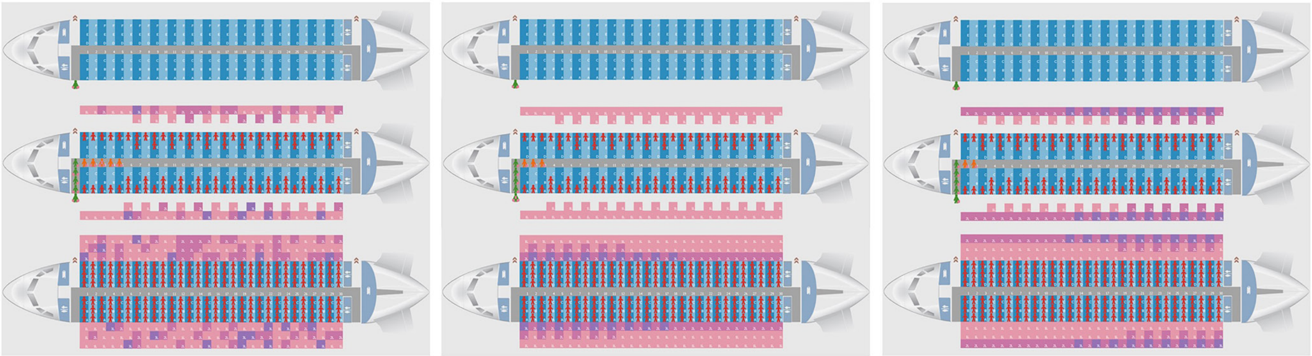


Fig. 4 An illustration of WS boarding strategy by applying three different luggage arrangement methods, including: Random (left), Ascending (middle), and Descending (right)

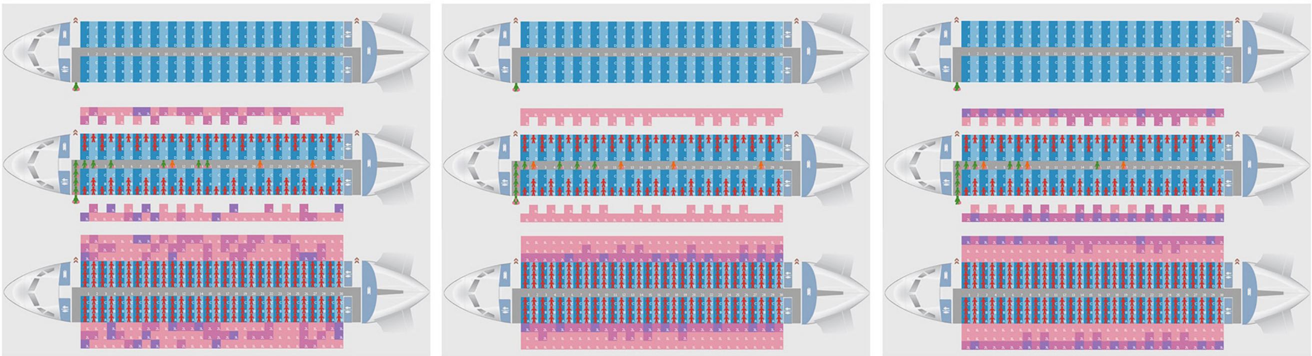


Fig. 5 An illustration of WG boarding strategy by applying three different luggage arrangement methods, including: Random (left), Ascending (middle), and Descending (right)

shown in Table 2. In other conditions, without any seat interference, the time required will follow the time-steps of each passenger, as shown in Table 3. Here, passengers in orange describe the situation from the moment they put the carry-on luggage in the overhead-bin until moving from the aisle to the respective seats.

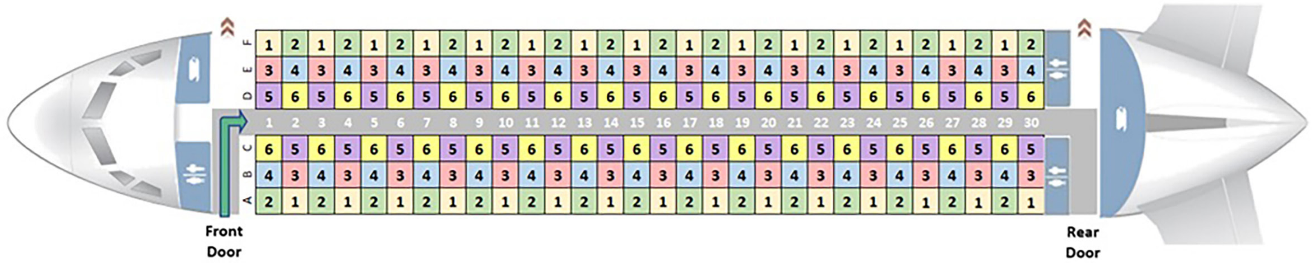
The simulation model ends when all passengers have sat in their seats (passengers' illustration in red), and the counter-step stops counting. Then, displaying information about the total boarding time (TimeConsume) is set in minutes.

In this study, the WS and WG boarding strategies are key to differentiating it from other boarding studies. This is because the two boarding strategies are an innovation of the authors. Previously, both boarding strategies were proven to be effective by simulations in normal and new normal period scenarios, but without any entry arrangements based on the number of passengers' carry-on luggage, or we call it just by random method only (Nugroho et al., 2021). Here, we will find out whether these two boarding strategies can be adjusted to become faster through the implementation of Ascending and Descending luggage arrangement methods or even other strategies that will be more effective and faster.

To understand the passenger boarding process using the WS and WG strategies within these three luggage arrangement methods, as illustrated in Fig. 4 and Fig. 5, we must know about these strategies' concepts and boarding layout. The WS strategy, which uses seat-assignment approach, lets the passengers board the plane one by one, with a strictly defined seat-number position, starting from the rearmost followed by another on the front but with a position across the aisle within one seat-row separate distance. This boarding layout creates a wave design (see Fig. 6(a)) whose concept is also combined with the order of entry starting from the window, middle, and aisle. Meanwhile, in the WG strategy, which uses the group-assignment approach, passengers are divided into six groups and board the plane based on the call order of the group number. The entry queue starts from the window, middle, and aisle positions. Passengers will randomly fill the seats on the left and right sides of aisle with alternating rows. This boarding layout also creates a wave design (see Fig. 6(b)).

By understanding the boarding concept of these two strategies, we can see the differences in the illustrations in Fig. 4 and Fig. 5, even though both of them adopted the design of the 'wave' layout:

(a)



(b)

Fig. 6 The boarding layout of the "wave" strategy: (a) wave-seat, (b) wave-group

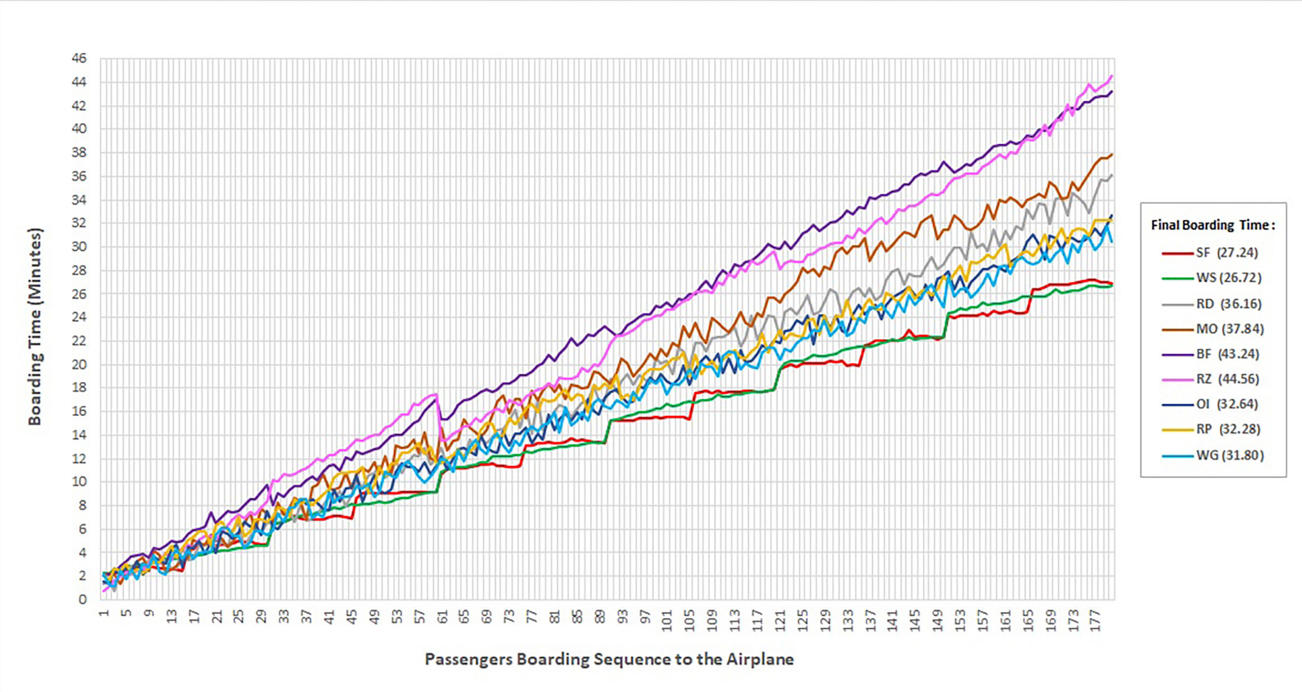
- In the Random luggage arrangement method, as shown in Fig. 4 (left) and Fig. 5 (left), the only visible difference is how passengers enter and fill their seats. By using WS strategy, passengers fill seats from the rearmost to the front in a strictly defined sequence, while in Wave-group, passengers fill seats randomly according to the group calls, starting from the window, middle, and aisle. On the other hand, the visualization of the bin luggage area when occupied by L1, L2, and L3 look random. The difference is only in the order in which it is filled, which follows the seat filling process by the passengers.
- In Ascending luggage arrangement method, as shown in Fig. 4 (middle) and Fig. 5 (middle), the visualization of the bin luggage area looks neat with L1 (pink) filling the entire outside and part of the middle. In contrast, L2 (magenta) fills part of the middle and inside, and L3 (violet) fills part of the inside. However, it can be seen that in the bin luggage area, the WS is neater than the WG due to the different methods of passengers enter and fill the seats.
- In Descending luggage arrangement method, as shown in Fig. 4 (right) and Fig. 5 (right), the visualization of the bin luggage area also looks neat, with L3 (violet) filling part of the outside. In contrast L2 (magenta) fills part of the outside and middle, and L1 (pink) fills part of the middle and whole inside. As in the previous point, it can be seen that in the bin luggage area, the WS is neater than the WG due to the difference in the methods of passengers entering and filling the seats.

Here, the comparison of effective boarding times between WS, WG, and other seven strategies is described in Subsection 3.1 below.

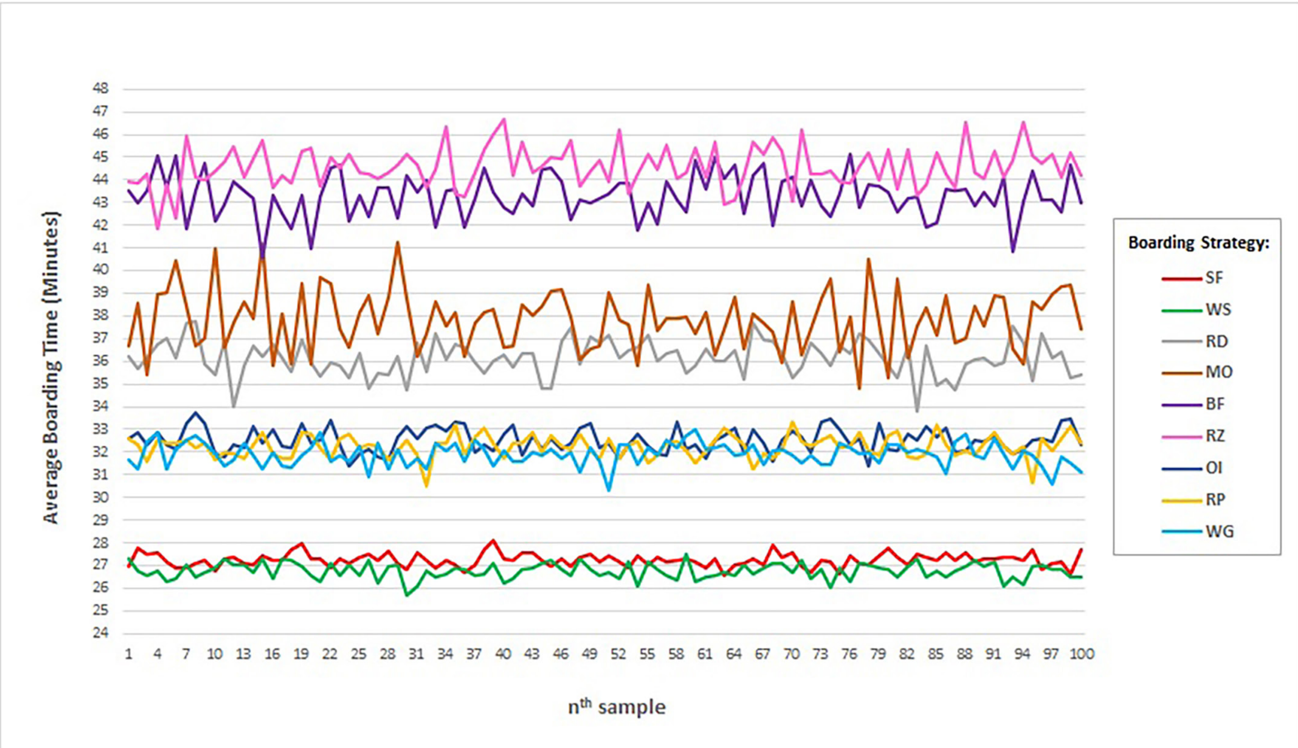
3.1 Boarding process by applying 'Random luggage' arrangement method

From a total of 10,800 samples collected, the boarding performance of the nine strategies tested with load factors of 70%, 80%, 90%, and 100% by applying passengers' entry sequence with the Random luggage arrangement method can be seen in Fig. 7 and Fig. 8. From Fig. 8, the average boarding time shown by the nine boarding strategies at four different load factor levels shows a stable sequence. The simulation also shows the WS as the fastest and the RZ as the slowest. Overall, the nine boarding strategies tested in this research represent three boarding approaches: seat-assignment, random-assignment, and group-assignment. Moreover, the boarding performance shown in Fig. 7 and Fig. 8 provides a clear picture of each boarding strategy's effectiveness.

Based on Fig. 7(a) and Fig. 7(b), it can be seen that the boarding pattern and frequency distribution achieved by the nine boarding strategies are grouped into four levels of boarding performance. The seat-assignment boarding strategy approach involving WS and SF strategies is the first level with the fastest average boarding time. The WS



(a)

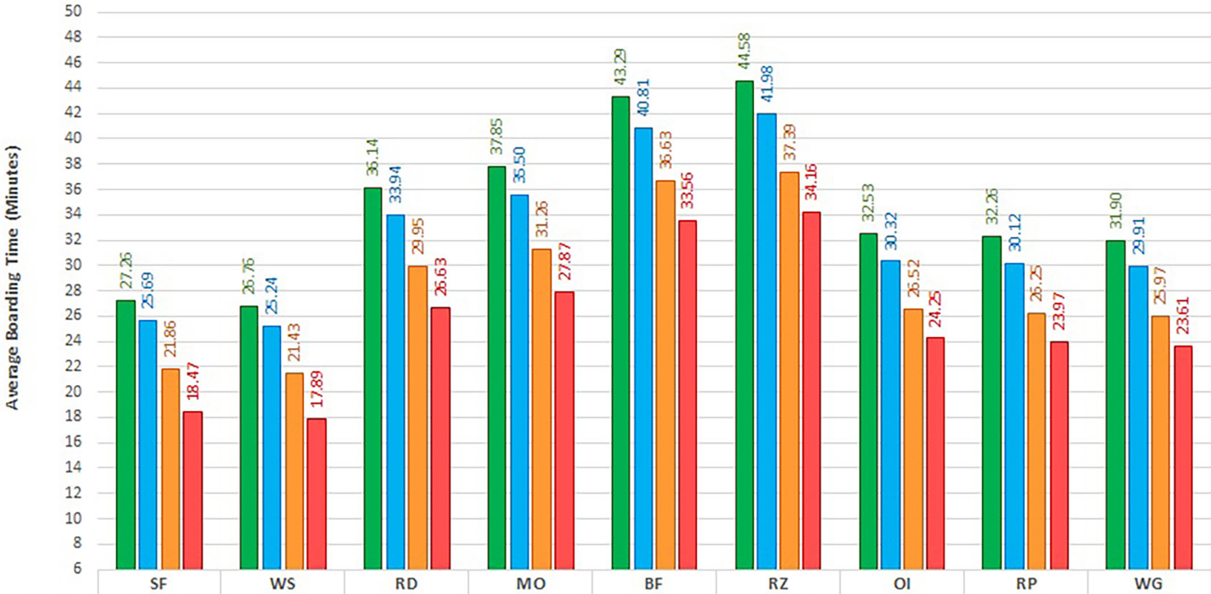


(b)

Fig. 7 Passenger boarding process with 100% load factor by applying Random luggage arrangement method: (a) boarding time pattern in a normal load; (b) frequency distribution of the boarding time

has a good performance compared with the SF and even outperforms it.

The good performance of the WS strategy is due to the fact that it has a higher frequency distribution of minimum passenger boarding time. Several passengers are organized to put the carry-on luggage simultaneously and sit on their respective seats. The model is started from the back to the front, and the sequence is from the window, middle part,



	SF	WS	RD	MO	BF	RZ	OI	RP	WG
LF 100%	27.26	26.76	36.14	37.85	43.29	44.58	32.53	32.26	31.90
LF 90%	25.69	25.24	33.94	35.50	40.81	41.98	30.32	30.12	29.91
LF 80%	21.86	21.43	29.95	31.26	36.63	37.39	26.52	26.25	25.97
LF 70%	18.47	17.89	26.63	27.87	33.56	34.16	24.25	23.97	23.61

Fig. 8 The average boarding time by applying the Random luggage arrangement method under four different load factors (LF)

and aisle of the plane, respectively. This condition eliminates the occurrence of seat interference, and aisle interference is minimized. This condition is different from the SF strategy that is applied only on one side. However, both strategies require strictly defined sequence control compared to other strategies, thus requiring greater effort by airlines. In contrast, these strategies force to provide time in preparation to arrange the sequence of passengers to enter the plane since they must be called individually.

The boarding strategies with group-assignment and random approaches are the next three levels with slower average boarding time. Three strategies have a very slight difference in the average boarding time at this level, including WG, RP, and OI. This research concludes that the WG strategy has a good performance compared with the RP, and OI strategies. It also interprets that the WG is the fastest strategy from the random and group-assignment approaches. In these three boarding strategies, the seat interference and aisle interference are possible to be minimized.

The third level of boarding performance consists of RD and MO strategies. In these two boarding strategies, the occurrence of seat interference and aisle interferences cannot be avoided since there is no given rule to fill seats in a column-way. In these models, the boarding strategies are not organized as follows: starting from the window, the middle part, and finally the aisle. In this case, it is found that the MO solution proposed by Steffen has a slower performance than the RD strategy.

Further, this research concludes that the BF and RZ have the two lowest boarding times. BF and RZ show that the occurrence of seat and aisle interferences is unavoidable. In addition, the implementation of passenger entry rules based on the row-seat zone creates limitations since the queues in one group require a longer completion time.

As aforementioned, the average boarding time of random and group-assignment are found to be less than the seat-assignment. However, those implementations are identified to be more efficient and effective. In the implementation process, the airlines only consider the boarding group number on the passenger's boarding pass.

This research interprets that the RD and BF strategies are valid following the real-world condition, especially for the Indonesia region. In Indonesia, the boarding time for an airplane with a 180-seat configuration and a load factor of 100% needs around 40 minutes applying the RD strategy, while the BF needs around 45 minutes. The developed simulation model in this research represents the real-world condition for further implementation and considerations.

Referring to Fig. 6, it is summarized that with every 10% of load factor decrease, the boarding process applying the Random luggage arrangement method will decrease by 3.04 minutes on average.

Since the performance of each boarding strategy shown in four different load factor levels is in stable sequence, then the resulting simulation output with a LF 100% was used as baseline data to be compared with two other luggage arrangement scenarios, namely Ascending method (L1L2L3) and Descending method (L3L2L1).

3.2 Boarding process by applying 'Ascending luggage' arrangement method

From 2,700 samples collected, the boarding performance of the nine strategies tested by applying passengers' entry sequence with Ascending luggage arrangement method can be seen in Fig. 9 to Fig. 11. Based on Fig. 9(a) and Fig. 9(b), it can be seen that the boarding pattern and frequency distribution of the boarding strategies by applying Ascending luggage arrangement method are also grouped into four levels of boarding performance as in the previous Random luggage arrangement method.

The boarding strategy with seat-assignment model consists of the WS and SF strategies remains in the first level with the fastest average boarding time. Despite experiencing a slight acceleration, the difference in time duration is slight and not significant enough. Those boarding strategies provide sufficient space to store passengers' carry-on luggage simultaneously. This condition provides a stable process not affected by any changes in the luggage arrangement method. In addition, both of them apply a combination of back to front and outside-in concepts, thus minimizing aisle interference while eliminating seat interference.

The group-assignment and random approaches are the next three slower levels considering average boarding time. The three strategies at the second level, WG, OI, and RP, experienced a significant enough decrease in performance, especially for the RP strategy. Here, the WG strategy remains the fastest while the RP becomes slower than the OI strategy. These boarding strategies apply the outside-in concept in three different ways, and the seat interference issues can be minimized. In this way, the process of storing more luggage by the passengers in the last sequence will not overly interfere with other passengers but takes longer due to more items with limited space remaining.

On the other hand, there are three strategies at the next two levels that have the most impact on decreasing boarding performance, including MO, BF, and RZ. In those models, the implementation of passenger entry rules based on the seat-row zone has an impact on a significant slowdown. It is because the remaining space in overhead-bin is limited while the passengers' carry-on luggage in the last sequence is more in number. Here, the MO strategy becomes 7.90% slower, BF becomes 14.04% slower, and RZ is about 13.13% slower. Meanwhile, the RD strategy is also experienced to be slower but not as significant as these three other boarding strategies. Even though the arrangement is made, the concept of this RD strategy will always result in a random view so that the implementation of Ascending luggage arrangement method becomes somewhat biased.

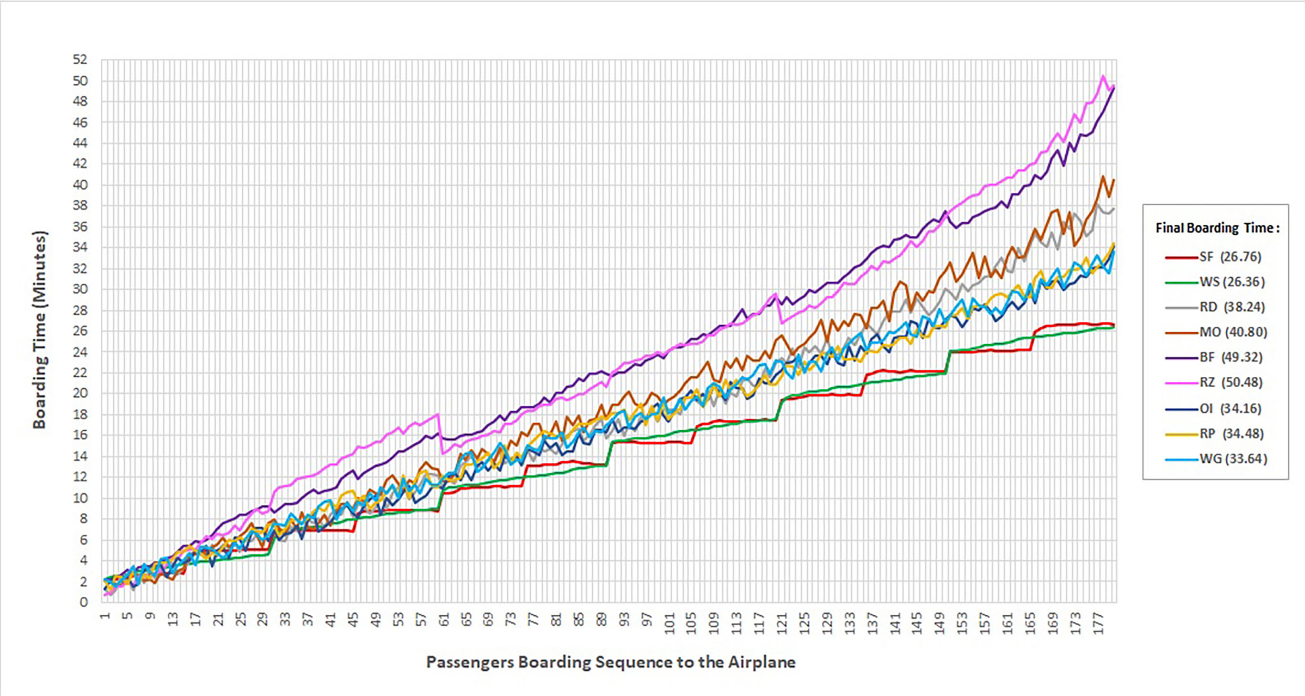
Overall, the boarding process by applying passengers' entry sequence with Ascending luggage arrangement method (L1L2L3) will reduce the boarding performance by 6.12% compared to the Random method. Therefore, this research does not recommend the Ascending luggage arrangement method since most boarding strategies get no benefit from it.

3.3 Boarding process by applying 'Descending luggage' arrangement method

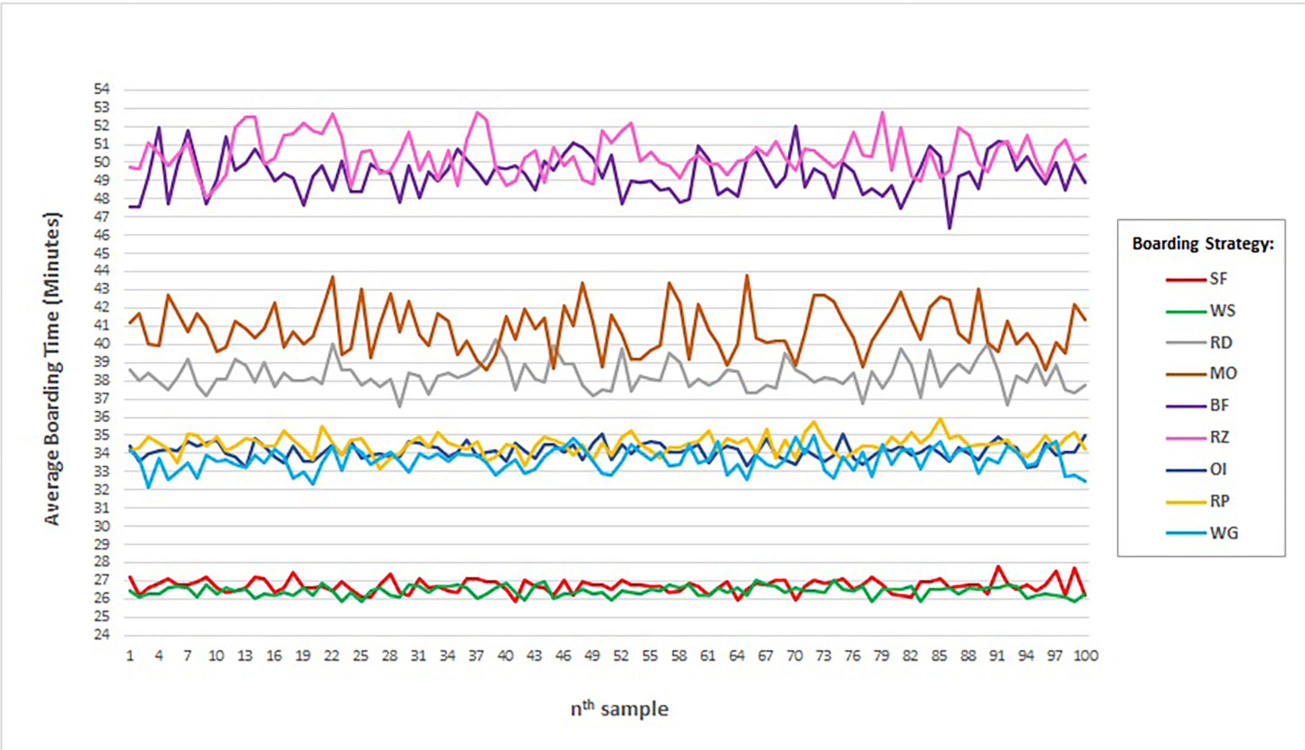
From 2,700 samples collected, the boarding performance of the nine strategies tested by applying passengers' entry sequence with Descending luggage arrangement method can be seen in Fig. 10 and Fig. 11. Based on Fig. 10(a) and (b), the boarding pattern and frequency distribution achieved by the nine boarding strategies by applying Descending luggage arrangement method are also grouped into four levels of boarding performance.

As in the two previous luggage arrangement methods, the boarding strategy with the seat-assignment approach consists of the WS and SF strategies remaining at the first level with the fastest average boarding time. These two boarding strategies also experience a slight acceleration in time duration, which is not significantly different. This fact proves that the parallel luggage storing concept adopted by these two boarding strategies brings advantages of completion time stability in passengers' boarding process with three different luggage arrangement methods.

With the same performance as in the two previous methods, the boarding strategies with group-assignments and random approaches are the next three slower levels of the average boarding time. This batch includes WG, RP, and OI, which have the most impact on increasing boarding performance. The concept of these three boarding strategies applies the boarding sequence based on column-way



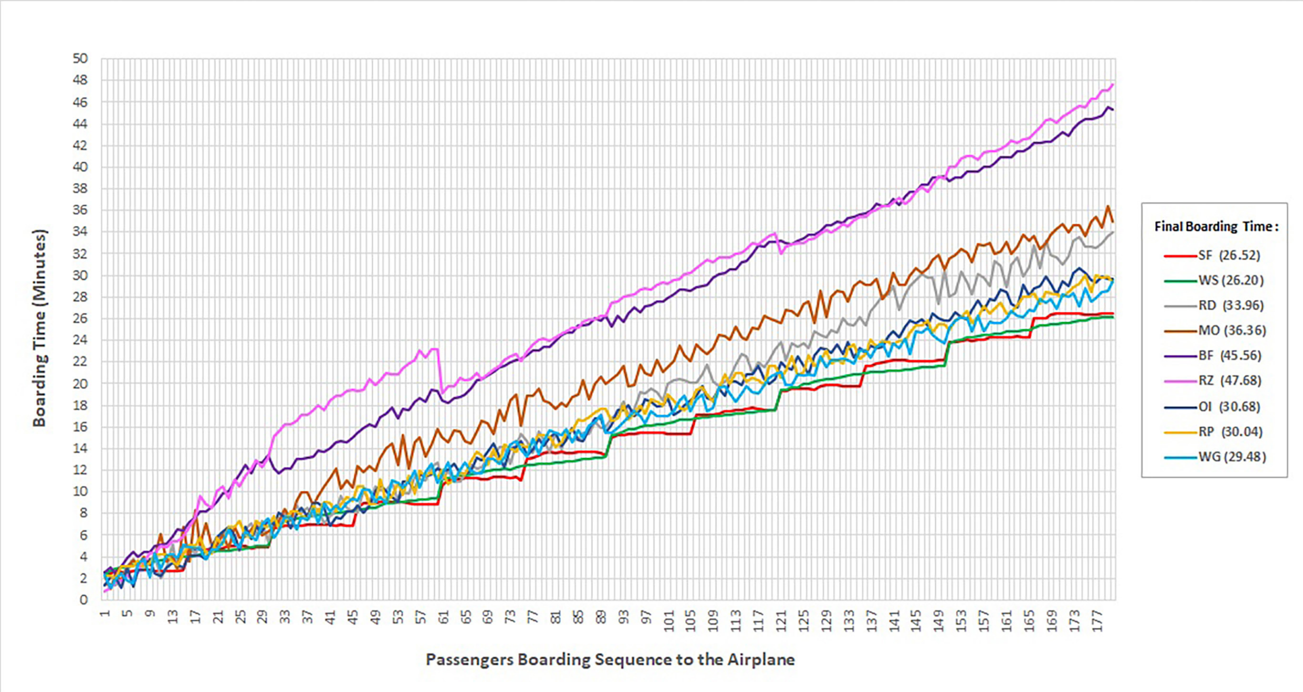
(a)



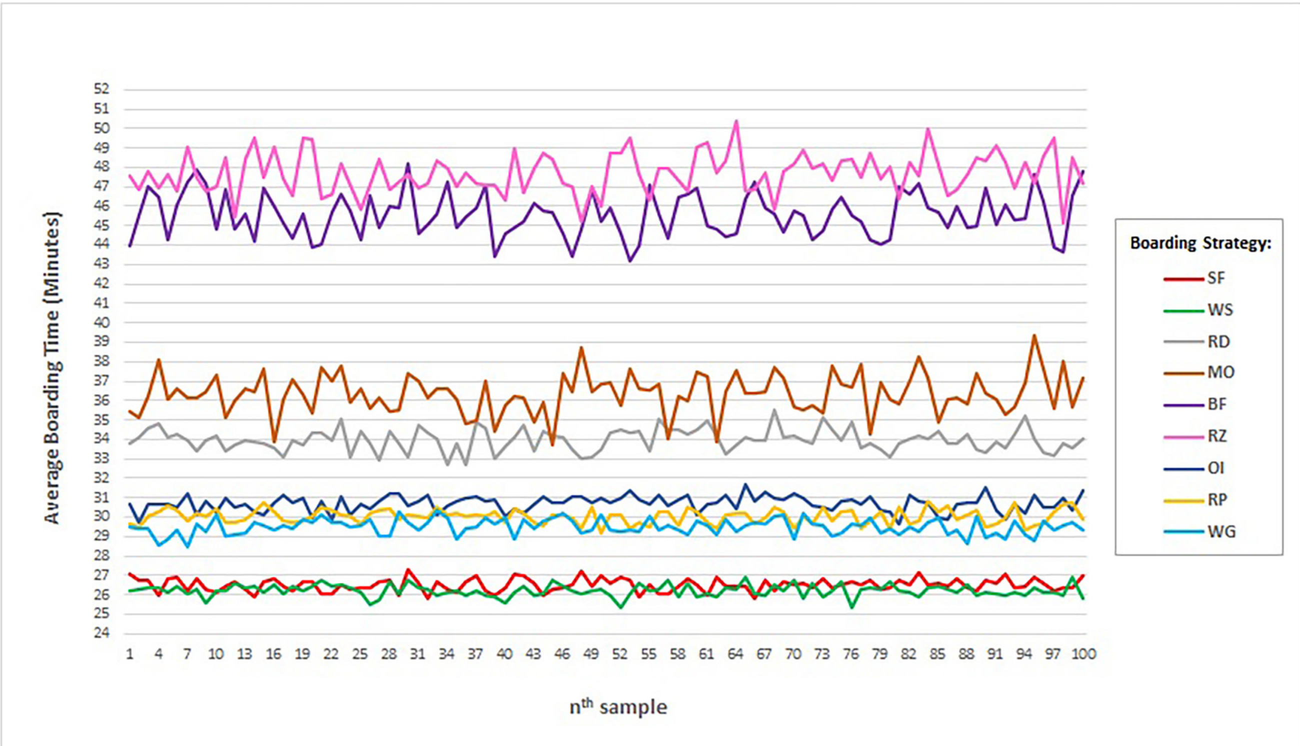
(b)

Fig. 9 Passenger boarding process with 100% load factor by applying Ascending luggage arrangement method: (a) boarding time pattern in a normal load; (b) frequency distribution of the boarding time

groups so that the first sequence of passengers, who have more carry-on luggage, can freely store all of their belongings into the empty bin. The concept of group passengers boarding in a column-way combined with the implementation of the Descending luggage arrangement method brings a higher probability of shortening boarding time, which is



(a)

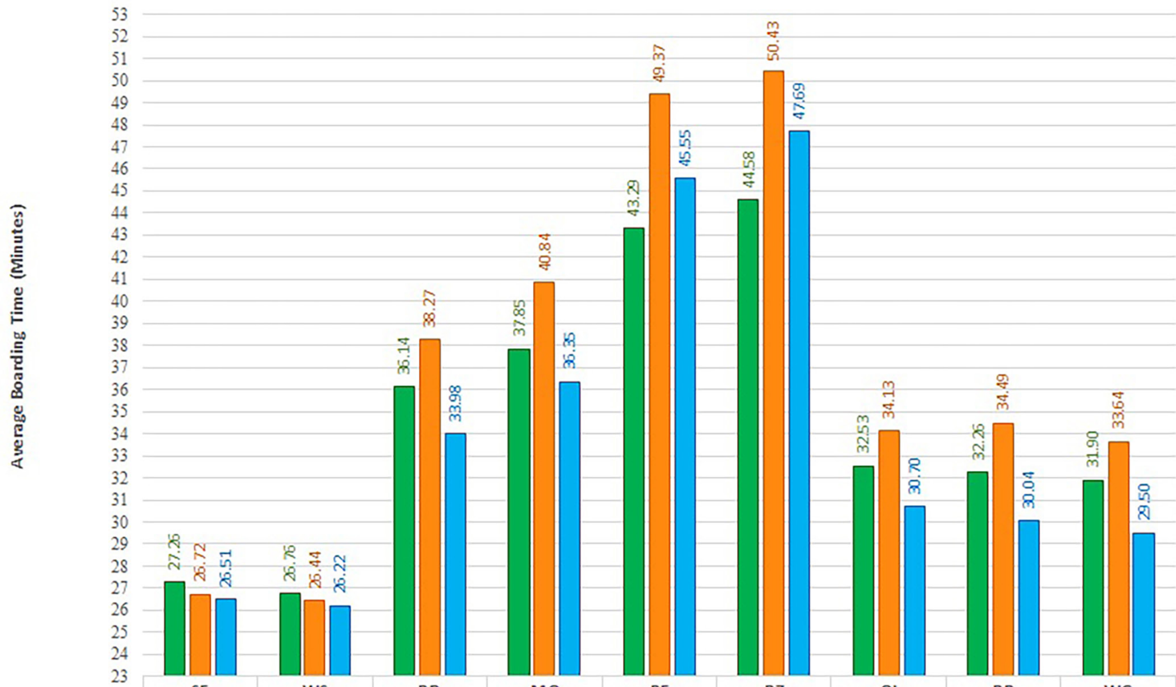


(b)

Fig. 10 Passenger boarding process with 100% load factor by applying Descending luggage arrangement method: (a) Boarding time pattern in a normal load; (b) Frequency distribution of the boarding time

more than 5.5%. Here, the WG strategy remains the fastest while the RP becomes faster than the OI strategy.

The two boarding strategies at the third level, RD and MO, also experienced an increase in boarding performance. However, the opposite situation is experienced by two other strategies at the fourth level, including BF and RZ. These two boarding strategies do not get the benefit from applying Descending luggage arrangement



	SF	WS	RD	MO	BF	RZ	OI	RP	WG
LF100% - Random	27.26	26.76	36.14	37.85	43.29	44.58	32.53	32.26	31.90
LF100% - Ascending	26.72	26.44	38.27	40.84	49.37	50.43	34.13	34.49	33.64
LF100% - Descending	26.51	26.22	33.98	36.35	45.55	47.69	30.70	30.04	29.50

Fig. 11 The comparison of average boarding time by applying three different luggage arrangement methods

method, where BF is 5.21% slower while RZ is 6.99% slower. In these two boarding strategies, the implementation of passenger entry rules based on the row-seat zone also creates limitations. Queuing in one group requires a longer completion time since the passengers' carry-on luggage in the first sequence is actually more in number.

Overall, the boarding process by applying passengers' entry sequence with Descending luggage arrangement method (L3L2L1) will increase the boarding performance by 2.50% compared to the Random method. This research recommends applying the Descending luggage arrangement method for most boarding strategies except the BF and RZ. Therefore, for these two boarding strategies, it is better to apply the luggage arrangement in the Random method only.

In this research, it is proven that some boarding strategies can still be optimized for their performance by implementing passengers' entry sequence based on their number of carry-on luggage, especially by Descending method. This research also found that the 'Wave' strategy model implemented in seat-assignment (Wave-seat) and group-assignment (Wave-group) model has been successfully simulated as a better passenger boarding strategy. It was found that this strategy proved its effectiveness and is recommended as a verified alternative to be applied in the real world of airline operations. Both strategies consistently achieved the fastest boarding time in the three luggage arrangement methods compared to other strategies. Therefore, this research has contributed to airlines a way to minimize potential delays in the airplane turnaround process by implementing an effective and efficient boarding strategy, which will result in significant savings.

4 Conclusion

This research has succeeded in designing and demonstrating the simulation model of passengers' boarding sequence with luggage arrangement method using agent-based modeling. The simulation shows that the overall boarding process by applying passengers' entry sequence with the Ascending luggage arrangement method will reduce the boarding performance by 6.12%. In comparison the Descending method will increase boarding performance by 2.50%, compared to the standard Random method.

To improve the boarding performance, this research recommends airlines to apply Descending luggage arrangement method for most boarding strategies, except for Back-to-front (BF) and Rotating-zone (RZ). Both these boarding models should apply the Random luggage arrangement method only. Meanwhile, this research does not recommend its application for the Ascending luggage arrangement method since most boarding strategies get no benefit from it. In addition, this research proves that the parallel luggage storing concept adopted by Wave-seat (WS) and Steffen Optimal (SF) strategies brings the advantage of completion time stability in passengers' boarding process and is not affected by the differences in luggage arrangement methods. Overall, these three luggage arrangement methods, the 'Wave' strategy implemented in seat-assignment (Wave-seat) and group-assignment (Wave-group) approach, have consistently produced a satisfactory result to achieve the effectiveness with boarding time. These models also provide a verified recommendation for the airlines to increase the effectiveness of boarding operations.

For further research, the model and technique in this research need further implementation and requirement analysis. In the other gap, it is possible to consider a scenario using the front and rear doors of the airplane, which is also commonly applied in the real world. It is due to the limited number of jet-bridges at the airport compared to the number of airplanes that must be served. In addition, some airports located in small cities sometimes do not provide a jet-bridge facility.

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