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# A dynamically optimized aircraft boarding strategy

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ABSTRACT

Airline carriers, airports and passengers have common interests in expediting the aircraft boarding process for economical, operational, and customer satisfaction reasons respectively. Several boarding strategies have been proposed in the literature aiming to reduce the boarding time. Several theoretical models were able to achieve near optimum performance, but ignored the important aspect of allowing family and groups to board together in cliques. Some other models achieved top performance by pre-assigning passengers to seats, which deprived them from the essential privilege of choosing their own seats. The Dynamically Optimized Boarding strategy is proposed to shorten the boarding time, reduce on-board interferences, and allow passengers' cliques to proceed together to their reserved seats. Passengers are sequenced in a boarding queue based on their seats' positions, associated cliques, and the possibility of interferences, immediately after the last check-in. They are required to board the aircraft according to their positions in the queue. A technology-aided announcement process can help in guiding batches of passengers to a small pre-boarding area in order to aggregate before boarding the aircraft. A simulation-based study showed that the proposed strategy achieved a near-optimum performance without breaching the passengers' right to walk in cliques to their preferred seats.



## 1. Introduction

The turnaround time that an aircraft spends at airports between inbound and outbound trips is an overhead cost that airline companies strive to reduce. Considering the lowest cost reported in the literature, a major airline carrier can save more than 50 million dollars in fiscal saving for a single minute reduction in turnaround time across all flights (Jaehn and Neumann, 2015). Passengers would also appreciate solutions that minimize the wait time at the gate, enhance the boarding experience, and eliminate causes for trip delay. Furthermore, busy airports can certainly benefit from an expedited boarding process that optimizes the number of served planes at a gate (Jaehn and Neumann, 2015). Numerous studies focused on optimizing the aircraft boarding process, to shorten the time an aircraft spends at the gate and to save few turnaround minutes. Some interesting solutions have been proposed to shorten the boarding time, which addressed two of the passengers' concerns: reduction of the wait time at the gate and the elimination of one cause of trip delay. However, very few studies paid attention to the passengers' boarding experience. In fact, most of the optimized approaches are less passenger-friendly than some of the sluggish ones. Segregating passengers' cliques (e.g. families or traveling companions) and boarding the clique's members individually at different time intervals is definitely not an attractive characteristic of any boarding strategy. In addition, facing several interferences onboard is a source of annoyance that should be reduced to the bare minimum. An interference usually occurs when a passenger is blocked by another, halting the normal procession to an assigned seat (Ferrari and Nagel, 2005). Two types of passenger interference (aisle and seat) may occur on board of a flight. Aisle interference occurs when a passenger is stuck in the aisle, preventing another from proceeding to a seat. On the other hand, seat interference occurs when a seated passenger hinders another from taking a nearby seat. In both cases, the blockage must be cleared before a passenger can proceed to a seat.

Unfortunately, the best boarding strategies that have been proposed in the literature placed more emphasis on the economical and mathematical aspects and ignored the people's perspective. For example, some of those strategies do not respect the passengers' interest to board in cliques, or do not account for the number of boarding interferences (Steffen, 2008; Tang et al., 2012b; Qiang et al., 2014; Milne and Kelly, 2014; Milne and Salari, 2016).

With the advent of telecommunication technology, pervasiveness of mobile devices, and ubiquity of mobile applications, it is incumbent on any aircraft boarding study to leverage existing

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technological capability in order to achieve performance improvement. However, very few studies considered the role of technology in enhancing the boarding process.

In this paper, we propose a new boarding strategy that allows passengers to board in cliques to their desired seats, within a near-optimum boarding time. The new strategy aims at reducing the boarding interference to improve the boarding experience – the lower the interference level the better the boarding experience. It also makes efficient use of the available technology to support the boarding process. The proposed strategy is labeled as the Dynamically Optimized Boarding (DOB) strategy since it does not entail a static boarding pattern, as widely adopted in several strategies. The DOB insures that the passengers' boarding pattern is derived on a flight-by-flight basis. It is mainly influenced by the percentage, sizes, and seating choices of the cliques onboard of an aircraft. Although some papers considered the amount of carry-on luggage as a decisive factor for forming dynamic boarding patterns (Tang et al., 2012b; Qiang et al., 2014; Milne and Kelly, 2014; Milne and Salari, 2016), none has considered the clique's attributes. The DOB is the first strategy that considers the clique's attributes to be the decisive factors in boarding passengers on an aircraft.

The new strategy is thoroughly described in a subsequent section after a brief literature review. The simulation work and corresponding results are discussed in separate sections towards the end of this paper.

## 2. Review

In this study, we consider some of the widely known aircraft boarding strategies in a comparative analysis to assess the impact of our proposed strategy, namely: Back-to-Front, Random, Windows-Middle-Aisle, Steffen, and Sorted-Boarding-Groups (a.k.a. Flying-Carpet).

One of the widely adopted strategies for boarding passengers on aircrafts is the Back-to-Front (B2F) strategy. Passengers are asked to board specific blocks of the aircraft from back to front. The aircraft seats are segmented into $n$ blocks, numbered from 1 (front-block) to $n$ (back-block). Passengers occupying the $n$th block will be called to board first. The occupants of the subsequent blocks will be called to board by their block number in descending order. No special sequencing is assumed within each block (Bazargan, 2007; van den Briel et al., 2003). Most airline carriers follow this strategy.

Another well-known and widely employed boarding strategy is the Random strategy. According to this strategy, all passengers are asked to board the aircraft at once as a single large block, without undergoing any pre-queueing procedure. Boarding will be done on a first-show-first-board basis (Ferrari and Nagel, 2005; Landeghem and Beuselinck, 2002). Some carriers follow this strategy.

The Windows-Middle-Aisle (WMA) boarding strategy arranges passengers to board in 3 subsequent batches according to 3 unique seat categories – Windows, Middle, and Aisle. The passengers in the window-seats batch board first. Those who are in the middle-seats follow next; and, last come the occupants of the aisle-seats No special queueing is assumed within each batch of passengers (Ferrari and Nagel, 2005; Bazargan, 2007; Nyquist and McFadden, 2008). The Reverse Pyramid (RP) boarding strategy is a slight variation of WMA. It arranges passengers in multiple groups who would board different diagonal blocks of the aircraft. A diagonal block includes segments of seats, arranged diagonally from back to front. One segment includes a group of seats existing in one column – windows, middle, or aisle. The seats in a given segment are the closest possible to the window side with respect to the other unoccupied seats at the same row levels. In an RP block, the closest segment to the window side is usually towards the front. Moving towards the back, the segments tend to be farther away from the windows making the entire block look like a reverse-pyramid – a V shape – (van den Briel et al., 2005). The RP strategy does not introduce a substantial performance improvement as compared to WMA. In addition, its implementation is more complex in practice (Jaehn and Neumann, 2015).

The Steffen strategy requires passengers to board according to their seat positions in the aircraft. It arranges passengers in a sequence based on a predefined sorting procedure. The sorted sequence of passengers starts with the occupant of a window seat on the last row. It proceeds with passengers in window seats on the same side from back to front, skipping one row at a time. When reaching the last possible window seat at the front end, the sequence continues with the windows seat on the other side of the aircraft – from back to front in the same row-skipping fashion. After reaching the front end again, the sequence continues with the window seats on the already skipped rows, back to front, one side after the other. The same procedure is applied for middle seats and then for aisle seats. The resulting sequence has been proven to yield the best boarding time compared to all known boarding strategies (Steffen, 2008; Steffen and Hotchkiss, 2012). The strategy does not take into consideration cliques of passengers who need to board together regardless of their seats positions. Regardless of its major limitations, the Steffen strategy is certainly an excellent theoretical benchmark to be used in gauging the performance of boarding strategies.

The Sorted-Boarding-Groups (SBG) strategy requires passengers to board in batches based on their orders of arrival. Each boarding batch normally includes passengers occupying seats that are randomly distributed across the aircraft. This is intrinsic to the random order of passengers' arrival in a given batch. A batch of passengers is formed within a fixed time-window. The passengers in a batch are sequenced in a pre-boarding area based on their seats positions – from back to front and window to aisle. No known research was done to verify the performance of this strategy. However, the Flying Carpet project is an existing application of the SBG strategy, but with no reported deployment (Wallace, 2013). The Flying Carpet project assumes the use of a pre-boarding area (Carpet) of $2.4 \times 8$ m, near the boarding gate. The Carpet features a sketched table of 36 rows and 6 columns representing seats in an aircraft. Before boarding, passengers in a batch are supposed to stand on labeled Carpet cells that match with their corresponding seats. It is evident that the cell size is too tight to accommodate a passenger carrying luggage. In this case, the passenger would need to occupy more than one cell. Thus, it will be impossible for other passengers occupying nearby seats to stand in their corresponding cells. This space constraint limits the number of passengers per boarding batch to less than 40. In addition, the contention to occupy nearby cells can be a great source of conflict and frustration among passengers. The problem is magnified with passengers traveling in cliques.

Some other boarding strategies considered passengers' individual properties such as the amount of carry-on luggage. In general, those strategies give priority to passengers that carry the highest amount of luggage (Tang et al., 2012b; Qiang et al., 2014). Tang et al. (2012b) relied on the Pedestrian Flow Model theory reported earlier in (Tang et al., 2012a) to factor the passengers' walking speeds into the process of assigning seats to passengers. The objective of pre-assigning seats to passengers based on their walking speeds is to board the faster passengers before the slower ones. The faster passengers are assigned seats towards the back of the aircraft; and, the slower ones are kept closer to the front. Passengers are expected to board individually in an outside-in fashion from back to front. It is also worth mentioning that Tang et al. expanded on their previous work to propose evacuation models in elementary schools based on the students' individual properties

(Tang et al., 2015). This can be instrumental in studying the aircraft evacuation problem which is beyond the scope of our study, and can be investigated further in (Cimler and Olsevicova, 2012). Qiang et al. (2014) considered the amount of luggage alone as being the decisive factor for pre-assigning seats to passengers. Passengers are then expected to board according to the Steffen method. Similarly, Milne et al. proposed the balancing of luggage across the aircraft by assigning passengers to seats based on the amount of their carry-on luggage. (Milne and Kelly, 2014; Milne and Salari, 2016). They relied on the Steffen method for boarding passengers.

All boarding strategies that considered passengers' individual properties reported improvement in the boarding time. These strategies set the precedence for dynamic non-deterministic boarding methods. In these methods, the boarding pattern cannot be determined until the last passenger checks in. The implementation of dynamic boarding strategies requires seamless integration among the information systems that supports the processes of booking, checking-in, and boarding. Without such integration, it is hard to generate and impose dynamic boarding sequences. Since most airline companies these days limit the amount of carry-on luggage to one piece, strategies considering luggage as a decisive factor in the boarding process might not be so efficient in practice. In addition, these strategies do not observe the essential passengers' requirement to choose their seats based on their personal preferences or physical constraints. For example, passengers who tend to seek front-windows seats in their trips will most likely not be satisfied to have a back-aisle seat. It is evident that dynamic boarding strategies expedite the boarding process; however, these strategies need to fulfill the essential passengers' requirement to board in cliques without compromising their choice of seats. This crucial requirement was ignored by most strategies that achieved optimal performance.

The scope of the aircraft boarding problem is definitely wider than just the procession of passengers down the aircraft's aisle. It starts with the efficient management of the check-in counters, and ends with the last passengers occupying a seat, including many steps in between such as clearing security gates. Several papers addressed the other aspects of the boarding problem. For a brief overview refer to Horstmeier and Haan's survey on the impact of ground handling activities on an aircraft's turnaround time (Horstmeier and Haan, 2001). A more recent related work was published by Qiang et al. (2016), in which they studied the relationship between passengers' inter-arrival time and the aircraft boarding time. They concluded that optimization should start with the airplane check-in process as it has direct impact on the boarding time.

DeVries (2009) proposed the use of digital displays and phone messages for asking passengers to board according to their seat positions. This approach should gain more credibility in the near future due to the vast and fast spread of smart phones and communication apps. By 2018, market forecast shows that more than one-third of the world population will own smart phones – nearly more than half of the traditional cell phone users (Statista, 2014–2019). Mobile technology will definitely open the door for a new breed of smart aircraft boarding strategies.

Several variations of the discussed boarding strategies have been proposed and investigated in the literature, which we did not capture in this paper. In a recently published comprehensive survey, Jaehn and Neumann identified most of the current aircraft boarding strategies, which are adopted in practice or studied in theory (Jaehn and Neumann, 2015). Their paper provides a general overview of the current literature, and discusses details of some key publications.

For a visual description of all the studied strategies, refer to the enclosed 3 min animated video. It is a screen-recording of the simulation's graphical output. This visual aid illustrates various boarding strategies through animated examples.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.jairtraman.2016.10.010.

## 3. Proposed strategy

The DOB strategy relies on a novel passengers sequencing process, executed right after closing the check-in counter and before opening the boarding gate. It iterates through the passengers' list and arranges them in a queue (sorted list), based on which they will be asked to board. Multiple iterations are usually required before all passengers are included in the queue. Later, the queued passengers will be invited on a one-by-one basis to line up in subsequent boarding batches. A novel lining approach is adopted to minimize delays and maintain continuity in boarding. To reduce boarding interferences, the order of passengers in a queue varies between different flights based on the cliques' number, sizes, and seats distribution.

The key guiding principle of the DOB strategy is to board passengers in an outside-in fashion while respecting the back-to-front order. As an exception, a passenger in a clique will accompany all clique members regardless of their seating positions, provided that they don't cause future seat interferences with subsequent passengers in the queue. Otherwise, this passenger along with the associated clique will need to board later, after the potential seat interferences are eliminated (i.e. after the passengers in the affected seats board first). The underlying queuing process of the DOB strategy is governed by three basic rules as discussed below.

*Rule (1)* – the passengers' order of boarding should be originally according to priority values assigned to their corresponding seats. The priority is highest when the value is 1; and, it decreases as the value increases. Within a given aircraft row, the window seats have the highest priority; and, the aisle seats have the lowest. From a column perspective, the back seats have higher priority than the front ones. The diagram in Fig. 1 shows 5 rows of a conceptual aircraft layout made of 20 rows and 6 columns. Each cell represents a seat with an alphanumeric identification – a letter for the column, and a number for the row. The rightmost and leftmost cells are the windows seats. The number inside each cell represents the corresponding original seating priority.

*Rule (2)* – passengers in a clique must board together regardless of their original seating priorities. If one of the clique's members is to be placed in the queue based on his/her assigned seating priority, the entire clique must be placed in the queue at that point regardless of the original seating priorities of its members. As an exception, if one of the clique members is in a seat that causes future seat interferences for subsequent passengers, the entire clique should wait until those seats are filled. For example, consider a clique of 4 passengers to be seated in 20A, 20B, 20C, and 20D as

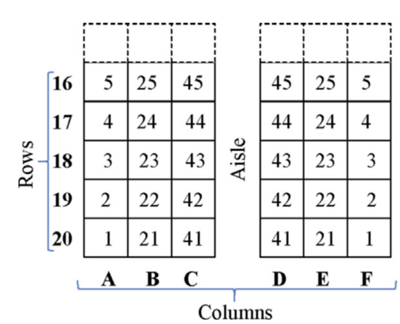


**Fig. 1.** Initial priority values assigned to seats according to DOB.

indicated in Fig. 2. Normally, those clique members should board at the moment when the occupant of seat 20A boards. However, since the occupant of seat 20D will cause interference for possible passengers in 20E and 20F, the entire clique cannot board before the occupants of 20E and 20F, in order to avoid potential seat interferences.

*Rule (3)* —Subsequent positions in the queue should not include passengers sharing the same aircraft row unless those passengers are all in one clique. This is a crucial rule in order to avoid aisle interference as passengers stow luggage in the cabin. Normally, 2 subsequent positions in the queue should include passengers that are 1 row-away from each other. However, if a queued passenger is a member of a clique, the subsequent position in the queue should include one of his/her clique members. Therefore, the next passenger coming after a clique must be in a seat that is n-row away from the first queued passenger of that clique; where, n is the clique's size. For example, consider a clique of 3 passengers seated in 20A, 20B, 20C who are to board as shown in Fig. 3. Passengers who occupy seats in rows 20, 19, and 18 should not immediately follow since their seats will be temporarily blocked by 3 stalled passengers. Evidently, those passengers need time to stow their luggage and occupy their seats. For this reason, the process should consider passengers who occupy seats at row 17 or below to be next in the boarding queue.

Guided by these 3 basic rules, the boarding process works as described in the flow chart of Fig. 4. In brief, the process starts with an empty queue and iterates through the list of passengers until all are placed in the queue. At each iteration, it goes through the list of un-queued passengers, by the order of seating priority, and decides whether to place them and their cliques in the queue or not. Queuing decisions are made in compliance with the three basic rules discussed above.

After including all passengers in the boarding queue, they need to board in batches according to their positions in the queue. The batch size depends on several factors such as the size of the aggregation area at the gate and the size of the aircraft. Ideally, the size of the batch should be equal to the number of rows in the aircraft. The passengers in a boarding batch must be aligned according to their order in the queue. Therefore, a particular procedure is required to ensure that passengers in a boarding batch are well aligned before they proceed to the gate. A special pre-boarding area may be dedicated for that purpose. For example, a batch of $k$ passengers can be aligned in two parallel columns, colored red and blue respectively. Each column should accommodate $k/2$ passengers to be standing in cells numbered from 1 to $k/2$. The cell's space does not need to be larger than a quarter square meter, just enough to fit a large-sized passenger possibly having a carry-on luggage. An area of $5 \times 1$ m$^2$ should be enough to comfortably fit 20 passengers, lining up in two parallel columns. As the passengers on the red column proceeds towards the gate, other passengers will be positioning themselves on the blue column, and vice versa. To mitigate the delay factors, passengers can be informed ahead of time about their corresponding columns and cells via a personal electronic message. The message can be communicated via a special mobile application, SMS message, or any free communication tool such as WhatsApp, and also through dedicated billboards. Passengers not carrying communication devices can be equipped with special notification devices, acquired at the check-in counter and dropped

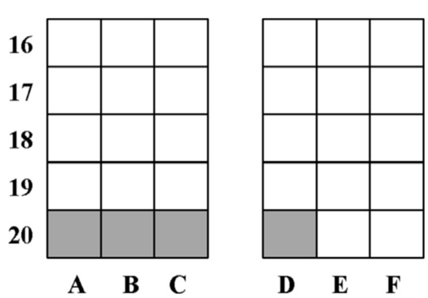


**Fig. 2.** Example of sharing priority value amongst passengers in a clique.

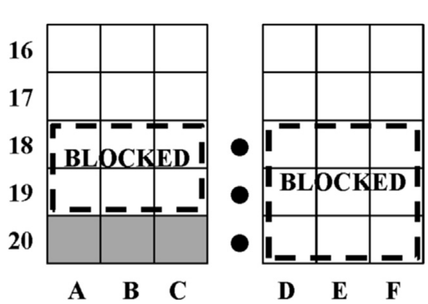


**Fig. 3.** Example of seats blocking by a clique of passengers.

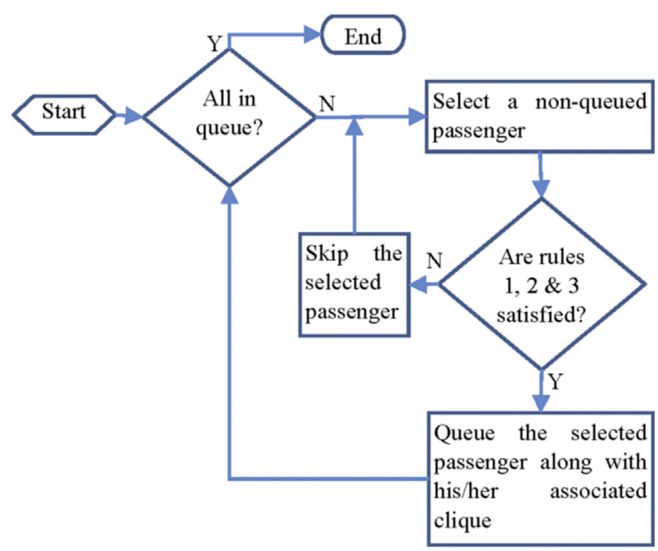


**Fig. 4.** The process to queue passengers based on DOB strategy.

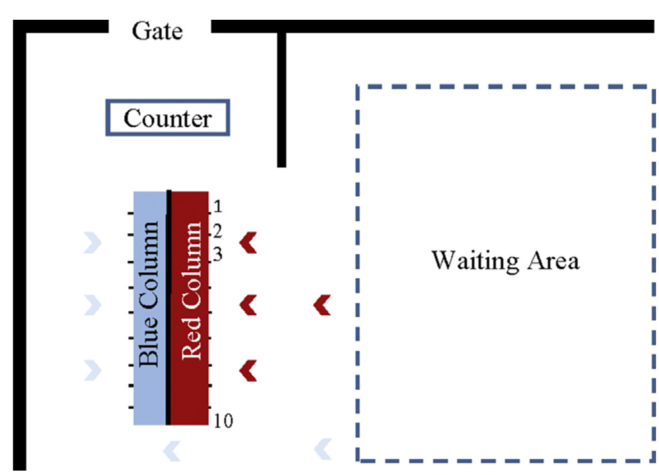


**Fig. 5.** Pre-boarding area to aggregate passengers before proceeding through the gate.

at the gate. Fig. 5 shows an abstract layout of the boarding area.

## 4. Simulation

To study the performance of the DOB strategy, we relied on a discrete event simulation, in which we modeled the behaviors of several boarding strategies and compared the performance results. In addition to the DOB strategy, the other boarding strategies that we modeled are: B2F, Random, WMA, Steffen, and SBG (Flying-Carpet). The use of discrete event simulations in studying the aircraft boarding problem is common in the literature. The simulation approach in this work builds on the cellular automata, discrete modeling schemes and related parameters reported in previous works (Ferrari and Nagel, 2005; Landeghem and Beuselinck, 2002; Steffen, 2008; Steffen and Hotchkiss, 2012; Tang et al., 2012b; Qiang et al., 2014; Milne and Kelly, 2014).

The standard time unit adopted throughout this study is the simulated time tick that models an elapsing time slot between two consecutive simulated events. The simulation's timer starts ticking when the first passenger enters the aircraft's aisle at the first row, and stops ticking when the last passenger sits down. We don't consider the time spent at the gate and on the bridge leading to the aircraft in this study. The modeled aircraft is a hypothetical layout of 20 rows and 6 columns, divided in half by a middle column representing the aisle. As in commercial aircrafts, the simulated aisle is too narrow to allow one passenger to bypass another. During the simulation run, we assign fixed average values to some essential parameters, such as the passenger's walking speed, the luggage's stowing time, the time to clear a seat interference, and the passengers' inter-arrival time. A seat interference can involve 1 or 2 seats depending on the number of passengers impeding the normal seating activity. Table 1 represents the values of some key parameters in time ticks as adopted throughout the simulation.

The average time to move down the aisle from one row to another is set to 1 time-tick throughout the simulation. Although the simulation results are in time ticks, it is worth mentioning that 1 time-tick is equal to 2.4 s as adopted in several research papers (Ferrari and Nagel, 2005; Landeghem and Beuselinck, 2002; Milne and Kelly, 2014). Furthermore, those papers assume that the time for a passenger to sit from a corresponding aisle position is more than the time to walk from one row to another by a factor of 3.3 on average. In the case of 1-seat interference, the time to clear the aisle is the time to sit multiplied by a factor of 3-one factor for the seated passenger to vacate the seat, one factor for the incoming passenger to sit, and one factor for the vacating passenger to sit again. In the case of 2-seats interference, the time to sit is multiplied by 5 - accounting for the time taken by the second interfering passenger to leave the seat and re-sit, in addition to the other 3 steps performed by the first interfering passenger. The average time to stow luggage is 3 time ticks according to the Bin Occupancy Model described in (Ferrari and Nagel, 2005). The stowing time is based on assuming one bin per half row with a bin capacity of 3 luggage items. The passengers' inter-arrival time at the aircraft depends on the time spent on clearing security at the gate. The average inter-arrival time is based on a Poisson distribution and set to 4 time ticks, which is close to the rate of one passenger every 9 s as observed through video footage in (van den Briel et al., 2005).

**Table 1**
Summary of main simulation parameters.

| Time parameters | Time ticks |
|---|---|
| Avg. walk time between 2 adjacent rows | 1 |
| Avg. time to stow luggage | 3 |
| Avg. time to sit with 1-seat interference | 10 |
| Avg. time to sit with 2-seats interference | 16 |
| Avg. passengers' inter-arrival time | 4 |

Some other parameters are used to indicate various simulation settings such as the percentage of customers that are in cliques of various sizes, and the percentage of passengers with carry-on luggage. The percentage of passengers who have carry-on luggage varied between 40% and 80% across different simulation runs. Furthermore, the percentage of passengers who are in cliques of various sizes varied between 25% and 75% across different runs. The size of a clique is between 2 and 6 passengers; around 80% of the cliques are of sizes 2 to 4. Clique members do not necessary sit in the same row. They might be spread across different seats at adjacent rows. At the start of every simulation run, the passengers are randomly allocated to seats, placed in cliques, and assigned carry-on luggage in accordance with the indicated parameters.

A full aircraft load is assumed, i.e. 120 passengers according to the adopted aircraft layout. The passengers are placed in a boarding queue according to one of the considered strategies, before starting the boarding process. The overall boarding time is the number of time ticks that elapsed from the beginning to the end of the boarding process. A simulation run is repeated 30 times for a given strategy and a specified set of parameter values.

## 5. Results and discussions

All simulation results are reported with a confidence level of 95%. Table 2 shows the boarding durations that are achieved by the considered boarding strategies, according to a given set of simulation runs. In these runs, the percentages of passengers with carry-on luggage or in cliques are assumed to be 80% and 50% respectively. The DOB strategy shows the closest performance to the optimum, which is recorded by Steffen. It performs slightly better than WMA. Although Steffen and WMA allows for fast boarding, their innate characteristic of not allowing clique of passengers to board together makes them impractical for civil aviation. The widely adopted B2F and Random boarding strategies show the lowest performance. The popularity of these 2 strategies is definitely not because of their performance, but stems from their simplicity and catering to the passengers' need to board in cliques. SBG shows an average performance, not in-line with what has been written in describing the supremacy of its Flying Carpet application. In addition, the reliance on an unguided and chaotic pre-boarding aggregation method makes the Flying Carpet an impractical choice. On the other hand, the pre-boarding process of the DOB strategy is certainly much more guided and organized. In addition, its solid performance, without compromising the passengers' need to board in cliques to their desired seats, makes it a favorable boarding option.

Table 3 shows the average boarding time per passenger. This is an important metric implying the level of aisle and seat interferences a passenger has to go through before occupying a seat.

**Table 2**
Boarding duration as achieved according to different strategies.

| Strategy type | Full boarding duration | Std. dev. | 95% confidence interval | |
|---|---|---|---|---|
| | | | Lower | Upper |
| B2F | 667.56 | 39.31 | 653.49 | 681.63 |
| Random | 661.26 | 32.92 | 649.48 | 673.04 |
| SBG | 547.56 | 20.83 | 540.11 | 555.02 |
| WMA | 496.86 | 26.5 | 487.38 | 506.35 |
| DOB | 490.1 | 21.74 | 482.31 | 497.88 |
| Steffen | 487.86 | 27.61 | 477.98 | 497.74 |

The shaded area shows time figures in time-tick unit (as reflected in Table 1).

**Table 3**
Average boarding time per passenger as achieved according to different strategies.

| Strategy type | Avg. boarding time per passenger | Std. dev. | 95% confidence interval | |
|---|---|---|---|---|
| | | | Lower | Upper |
| B2F | 41.78 | 4.25 | 40.25 | 43.30 |
| Random | 30.01 | 3.26 | 28.83 | 31.17 |
| SBG | 19.82 | 1.62 | 19.23 | 20.40 |
| WMA | 13.28 | 0.17 | 13.22 | 13.34 |
| DOB | 13.17 | 0.10 | 13.14 | 13.21 |
| Steffen | 12.95 | 0.10 | 12.92 | 12.99 |

The shaded area shows time figures in time-tick unit (as reflected in Table 1).

It is an important quality of service measure to gauge passengers' satisfaction with the boarding process. A smooth uninterrupted procession down the aisle is more appealing to a passenger than a jerky walk in a lane jammed with people. Steffen, being the optimal strategy as described earlier, has zero aisle and seat interferences, and provides passengers with the optimal walk time in the considered craft layout. The DOB strategy is not far from the optimum with respect to this metric, with a slightly better performance than WMA. WMA suffers from some aisle interferences due to the random order of passengers in a batch. The higher level of randomness in B2F, Random, and SBG strategies causes more aisle interferences as evident in the results. In the DOB strategy, although all passengers are arranged to proceed to their seats in a pre-calculated manner to eliminate seat interferences, minimal interferences are inevitable. Passengers in a boarding batch might cause some aisle interferences to passengers in a subsequent batch. Such scenario is typical when some passengers don't complete their stowing and seating procedure before a new batch enters the aisle. It depends on the inter-arrival time and happens mostly at the front side of the aircraft. In our study, we assume no special delay between batches other than the adopted inter-arrival time.

Table 4 shows the average number of seat interferences during the boarding process corresponding to the investigated boarding strategies. This is another quality of service metric for assessing passengers' satisfaction. It is not surprising to see that Steffen, DOB and WMA have zero seat interference since these strategies guarantee that passengers sharing a row will board in an outside-in fashion. On the other hand, 50–60% of passengers will experience a one-seat or two-seat interference when boarding according to B2F, Random, or SBG strategies.

To gauge the sensitivity of the investigated strategies with respect to the luggage load and percentage of passengers in cliques, we vary the corresponding parameters and collect the results. Under the normal assumption that a passenger takes on average 3 time ticks to stow luggage, none of the top performing strategies (i.e. DOB, WMA and Steffen) shows any sensitivity to varying the luggage load. This is attributed to the relatively short time to stow with respect to the inter-arrival time. A minor lag was noticed in the case of B2F and Random strategies. However, to better understand this sensitivity, we need to increase the possibility of aisle interferences by either increasing the time to stow luggage or decreasing the inter-arrival time. If the chance of interference is low, varying the percentage of customers with luggage will have negligible impact on the boarding time. Therefore, we opted to set the average time to stow luggage to a relatively high value equals to 12 time ticks in order to study the performance under worst case scenarios.

**Table 4**
Number of seat interferences according to different strategies.

| Strategy type | Number of 1 seat interference | Number of 2 seats interference |
|---|---|---|
| B2F | 58 | 26 |
| Random | 57 | 26 |
| SBG | 54 | 9 |
| WMA | 0 | 0 |
| DOB | 0 | 0 |
| Steffen | 0 | 0 |

The shaded area shows counts (number of interferences that occured during the entire boarding process).

Fig. 6 is a chart reflecting the sensitivity of each studied strategy to the percentage of passengers with carry-on luggage. For all strategies, the chart shows a positive correlation between the percentage of customers with one piece of luggage and the boarding time. Under the assumption of an extensively long stowing time, the boarding time increases linearly as the percentage of passengers with luggage increases. The rate of increase in DOB, Steffen and WMA is slower than B2F and Random. The worst rate is recorded in the B2F strategy. This degradation in performance is attributed to the level of aisle and seat interferences caused by the long stowing time. With moderate to low luggage ratios, the DOB strategy tends to provide a performance much closer to the optimum. This is attributed to the reduction in stowing activities happening at the front rows, which could cause interferences with a subsequent batch of passengers.

Fig. 7 is a chart showing the sensitivity of the studied strategies to the percentage of passengers who are traveling in cliques. For some strategies, a positive correlation exists between the boarding time and the percentage of travelers in cliques, especially when the stowing time is extensively long. It is not surprising to see that the boarding times of Steffen and WMA remain stable since both strategies do not observe the clique's characteristic. They require passengers to board the aircraft individually regardless of their associations with cliques. On the other hand, the boarding time according to DOB, B2F or Random strategy tends to be longer with more passengers being in cliques. When the percentage of cliqued passengers is moderate, DOB performs slightly better than WMA and tends to be closer to the optimum. However, when this percentage increases, WMA slightly outperforms DOB. With the DOB strategy, a sequence of passengers being in clique usually takes longer time to board than a similar sequence of passengers not being in clique. Clique's members may need to wait for other members in the clique to stow luggage before proceeding to their

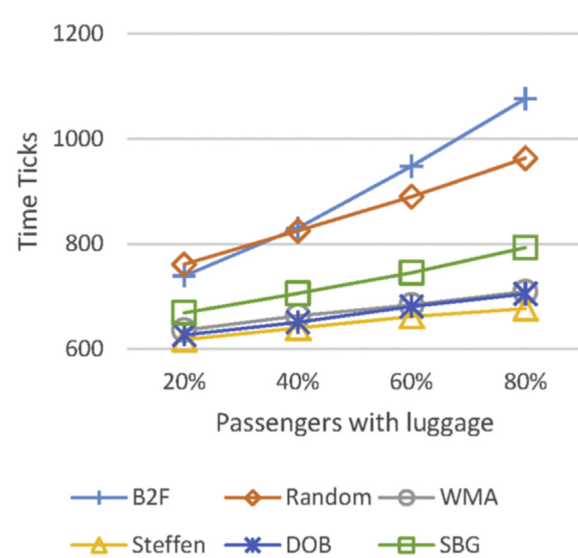


**Fig. 6.** Sensitivity to the percentage of passengers with carry-on luggage.

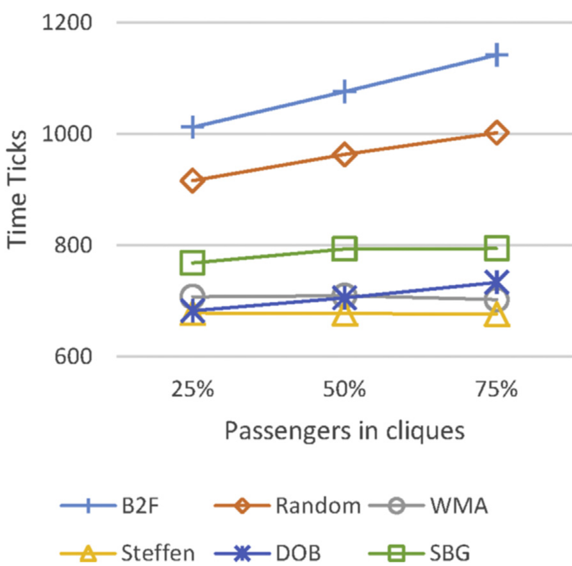


**Fig. 7.** Sensitivity to the percentage of passengers in cliques.

seats. On the other hand, a sequence of passengers traveling solo does not get blocked by a stowing passenger since the DOB strategy makes sure that independent passengers in a sequence are seated at different rows. Thus, having more cliques means more intra-clique interferences, which would lead to an increase in boarding time. Even though the noted increase is minimal and not worrisome, it is highly unlikely to occur. Statistical reports indicate that the number of passengers traveling in cliques does not exceed 50% of the total passengers count in a normal commercial flight (Jaehn and Neumann, 2015).

Fig. 8 is a chart representing the sensitivity of the boarding strategies to the passengers' inter-arrival time. For all strategies, the chart depicts a positive correlation between the inter-arrival time and the boarding time. The DOB, Steffen and WMA strategies maintain their optimal performance and supremacy compared to the B2F, Random and SBG strategies across all the tested inter-arrival times. The boarding time increases by increasing the inter-arrival time for all strategies, but at different rates. The best performing strategies seem to suffer more than the other strategies.

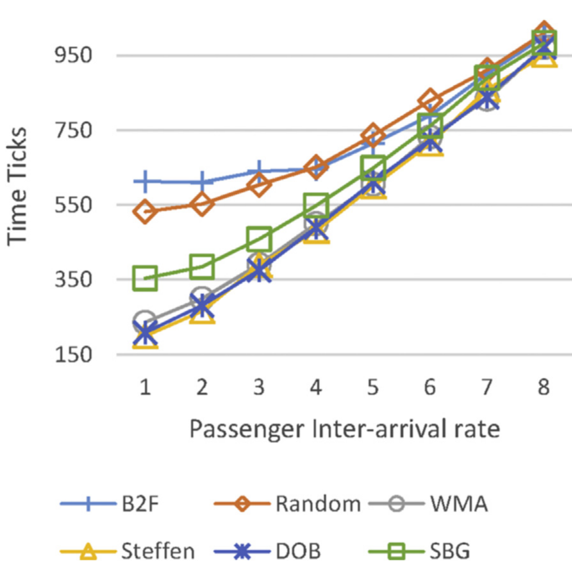


**Fig. 8.** Sensitivity to the passengers' inter-arrival rate.

With longer inter-arrival times, all strategies tend to converge and yield close boarding times.

## 6. Conclusion

In this paper, we proposed the Dynamically Optimized Boarding (DOB) strategy as a novel approach to reduce the aircraft boarding time. The new strategy not only helps the airline companies and airports to reduce turnaround time, but also satisfies the passengers' crucial need to board in cliques. Furthermore, it ensures the seating of passengers in their preferred seats with minimum boarding interferences.

The underpinning core of this strategy is a queuing process that dynamically arranges passengers in a boarding sequence. The objective of the queuing process is to minimize seats and aisle interferences. It also has to observe the clique's crucial requirement to proceed together to their preferred seats. This process is applied right after the last passenger checks in. To implement the DOB strategy, airline companies need to amend their booking information systems in order to automatically sort the passengers' list and place them in a queue (sorted list) right after closing the check-in counter. Once the queue is ready, the boarding process can start by posting or sending personalized notifications to passengers asking them to line up according to their positions in the queue. Technology could be a perfect aid to manage the boarding process. Airline companies need to adopt electronic notification systems for disseminating boarding information to passengers through their personal devices or other public messaging tools. To impose order and reduce jitters in arrival time at the gate, a small pre-boarding area is assumed to aggregate batches of passengers before they proceed to board the aircraft. In this case, the airline companies and the airports should cooperate to dedicate special pre-boarding areas and to use special notification billboards.

The DOB strategy yields a near-optimum performance as compared to the Steffen strategy, which provides optimum boarding time but without observing the passengers' requirement to board in cliques. The DOB provides a slightly better performance than the WMA strategy, and a substantial improvement as compared to the widely used strategies – Random and B2F. In addition, the DOB strategy proves to be resilient and robust against variations in the percentage of carry-on luggage, the percentage of passengers in cliques, and the passengers' inter-arrival time.

Future work could investigate and compare boarding processes through quantitative and qualitative analysis involving passengers' feedback. In addition, some valuable insights could be gained from analyzing the sensitivity of the boarding time with respect to the unorderly arrival of passengers at the gate.

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