Robustness of Efficient Passenger Boarding in Airplanes

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Abstract

A common wisdom is that airplanes only make money when they are in the air. Therefore, turn-around times ("turn times") on the ground should be reduced as much as possible. An important contribution to the turn time is airplane boarding. Many different schemes are in use here, from random seat selection to sophisticated boarding groups. This paper describes a simulation model to evaluate different boarding strategies. In contrast to earlier work, it puts special emphasis on disturbances, such as a certain number of passengers not following their boarding group, but boarding earlier or later. A surprising result of our work is that the typical "back-to-front" boarding strategy in fact gets improved when passengers do *not* follow their assigned boarding group. We also propose strategies that still consist of small numbers of boarding groups, but are both faster and more robust against disturbances.

1 Introduction

Today's airline problems are based on the competitive morality and the pricing pressure. The companies have to reduce their costs an any level. The airplanes have to work at full capacity and the airplane turn-around time ("turn time") has to be minimized. Nevertheless the punctuality of flights should be ensured. Masses of passengers waiting for hours and overcrowded airport facilities indicate that this goal is not yet achievable in holiday season. To reduce the idle time of airplanes, optimisations can start at any point between arrival and departure.

The deplanation process, aircraft cleaning and passenger boarding are the three elements from which the turn time is depending. The passenger boarding is the part that takes the longest time and is therefore the most important one. Different solutions have been proposed to reduce the boarding time and there are a lot of airlines using different methods. The main goal is to get the passengers sitting on their favorite seat in a fast and efficient way. This is highly dependent of the passengers behavior inside the craft. The aisle is typically narrow, the passengers are often carrying luggage that disables them to pass and a even few persons can delay the whole process.

To reduce disturbances, passengers are often divided into so called boarding groups entering the craft one after another. Inside the aircraft these groups are arranged over the seats in a manner that should avoid interferences between passengers. The number of boarding groups should be as small as possible, otherwise the call-off gets complicated. To test the behaviour of boarding strategies under different conditions we designed a sophisticated simulation environment. It does not only enable us to take a closer look at existing solutions but lets us also easily implement new strategies to achieve even better results. The solutions proposed in this paper will improve the passenger boarding process considerably. Airlines introducing such strategies will reduce their costs by minimizing the turn time of their fleet.

2 Other Solutions

We found only a few published papers on optimising the passenger boarding process of airplanes. A wide palette of boarding strategies has been simulated systematically by Van Landeghem and Beuselinck (VLB) (*1*). Their results will be discussed throughout the paper, in comparison with our own results.

The aircraft boarding problem has also been analysed theoretically as a nonlinear assignment problem (*2*). The problem is modeled as a binary integer program where the objective function is the minimization of the total number of interferences. The study showed that outside-in loading strategies perform better than back-to-front do. Disturbances have not been taken into account.

And finally the whole turn time process was investigated using a enplane-deplane simulation for Boeing (*3*). Various interior configurations of a Boeing 757 have been tested on different boarding strategies using a discrete event simulation. Boeing also verified the results with real passengers representing a typical traveling population.

Kirchner at al have used a simulation technique similar to ours (*4*). They concentrate, however, on egress behavior, which is easier to model since all passengers have the same destination ("outside"). This statement still holds if there are multiple exit doors, since even with multiple exit doors, the driving force can be generated by a single potential which is the same for all passengers. In contrast, they have compared their simulation results with actual field measurements. In consequence, a fair amount of effort in their work is spent on calibration and sensitivity testing with respect to passenger movement parameters.

3 Our Solution

Our examination is based on the studies of VLB. Our work differs to their work in some important points:

- While their model uses random process times with triangular distribution for passengers movement, our model applies deterministic constant process times as described in section 3.2. In addition, some details such as the luggage loading delay, are not fully described in their paper.

  It will turn out that the results are robust under such simplifications and assumptions. The main result is, as in VLB, that completely random boarding is faster than the standard "back to front" boarding used by many airlines (*).

- We will also look at the robustness of the strategies under disturbances. By disturbances we mean that passengers do not enter together with their assigned boarding groups, but earlier or later. Since early boarding can be prevented by the staff, this is treated separately from late boarding. We will then also look at strategies that are both simple to implement *and* robust under such disturbances.

Rather obviously after the result denoted by "(*)", the typical boarding strategy, "back to front", becomes *more* efficient under disturbances. That is, in the interest of efficient boarding, passengers should be encouraged *not* to follow the row announcements. There are, however, strategies that are more efficient than random, and predictably, their performance degrades under disturbances.

3.1 The Aircraft Model

For our considerations, we are interested to optimize short haul flights, because their percentage of the turn time is much bigger than those of long intercontinental flights. For comparability, we use the same standard airplane as VLB that is typical for such flights. The aircraft has 132 seats consisting of 23 rows. Row 1 and 23 have 3 seats only, the others 6. It is clear that the same simulation model can also be used for other airplanes.

As said above, we use an entirely cell-based representation of the airplane: Our plane is discretisized into rectangles, where every seat and the width of the aisle corresponds to exactly one field. We assume that a passenger with luggage takes as much room as a seat and there is no space modeled between the rows. The airplane is always entered by the front door. One important result of this paper will be that such a simplified representation of space leads to results that are very similar to the results obtained with a model with continuous space representation.

3.2 The Passenger Model

VLB use a triangular distribution for passenger movement, with values $(1.8, 2.4, 3)$ (i.e. a tri-angle starting at 1.8, reaching its maximum at 2.4, and ending at 3). Our model, in contrast, uses a deterministic process, where a passenger can move one cell/row forward per time step, if the destination cell is free. This means that one time step of our simulation corresponds to 2.4 seconds of VLB's simulation. We will only compare the efficiency of strategies measured in steps and will not calculate absolute boarding times.

During one simulation timestep all cells representing passengers are processed once and in random order. All actions are based on one grid, therefore our simulation implements a serial update of passengers state/position.

Passengers will enter the front door and queue in a single line until they reach their assigned seat. The passenger will now put his/her carry-luggage into the overhead bin or place it underneath the seat and finally sit down. Different conflicts can occur during this process:

- As passengers enter, the overhead bin fills up and it takes longer to find free room for luggage. They may even have to move to another row to store their luggage, but this will not be included into the simulation.
- The second interference is caused by seated passengers. E.g. a passenger seated in an aisle seat is in the way if another passenger has to get into the window seat. In this case the sitting passenger has to get up, leave the row and sit down again after the passenger near to the window has installed. We will call this kind of interference *seat interference*.

In both cases, upstream passengers need to wait until the process is finished.

3.2.1 The Bin Occupancy Model

There is an overhead bin for each row on each side of the aisle. We include a similar bin occupancy model as in the simulation of VLB. To every passenger a random number of pieces of luggage is assigned as listed in Tab. 1. The time (in simulation time steps) that the travelers need to store their pieces depends on the luggage they carry and the occupancy of the overhead bin as follows:

$$t_{sl} = 2 + \frac{n_{bin} + n_l}{2} * n_l \ , \tag{1}$$

with
t_{sl} : the time to store all pieces of luggage [simulation time steps]
n_{bin} : the number of pieces of luggage already in the bin
n_l : the number of pieces of luggage carried by the passenger

Fractional results for t_{sl} are rounded to the next integer. Note that according to Tab. 1 all passengers in our simulation carry at least one piece of luggage.

The values of n_{bin} refer to the corresponding half-rows underneath; passengers always put their luggage into the bin corresponding to their half-row.

In reality, if the overhead bin gets full, passengers may have to move to other rows to find a suitable location for their luggage. This is not reproduced directly by the simulation; however, note that t_{sl} becomes rather large for full bins. – The equation used by VLB was not available.

3.2.2 The Seating Model

The time passengers need to sit down depends on the number of interfering passengers that are already seated. Those interfering passengers passengers have to get out of their row, and then sit down again after the seating passenger has taken place. The mathematical form of this is (once more in simulation time steps)

$$t_s = t_p + 2 * t_p * n_s = t_p\,(1 + 2\,n_s)$$

where
t_s : total time for seating [simulation time steps]
t_p : time used to get from the seat into the aisle or back [steps], t_p = 1.5
n_s : number of occupied seats in front of the passenger's seat .
Once more, results are rounded to the nearest integer.

The formula of VLB was not available. Their text implies that they use $t_s = n_s\,t_{out} + (n_s + 1)\,t_{in}$, with different times t_{out} and t_{in} for getting up and sitting down. Those times are tri-angular distributions; in simulation time steps, the values of the corner-points are $(1.25, 1.5, 1.75)$ (mean 1.5) and $(2.5, 3.75, 12.5)$ (mean ≈ 5.9). That means that our t_{out} is similar to theirs, but our t_{in} is considerably faster. This should be kept in mind since it will explain why their results have larger differences between conflict-rich and conflict-poor strategies than our results do.

3.3 Disturbances

In our simulation we introduced different disturbances

- Early and/or late passengers: If passengers are divided into boarding groups, it will often occur that some arrive late or early. The number of these passengers will increase with the number of boarding groups. At the ticket reader system, the boarding staff has the possibility to reject passengers that enqueue in a earlier boarding group. For travelers that are arriving late, access is always granted. We will see how much the ratio of late and early arriving passengers will influence the quality of the boarding strategies.
- Aircraft dimensions: A boarding strategy should be robust under the use of different airplane layouts.
- Occupancy level of the airplane: Airplans are not always full, and therefore boarding strategies should be efficient also with smaller occupancies. However, boarding with the same strategy but with fewer passengers will in the average always be faster than when the plane is full. As long as the scheduled turn times (and therefore the flight schedule) are not adjusted to the expected demand, there is little need to test boarding strategies for reduced occupancy. Nevertheless, for completeness we will add such results.

  For reduced occupance, there are four criterias that influence to which seat a passenger is assigned.

  - To avoid balancing problems, the number of passengers sitting on the right side of the aisle should be about equal to the number of passengers sitting on the left side.
  - For the same reason, the number of passengers sitting in the front area should be equal to the number of passengers sitting in the back area.
  - Window and aisle seats are assigned first.
  - Passengers have preferences (e.g. exit row, seat near front of airplane for quicker exit). This is not modeled by the simulation and will therefore not be taken in further account.

  Technically, our simulation assigns first all window seats randomly, then all aisle seats randomly, and then all center seats randomly. That is, there are no preferences for any part of the airplane, but fluctuations generated by the randomness are accepted.

3.4 Boarding Strategies

In a first step we simulate the same boarding strategies as VLB under varying conditions. In a later part we compare improved boarding strategies using the same nomenclature. The strategies are also depicted graphically in the appendix.

- *block*: to build boarding groups, the airplane is divided vertically (from back to front) into blocks.
- *half_block*: the airplane is divided into boarding groups vertically and horizontally (right and left side of the aisle).
- *block_des* means that the blocks are called in descending order.
- *block_X_alt_Y* means that there are X blocks which are called in alternating order, skipping Y blocks. For example, in a scheme with 5 blocks one could first call them in the sequence 5,3,1,4,2. We would call this *block_5_alt_1*.
- *row*: every boarding group corresponds to a row. For an airplane with R rows, *block_R_...* and *row_...* is the same.
- *half_row*: every boarding group corresponds to the half of a row divided by the aisle.
- *row_alt_Y* means once more that Y rows are skipped.
- *letter*: the letter of the seat indicates the place in a row; every boarding group corresponds to one or more letters/columns. When the airplane is boarded from the front, and the front is assumed to be on the bottom, then letters ascend from the right to the left.

  letter_wintocorr means sequence F, E, D, A, B, C. *letter_alt* means sequence F, A, E, B, D, C. No systematic differences between these two strategies are expected. *letter_outsidein* means sequence (F,A), (E,B), (D,C), where the brackets indicate that the corresponding columns are boarded as one boarding group.
- *seat*: the sequence of every single passenger is determined, every boarding group consists of only one seat.

  The advantage of this is that passengers can be lined up exactly; for example, one can, for letter F, have the passengers enter exactly in the right sequence, then for letter E, etc.; this is called *seat_des_row_letter*. It is intuitively clear that this is a very good strategy. However, because the number of luggage pieces varies stochastically from one passenger to the next, it is not necessarily the absolutely optimal for a given set of passengers with given luggage. Nevertheless, the simulations confirm that this strategy has the best average performance. It is, however, too complicated for real-world use.

  In order to gain some more intuition with complex strategies, variations of seat strategies are tried. These are too complicated to describe in words; please consult the appendix.

Both *letter* and *seat* strategies make neighbors enter the airplane at different times. This may be undesirable when the neighbors know each other and want to travel as a group.

3.5 Call-Off Systems

To control the sequence of the boarding groups, a call-off system is needed. Typically, gate agents announce which boarding group is allowed to board. The passengers are often called in rows e.g. “rows 10 to 15”. Alternatively, boarding groups could be denoted by numbers on the boarding cards, or by colors of the boarding cards; and the boarding groups could be announced or indicated by colored lamps. Another possibillity is the use of numbered tickets and a display that indicates the current boarding number comparable to those used in banks, post office or supermarkets. An alternative to the display would be the use of numbered marks on the floor, to which people have to enqueue before boarding. The last two systems are only applicable if passengers board through a fingerdock.

4 Validation

We modeled the same boarding strategies as VLB. To be consistent with their work, we did the same as they did and performed five replications of each strategy and averaged over them. The occupancy level of the airplane is 100%, all kind of disturbances are ignored.

4.1 Average Boarding Time

First we compare the results for average boarding times, see Fig. 1. Simulation time steps are multiplied with 2.4 sec/step as is plausible from Sec. 3.2.

The somewhat surprising result of this is that our much simpler simulation re-generates nearly exactly the performance profile of VLB. If one would multiply our results of Fig. 1 by 1.25, then our results would nearly completely co-incide with their results. In fact, the most important exception to this is the optimal strategy *seat_des_row_letter*, the advantage of which over the other strategies is less in our simulations than in theirs. The authors were contacted about possible reasons for that difference, but no reply was obtained. Yet, even without completely understanding those differences, it is a strong indication for the robustness of these simulations that a simple reimplementation with a different technology leaves the relative strengths of the different strategies completely intact.

The general interpretation of this figure, consistent with VLB, is as follows:

- Block strategies (*block_N_X*) are most efficient with just one boarding group and become increasingly inefficient with more boarding groups. Note that *block_1_des* is just plain random boarding.
- Filling up the airplane from the back row by row is inefficient. This is due to the fact that there are always conflicts in the area where passengers are in the process of seating themselves, while no seating is done in other areas of the airplane. Row strategies become better when rows are skipped.

  These two results together already give a very important conclusion: *Boarding by row from the back is inefficient* because of localized conflicts. Making the blocks larger reduces those conflicts, and they are maximally removed when there is only one block, i.e. random boarding. VLB had exactly the same result.
- The performance of left-right block strategies (i.e. first left then right; *halfblock_N_X*) ist slightly better than those of normal block stategies but not significantly better than random boarding.
- Combining left-right, by-row, and alternating rows can be fairly efficient, as *halfrow_alt_2* shows. Unfortunately, this strategy is rather complicated.

  VLB explain this: Such strategies are efficient if the number of "jammed" people fits in between the "busy" rows. For example, if passengers board by half-rows, then there are 3 people busy with a half-row, using up the row itself plus two rows upstream. Therefore, those two rows need to be skipped in order to arrive at the next row that can be used efficiently. This leads, with our airplane, to "*alt_2*" for efficient half-row strategies, and to "*alt_5*" for efficient row strategies.
- Boarding from the window to the corridor (*letter_wintocorr*) is more efficient than random boarding.
- Completely determining the boarding sequence allows to obtain significant improvements, nearly halving the boarding time when compared to random boarding or to block boarding. This is however even more complicated than *halfrow_alt_2*.

The overall result is that block boarding is even less efficient than random boarding (i.e. no system at all), and that within the considered strategies, there are no simple and good alternatives. This statement is consistent with VLB.

At first sight it is not obvious why the block strategies fail. Looking at the graphical representation of the simulation it reveals that there are a lot of passengers sitting in the same row as their predecessor. As there is only room for one passenger in the aisle while storing luggage, the consequence is a tailback. This effect increases with the number of blocks since there is a higher probability that passengers entering together will also be in similar rows. In contrast, alternating the sequence can help. In all cases, random boarding is more efficient and does not need any call-off system. From the point of view of boarding efficiency, *there is no reason for using block-strategies*.

4.2 Average worst case

As discussed above, for airlines introducing new boarding strategies not only the average boarding time is of interest but above all the possiblillity of very bad boarding times. Taking this into consideration, we will now no longer score boarding strategies after the average boarding time but after the average worst case of the boarding time measured in timesteps. The average worst case is calculated using the Root Mean Squared Error, as follows:

$$AverageWorstCase = AverageBoardingTime + 3 * RMSE \ ,$$

where $RMSE = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} (s_i - \overline{s})^2}$,
$s_i =:$ boarding time of run i,
$\overline{s} =:$ average of all boarding times for this strategy,
$n =:$ number of replications.

To justify the use of the Root Mean Squared Error, Fig. 2 shows that the distribution of the boarding times is symmetric. This plot is representative for all other strategies examined. Although no further attempts have been made to justify that the underlying distribution is exactly Gaussian, the plausible interpretation of our measure is that approximately 95% of all boarding events are faster than our number.

Average worst performance is shown, together with average performance, in Fig. 3. Boarding strategies that have a good average performance also have a good average worst case performance. Importantly, the absolute difference between average standard and average bad performance increases with increasing average boarding time. That is, strategies that are already bad have even stronger fluctuations to the worse. Nevertheless, the ranking of the strategies according to bad case performance is similar to the ranking of the strategies according to average performance. – VLB have a similar result.

5 Robustness of boarding strategies under disturbances

An important aspect of real-world boarding is that passengers often do not follow their boarding groups. Passengers attempting to board early can be caught by the personnel, but at the expense of leaving an unfriendly impression. Nothing reasonable can be done about late passengers. The important question here is in how much early and late boarders affect the efficiency of the strategies. Two questions seem of particular importance:

- What is the advantage/disadvantage if personnel lets early boarders slip through?
- What is the average worst performance of a strategy? A strategy with a good average performance but frequent outliers may be less desirable for an airline than a strategy that is worse in the average but more reliable.

In contrast to Sec. 4, 50 replications of the runs are used to achieve more accurate results.

5.1 Effect of Early / Late Passengers

To examine the effect of early and late passengers on the average worst case, we perform 50 replications on every strategy using a full aircraft. We simulate the case where a given percentage of the passengers enters late and the case where they arrive early *and* late. Results showed that there is no significant difference between the two possibilities. In other words: If 20% of the passengers are off-time, half of them early and half of them late, then the effect of the disturbances can be reduced to 10% if all early boarding attempts are rejected.

In Figure 4 curves for the average worst case under 20%, 40%, and 80% of late arriving passengers are plotted. When increasing fractions of passengers arrive late, then the boarding time approaches the value of the *block_1_des*-strategy, since that strategy just means that all passengers enter randomly.

The simulations show that, also under disturbances, the block strategies continue to perform worse than plain random boarding. More importantly, the more passengers do *not* follow the boarding groups, the *better* the block strategies become. The effect becomes more pronounced with more boarding blocks. In some sense, this is clear since we had already established that random boarding performs better than boarding by block, and so it is clear that introducing randomness will pull the block boarding strategies towards the random boarding performance. In another sense, however, the result is quite troubling, because it says that a passenger *not* obeying the airline boarding call in fact *improves* boarding efficiency.

Since this goes against conventional wisdom, let us expand on this point a bit more. Boarding back-to-front essentially means that there is a lot of conflict-causing loading activity in the current boarding block, while there is no loading in other parts of the airplane. In this situation, passengers boarding at times when they are not called means that they will do loading in areas of the airplane with little current activity, thus increasing the amout of loading that can occur “in parallel”.

Descending halfblock-strategies are very stable on passenger conflicts, but do not improve the effiency compared to the random-strategy. The average worst case of the boarding time will increase with the number of halfblocks for the same reason as for block-strategies. Alternating halblock-strategies seem to be stable also, *halfblock_6_alt_1* and *halfblock_10_alt_1* reach a good performance. These strategies need twice as much boarding groups as comparable block-strategies. *Halfblock-strategies are also not recommended*, but in case they are used anyway, then alternating variants should be preferred.

The highest (= worst) peak in Figure 4 belongs to the Row-strategy, because every seat interference will interrupt the boarding of the actual group. Alternating row-strategies can improve this once more.

The descending halfrow-strategy results in bad performance. Alternating the half rows helps massively but the strategies seem to get very unstable if passengers do not arrive at time. The probability for passengers arriving late can be expected to be quite high as a consequence of small boarding groups. *Alternating halfrow-strategies are only recommended in combination with a reliable call-off system*.

Letter-strategies show an acceptable stability and are easy to introduce in practice as they need small numbers of boarding groups. *We recommend using letter-strategies*.

Seat-strategies determine the sequence of boarding passengers to the individual. Every boarding group has so to say only one member. In practice it will be costly to introduce such a system and in addition it needs to be very reliable because of great unrobustness in case of passenger disturbances.

5.2 Free Seat Choice

Some airlines do not offer any numbered tickets at all, the passengers choose their favourite seat once they are inside the airplane. As the number of sold tickets is limited to the capacity of the plane, no booking system is necessary. This kind of boarding puts the travellers under pressure; it is therefore unsuitable for business- or first class-passengers.

Free seat choice models are more difficult to simulate than models with fixed seats since for free seat choice a model of human behavior needs to be included. For our simulations, the following assumptions were made:

- window seats and seats near the aisle are the passengers' favourite
- free rows will be preferred
- before sitting down, the passenger will ensure that there is no better place in the next few rows
- if passengers are queueing, it is possible that they lose their patience and accept a more unsuitable seat as they expected
- if a passenger arrives at the last row with free seats he will sit down there
- passengers will not change their walking direction to find seats

It is very hard to predict the exact behaviour of passengers and other assuptions will probably lead to different results. Nevertheless we can obtain a good impression how this strategy will behave. The simulation shows that at the beginning people board the plane fast. Later the strategy gets very inefficient, because of increasing seat interferences (middle seats are occupied last), black line in Figure 6. *Free seating should not be used* if fast loading of fully booked airplanes is the objective. However, if low administrative overhead is needed and airplanes are usually not full, then they are a viable alternative.

5.3 Improved Boarding Strategies

We will try to modify the best case (*seat_des_row_letter*) to decrease the number of boarding groups while retaining as much of the good performance as possible. As we will see there exist strategies that are reasonably simple, but still fast and robust.

- Seatgroup strategies: We fill the airplane corresponding to the *seat_des_row_letter*-strategy but instead of single seats we use groups of seats. The seating is divided horizontally into a specified number of groups and horizontally by coloumns (letters). The boarding groups are called in descending order from back to front and from the outside to the inside. For an airplane with R rows, *seatgroup_R_des_row_letter* and *seat_des_row_letter* is the same.
- Pyramid strategies: The number of boarding groups can be further reduced while retaining some of the good performance of the seatgroup strategies by merging passenger groups from the seatgroup-strategy diagonally. We will call this strategy *pyramid_des* as the passengers board the craft pyramid-shaped.

  This is a combination of outside-in and back-to-front: the window seats at the back of the plane are boarded first (group 1); then the window seats in the middle part of the plane and the middle seats at the back of the plane are boarded (group 2); then the window seats at the front of the plane, the middle seats in the middle of the plane, and the aisle seats at the back of the plane (group 3); and so on. Supposedly, American Airlines is already using this strategy.

Figure 4, on the right, also shows the two improved strategies as just described. They achieve very fast boarding. Pyramidal boarding needs fewer boarding groups than seatgroup boarding, but is slightly slower. *Both strategies are recommended*.

One should, however, note that all efficient strategies have a tendency to separate neighbors from each other. This may not be desired by passengers traveling together. However, conflicts to a large extent stem from passengers entering a row in the wrong sequence. Since this is not to be expected from passengers traveling together, there is a good chance that leaving row neighbors together even if that is inconsistent with the boarding group will *not* make the boarding system inefficient. Such tests could be the focus of future work.

6 Sensitivity

6.1 Effects of Aircraft Dimensions

As we score boarding strategies, we always refer to our standard airplane dimension. There are strategies that are expected to be dependent of the aircraft model.

We perform the same simulations on a second aircraft model with the same number of seats, but eight instead of six passengers in every row. Figure 5 shows the average worst cases for the standard and the modified airplane model. As one can see, the boarding takes more time overall, but there are some strategies that behave particularly bad, e.g. *row_alt_4* or *halfrow_alt_2*. In contrast, seat-strategies are more robust, as are letter, seatgroup and pyramid-strategies. The other strategies show great instability.

Note that the size of the luggage bins remains unchanged, which in our model formulation means that the 4th passenter in a row is faced with strongly increased luggage storing times. Nevertheless, the fact that the fastest strategies are nearly unchanged between the two airplane layouts indicates that luggage storage is only a small part of the boarding time.

The conclusion is: If a robust boarding strategy is intended to be used for different seat layouts, only *letter-, seat-, seatgroup- and pyramidal-strategies are recommended*.

6.2 Effects of Aircraft occupancy

To find out how the efficiency of strategies depends on the aircraft occupancy we choose a representative strategy of every group. These strategies are evaluated under different occupancies between 10% and 100%. The plots of the results are more or less parallel. If the airplane is loaded more than 50% the scoring remains almost the same. There are some strategies that seem to work slightly more efficient than others if the occupancy remains under 40%. This behaviour will not influence our final results, because in these cases the time required for passengers to board is short and will therefore affect the turn time very little. However, average occupancies can expected to be higher than 50%.

6.3 Aspects of luggage loading

A currently much-debated issue is in how far the restriction of carry-on luggage will reduce boarding times. In general, just restricting the amount of carry-on luggage will accelerate the boarding process, since the average luggage storing times according to Eq. (1) will be reduced. The issue gets more complicated when there are correlations – for example privileged passengers with more carry-on luggage concentrating in the front of the airplane. Such considerations were outside the scope of this paper. However, the microscopic simulation approach would allow to easily add such aspects and evaluate them in a systematic way. Since this involves correlations between seating and carry-on policy, this should probably be done in collaboration with an actual airline.

7 Summary

- Using a model for airplane boarding that is only roughly based on previous work reproduces the results surprisingly well.
- The often-used block-strategies are inefficient as they *prolong* the passenger boarding process compared to random boarding. In fact, passengers ignoring the boarding calls *improve* the performance of those strategies.
- Halfblock-, row and halfrow-strategies are not recommended, the benefit is too small compared to the large number of boarding groups. Some of the halfrow strategies display good performance, but that is highly dependent on changes in the skip amount (number of skipped rows between boarding groups).
- “Boarding by column” (letter) strategies are recommended. They are less efficient than some of the “halfrow” and the explicit “seat” boarding strategies, but more efficient than the block strategies. Also, the result is more robust than for the “good” halfrow strategies, in the sense that it does not depend on implementation details such as the exact number of skipped rows. Finally, the number of boarding groups is relatively small.
- The best choice are seatgroup-strategies. They provide excellent efficiency and good stability combined with a relatively small amount of boarding groups.
- It is possible to combine some of the seatgroups in a diagonal pattern. This leads to a small number of boarding groups, with a performance that is still better than random boarding.
- The good strategies are reliably good even for changes in aircraft layout and for occupancies less than 100%.

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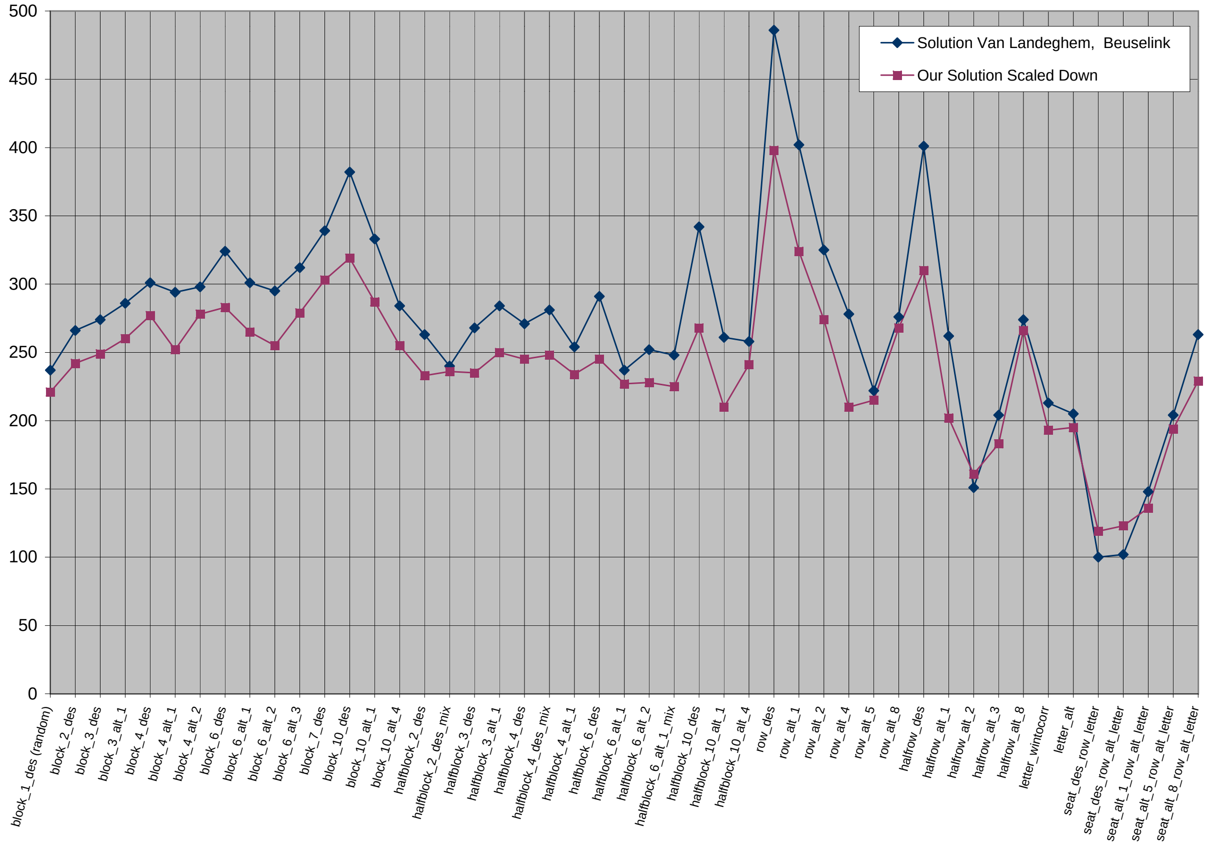


FIGURE 1: Comparison of average boarding times. Boarding times, on the y-axis, are given in seconds. Conversion of simulation steps into seconds is based on the "2.4 seconds per simulation step" explained in the text.

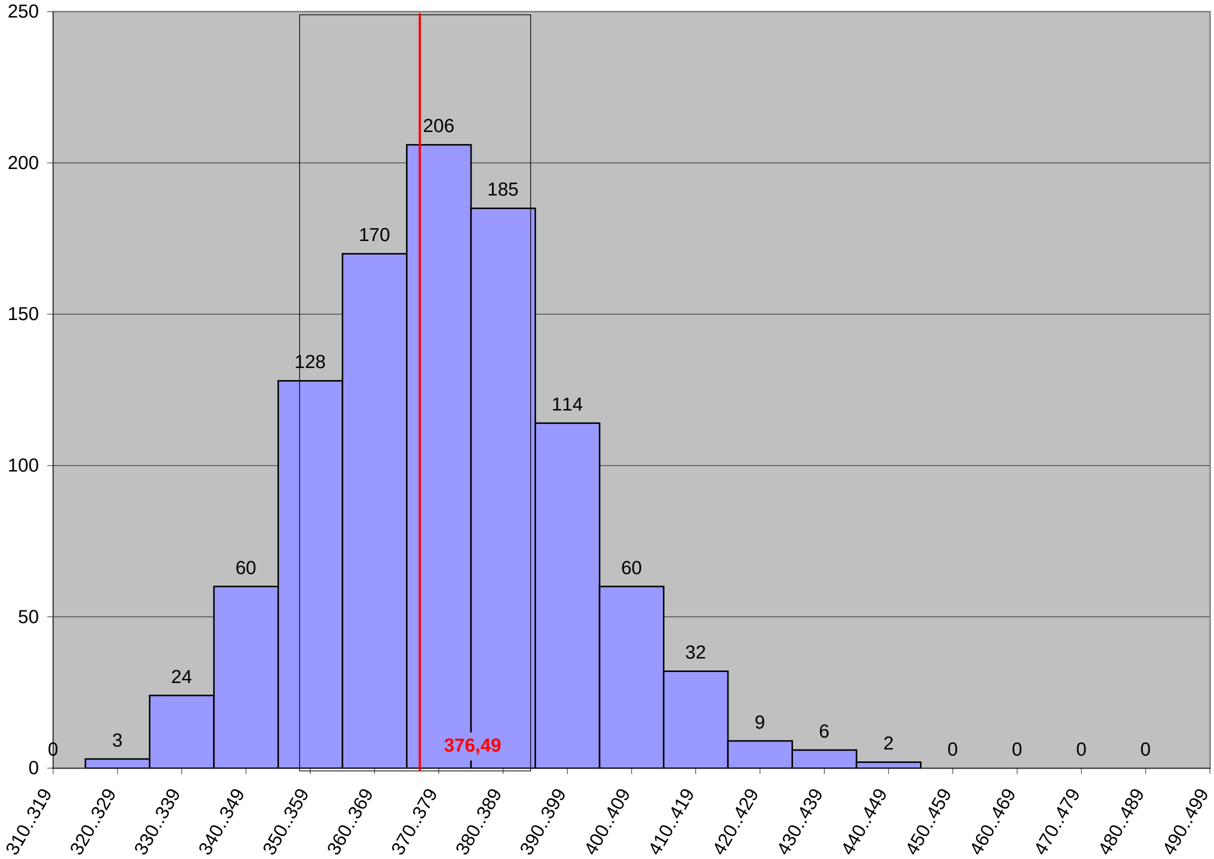


FIGURE 2: Distribution *seat_des_row_letter*, 20% late passengers. Boarding times, on the x-axis, are given in simulation time steps.

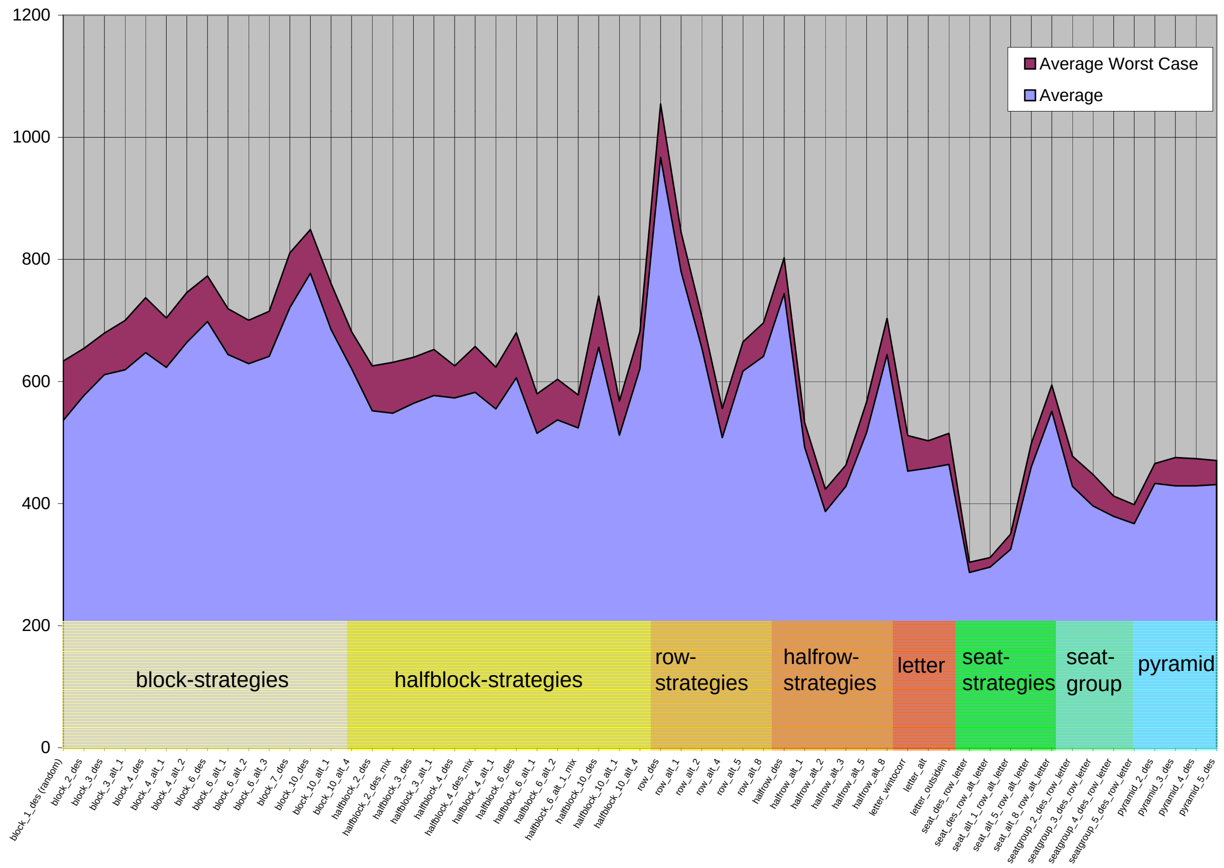


FIGURE 3: Average boarding times vs average worst case boarding times. Times are given in simulation time steps.

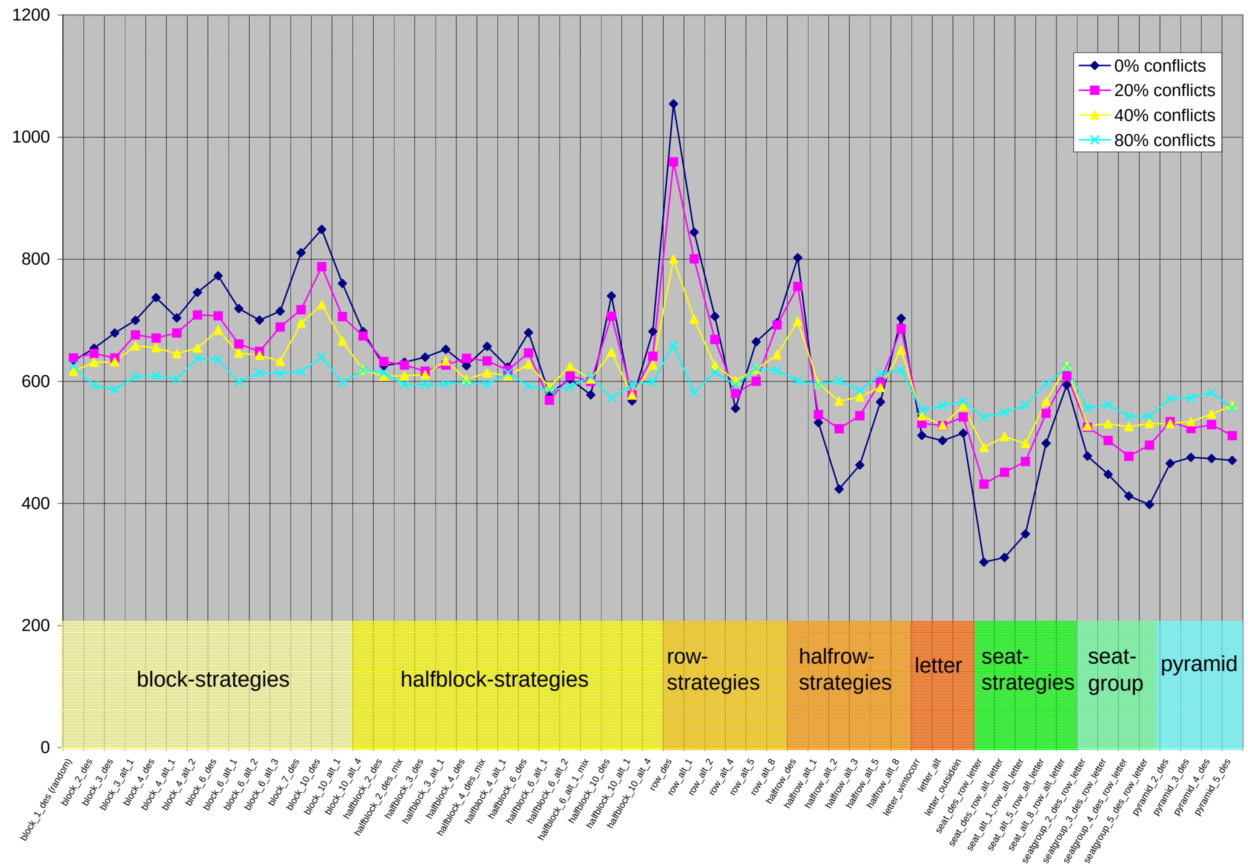


FIGURE 4: The effect of disturbances (passengers boarding late). The plot shows the average worst case boarding time, in simulation time steps, with 0, 20, 40, 80% of all passengers entering late.

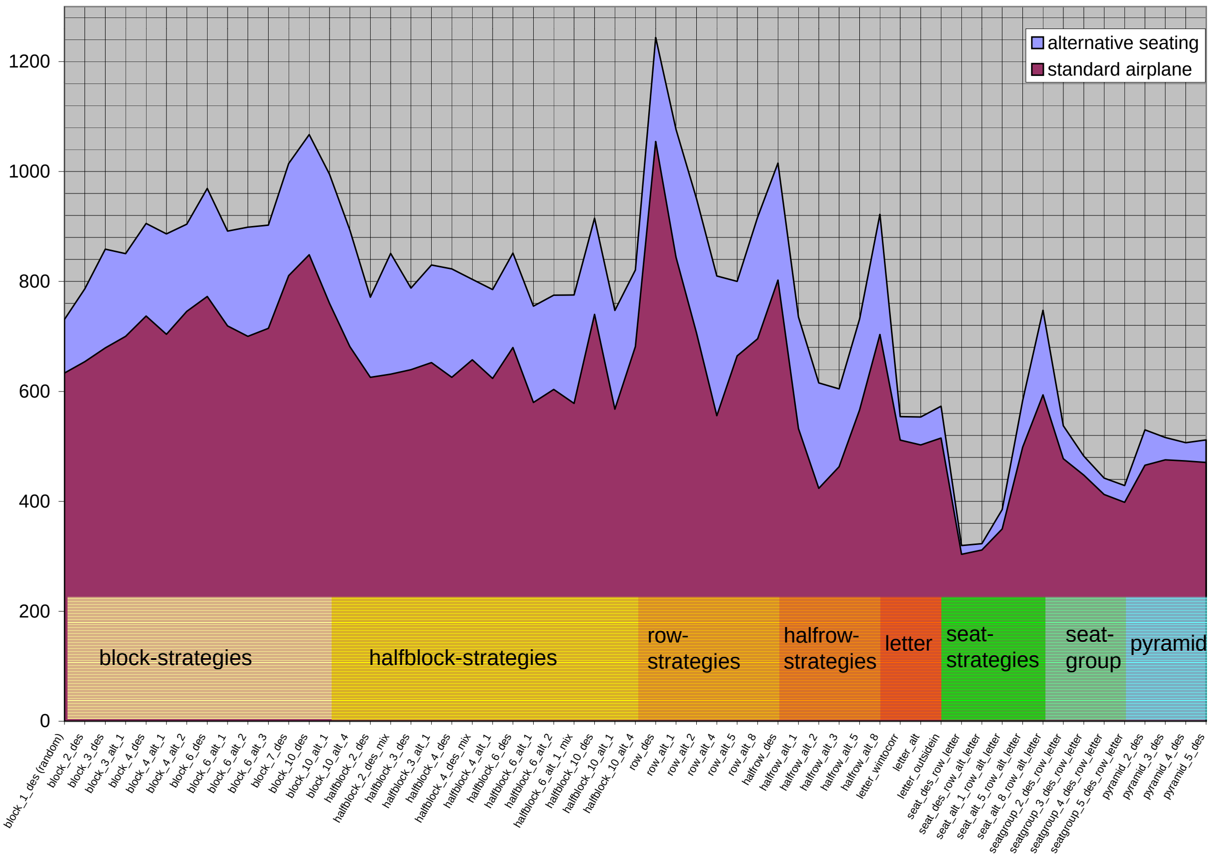


FIGURE 5: Average worst case for our “standard” airplane, and for a different layout of the same number of seats, with 8 instead of 6 seats per row. Boarding times are given in simulation time steps.

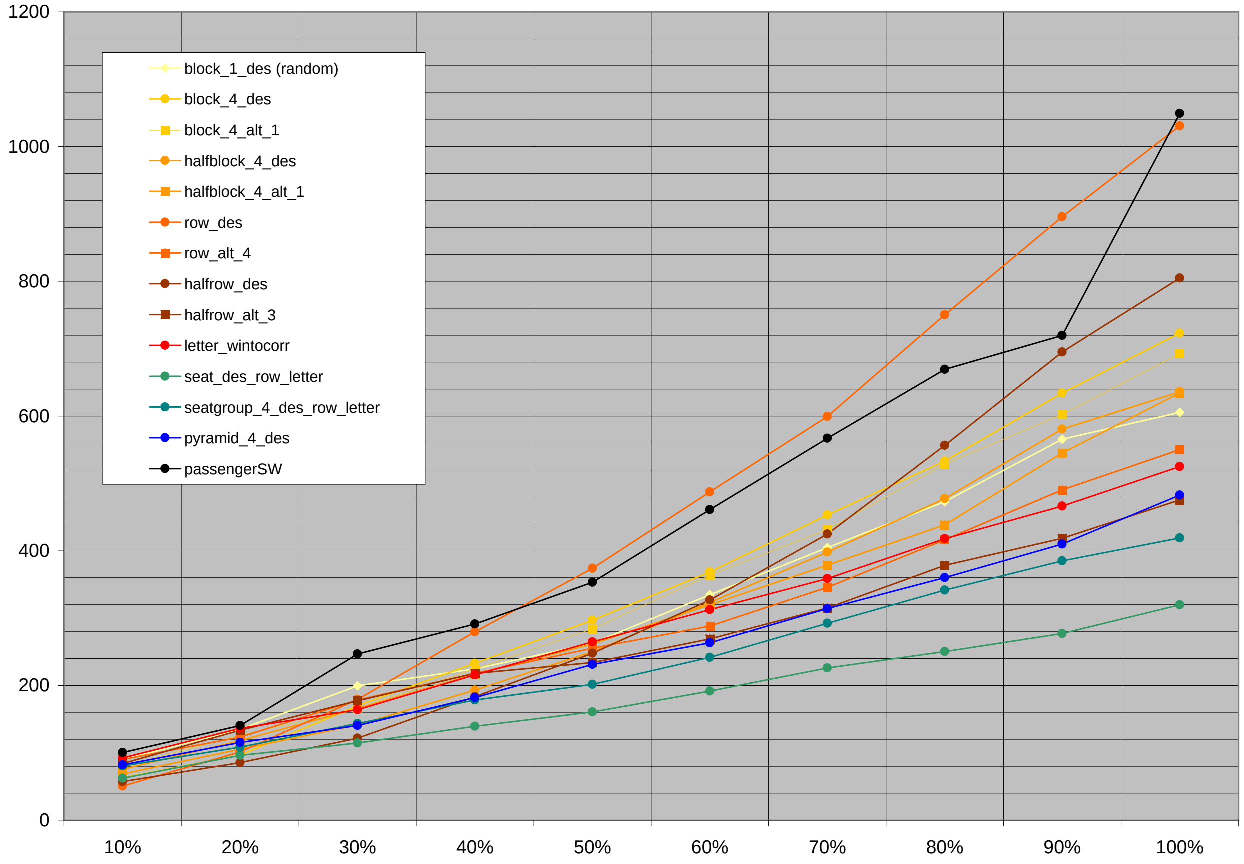
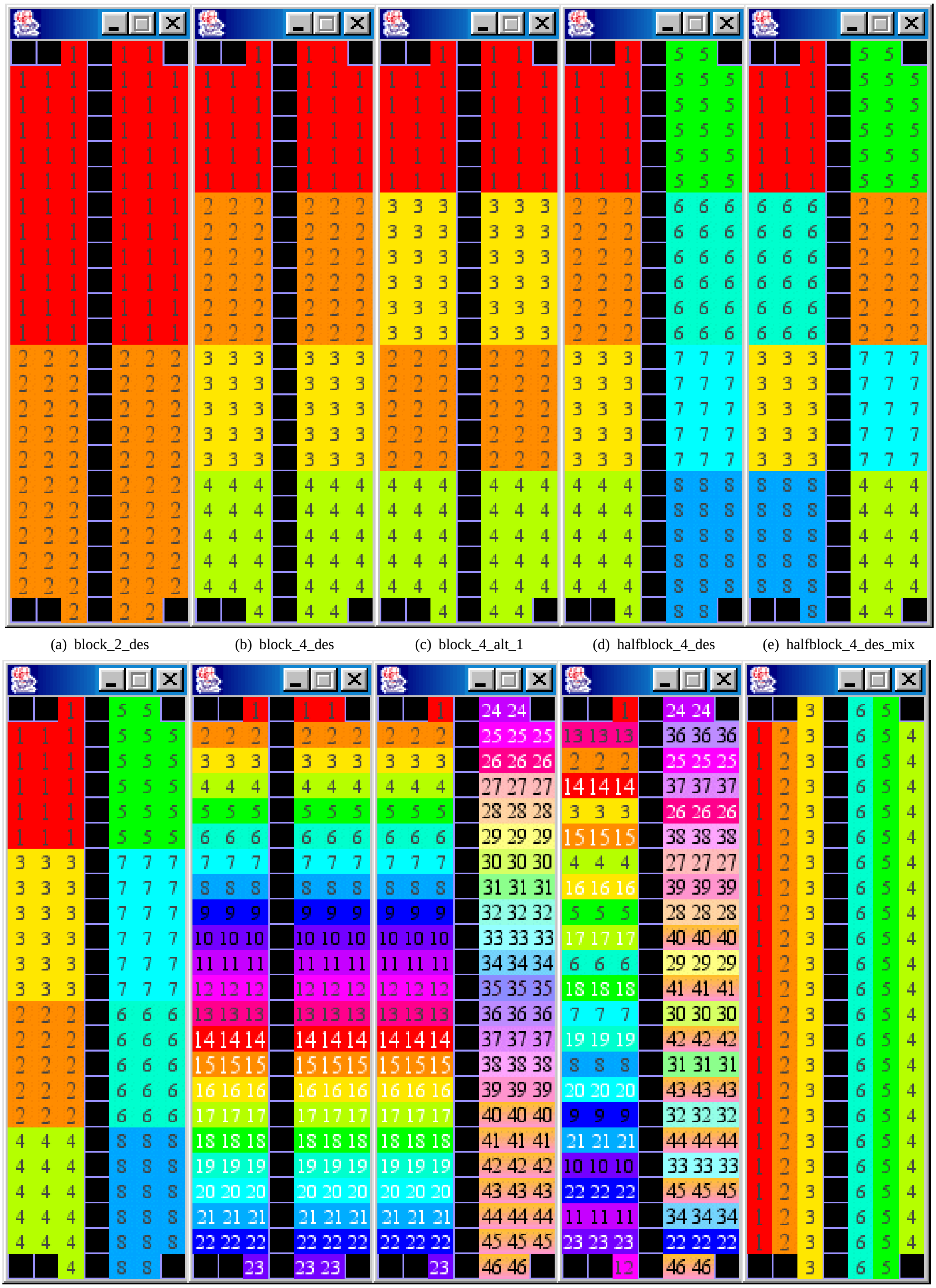


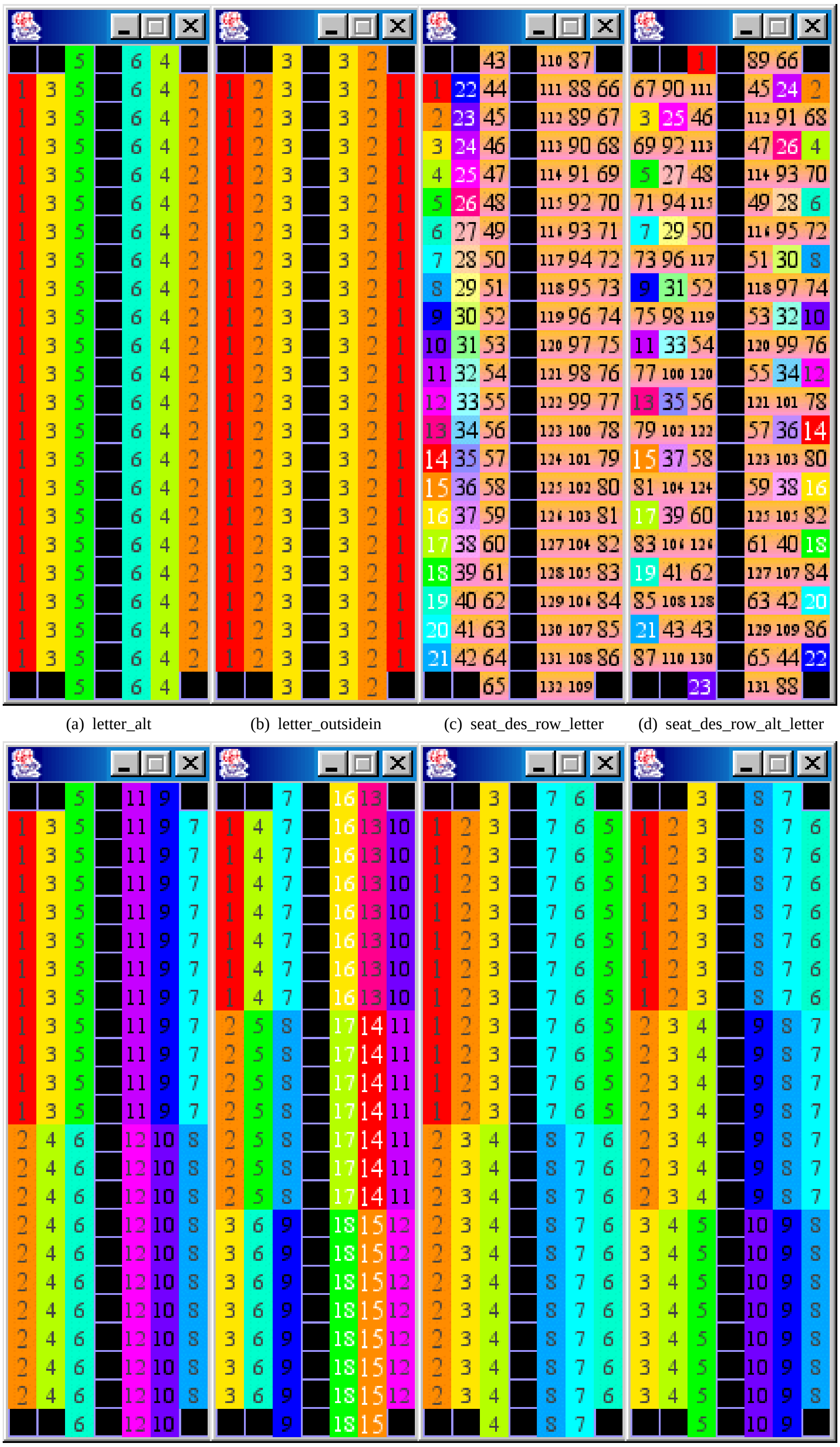
FIGURE 6: Average worst case of chosen strategies under different occupancies. Boarding times are given in simulation time steps.



(a) block_2_des (b) block_4_des (c) block_4_alt_1 (d) halfblock_4_des (e) halfblock_4_des_mix

(f) halfblock_4_alt_1 (g) row_des (h) halfrow_des (i) halfrow_alt_1 (j) letter_wintocorr

FIGURE 7: Graphical representation of boarding strategies



(a) letter_alt (b) letter_outsidein (c) seat_des_row_letter (d) seat_des_row_alt_letter

(e) seatgr_2_des_row_letter (f) seatgr_3_des_row_letter (g) pyramid_2_des (h) pyramid_3_des

FIGURE 8: Graphical representation of boarding strategies

luggage per person	ratio
one piece of luggage	60 %
two pieces of luggage	30 %
three pieces of luggage	10 %

TABLE 1: Luggage distribution