The Airplane Boarding Problem

Carlos Miguel Freitas
MIEIC
FEUP
Porto, Portugal
up201504749@fe.up.pt

Luis Noites Martins
MIEIC
FEUP
Porto, Portugal
up201503344@fe.up.pt

Miguel Mano Fernandes
MIEIC
FEUP
Porto, Portugal
up201503538@fe.up.pt

***Abstract*—The turnaround times inherent to each flight are a monstrous money sink for airlines and optimizing them should be of utmost importance for them. This study explored multiple popular and a couple more experimental airplane boarding methodologies to try and determine which perform best and are deemed viable to introduce in airlines. To more objectively track results, an aircraft was modelled using NetLogo tools and simulations where we attempted to fill the airplane in accordance to a specific process. Multiple parameters have been taken into account to simulate human behaviour at its max, like passengers allowing others to scoop through and go up the aisle. This report also features an analysis of viability of each boarding method given the fact that a few procedures see humans organizing themselves in unrealistic structures thus making them impractical for real-life implementation.**

***Keywords*—agent-based modeling, NetLogo, simulation, aircraft boarding, boarding strategies, human behaviour, satisfaction, real-case scenarios**

I. Introduction

The airplane boarding problem is based on trying to find the most optimal method of boarding passengers on an aircraft.

Turnaround time is the time required to unload an airplane after its arrival at the gate and to prepare it for departure again – and it's crucial to airlines. Because of safety and operational constraints, passenger boarding is the last task performed in the turnaround process timeline. This extra time is not only strongly linked to financial losses but also a passengers' poor perception of the carrier's service quality [Kalic et al., 2013].

The number of times passengers wait for or traverse each other, whether in the aisle (an aisle interference) or within a given row of seats (a seat interference) [Steffen and Hotchkiss, 2012] all add up to this long and costly process.

Actually, the cost to an airline company for each minute spent at the terminal is roughly $30 [Steffen and Hotchkiss, 2012], so carriers are continuously on the lookout for new ways to reduce turnaround time [Kalic et al., 2013], even if they end up not implementing them because of the human factor involved. Short turnaround is about 23 minutes and its critical path is the disembarkation of passengers, cabin servicing and passenger boarding [Kierzkowski and Kisiel, 2017].

It's crucial to factor in the human nature of the whole process when presenting new methodologies to carriers. In fact, the most efficient boarding procedure has already been found. It's Jason Steffen coined method *Steffen Perfect*. Albeit it being time perfect, it's operationally flawed because of its unrealistic and fairly dehumanizing organizational requirements. There are a lot of strategies but most of them do not take into account many aspects related to the human factor [Kierzkowski and Kisiel, 2017], rendering them impractical for real-life use.

The gist of matter lies on finding a satisfying tradeoff between speed and simplicity.

Through the metrics discovered and collected in [Kierzkowski and Kisiel, 2017] this project aims to analyse how the main boarding methods perform when human behaviour is considered. In order to better scope the problem we won't take care of priority boarding or first class passengers. In fact, with this project we aim to verify if the least time consuming methods still stack up when real scenarios are applied. With this investigation we believe it will be possible for future research on the matter to better use simulation with real human behaviours and more realistic scenarios.

II. Literature Review

A. Background

1) Boarding process: All literature on the airplane boarding problem understand the importance of speeding the boarding process for airlines. Reactionary delays generate significant costs not only for a single flight but also other flights in the network [Delcea et al., 2018b]. A fair share of *controversy* lies on the concept of randomly boarding an airplane apparently being faster than more commonly-adopted protocols like *back-to-front*. Is not organizing people more efficient than doing so?

Also, is delaying the process somehow more lucrative to airlines? We may hypothesize on why after over a decade of research, airlines still haven't settled themselves on an industry standard when it comes to airplane boarding:

- Some airlines purposely introduce heavy deviations on individual boarding time because of their premium boarding passes. If the times were uniform, there would be no incentive to sell board-first tickets.
- To reduce the chaos of every passenger boarding all together, airlines rely on group boarding. This also plays into the previous point.

TABLE I
BOARDING METHODS ADOPTED BY MAIN AIRLINES

Boarding	Features
Back-to-front	Air Canada, Alaska, American, Delta, British Airways, Frontier, JetBlue, Spirit, US Airways, Virgin Atlantic, Lufthansa
Random	Southwest Airlines, US Airways, American Airlines, Lufthansa
WILMA	United Airlines

- Therefore, it's most likely airlines understand it's more lucrative to charge people extra to board first instead of saving money on turnaround times.

2) Aircraft layouts: Virtually every paper works with a single-aisle layout for their simulation purposes likely because of both its simplicity and its widespread use. In fact, both of the most successful commercial jet airliners – the Boeing 737 and the Airbus A320 – feature this setup.

Fig. 1. Airbus A320 single-aisle layout taken from this

In order to understand this problem it is necessary to take into consideration some of the most important concerns related to people's behaviour as well as the conditions which restrict some situations.

In fact, while analysing a boarding problem it's imperative to consider that there's a specific layout and each passenger can only move forward if it has free space to move. Otherwise, it'll have to wait for the other passengers to seat or stow their luggage. When a passenger cannot move forward, seat or stow the luggage, it is considered an aisle interference. Another important kind of interference happens when a passenger discovers someone between him and his seat. In this case he must ask the other passenger to move away so that he could seat himself creating a seat interference in the system. This situation may cause a significant delay on the overall boarding time as it should be avoided as much as possible.

Although there are already plenty of boarding methods and some of them are virtually perfect regarding interference, they're not totally adapt to be used in a real scenario because of their consideration for total pre-ordering of the passengers before boarding or the fact that they don't take into consideration that sometimes there are people who must have to board together (such as families).

B. Related work

TABLE II
MAPPING TABLE

Paper Index	**Features**										
	f0	***f1***	***f2***	***f3***	***f4***	***f5***	***f6***	***f7***	***f8***	***f9***	***f10***
[Delcea et al., 2018b]	X	X	X	X	X	X		X	X	X	X
[Kierzkowski and Kisiel, 2017]	X	X	X	X		X				X	X
[Kalic et al., 2013]	X	X	X	X		X	X	X	X	X	
[Steffen and Hotchkiss, 2012]	X	X	X	X		X	X	X		X	
[Delcea et al., 2018a]			X	X	X	X		X	X	X	X
[Cimler et al., 2012]	X	X	X	X	X	X		X	X		
[Mas et al., 2013]	X	X	X			X		X	X		

1) Mapping - Table: We compiled 11 relevant parameters to take into account whilst analysing each literature.

- **f0** – considers aisle interferences;
- **f1** – considers seat interferences;
- **f2** – considers time spent stowing luggage;
- **f3** – considers a variable luggage count;
- **f4** – analyses 4 or more boarding methods;
- **f5** – uses a single-aisle layout;
- **f6** – has a passenger satisfaction metric;
- **f7** – finds an average boarding time;
- **f8** – uses simulation instead of just observation;
- **f9** – finds a deviation for individual boarding;
- **f10** – considers human behaviour.

2) Gap analysis: Most of the work already developed in this area does not take into account human factors like variable stowing time. User experience and viability of the method isn't analysed by many researches either. This project tries to bring together simulation and human factors so that it can be easily verified which methods really are effective when these variables are brought to the problem.

III. PROBLEM FORMALIZATION

Firstly, we should start by specifying which metrics are to be analysed as well as their scope.

In order to better understand how well a boarding process really performs, we collect some metrics from the simulator which can be divided in 2 major groups: the metrics related to the whole boarding process and those related to the boarding of each individual passenger.

A. System Metrics

- tbt: representing the number of ticks needed for all passengers to board, starting from the moment the first passenger boards until the moment all passengers are seated.
- nai: representing the number of aisle interferences. Although a single aisle interference can cause multiple interferences in many passengers at the same time (since they are organized in a queue), it is considered just as one for the system because once the top interference is solved all the others will also be fixed.
- nsi: representing the number of seat interferences.

B. Passenger Metrics

For each passenger we considered some metrics which helped better understand how each boarding method performs from the point of view of a passenger since user experience is also important for keeping some credibility and quality of the system. Each passenger will have a satisfaction metric which is defined by the following variables:

- $\boldsymbol{tibt}$: total individual boarding time which is considered as the number of ticks needed for the passenger to take its seat.
- $\boldsymbol{iai}$: total time spent in aisle interferences.
- $\boldsymbol{isi}$: total time spent in seat interferences.

In order to calculate the degree of satisfaction of each passenger we decided to set a way to calculate the dissatisfaction of a passenger and then analyse it in a way that the minimum dissatisfaction is better the maximum one. This dissatisfaction was defined as follows:

$$dissatisfaction = 0.7 * tibt + 0.2 * iai + 0.1 * isi$$

The most important metric is $tibt$ since it is important for both the airline and the passenger to take the minimum time to board, followed by iai because each seat interference makes the passenger get up and move between seats in the same row which are usually too narrow. The least important isi isn't as critical since it only implies one must stop moving on the aisle which is obviously not pleasant but doesn't compromise the whole experience as hard.

For each variable we defined the following domains:

$$tbt, nai, nsi, tibt \in \mathbb{N}_0^+$$
$$iai, isi \in \mathbb{Q}_0^+$$

Each boarding method can be analysed from both the perspective of the whole boarding process as well as the passengers' perception, with an end goal of trying to understand which methods are the best regarding both points of view.

IV. Methodological Approach

A. System model

The airplane boarding problem can be modelled as a discrete-event simulation (DES). As such, we can assume each event as a move by each passenger, like a board game, but all the pieces make a move at the same time.

All the agents in the system are identical to each other and represent passengers on board of the aircraft. Each communicate with each other by asking permission to move aiming to solve an interference and allowing process to resume.

B. Logical and Conceptual model

Since we are considering both simulations with and without human factors we may review two different logical models regarding these approaches.

The one which doesn't consider the human interactions is the simplest, as explained in the flowchart at Figure 3. A passenger enters the queue by boarding the plane. It'll have to wait for others who have boarded before to stow their luggage and seat themselves. When there's free space a passenger – should it have luggage –, stows the bag and seats itself. If the path for its seat is occupied, the passenger should ask the passenger who is in its path to move so it too can seat.

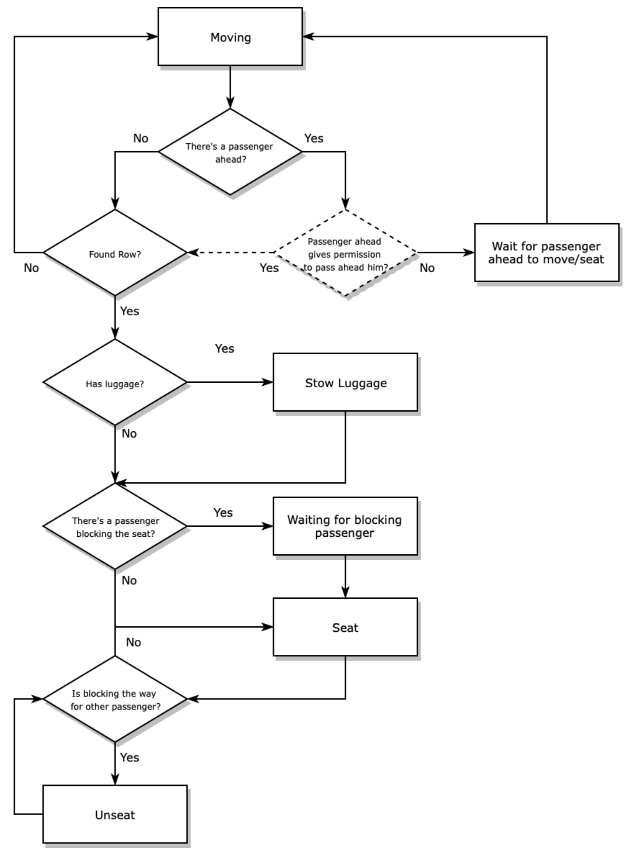

Fig. 2. General flowchart for airplane boarding method modelling

Regarding the movement on the aisle when considering human factor, in some cases one (B) can ask the passenger immediately before him (A) in the queue to let him pass while A is stowing luggage. This situation can also happen when A is immediately before B and A is ready to sit as well as B. If this situation causes a seat interference between A and B in the next movement, then A could let B pass and occupy its place before A, thus avoiding a seat interference.

As for conceptual model, it finds a relationship between the time a passenger needs to seat himself and the number of times it'll have to stop due to an interference. Its perception of the quality of the service is also somehow affected by this kind of situations.

C. Coding

The simulation was coded using the proper software *NetLogo* (Wilensky,1999), a programmable modelling environment for simulating natural and social phenomena.

NetLogo was used throughout the project to accomplish implementations of the specified scenarios, and also for testing said scenarios vigorously.

In order to allow multiple analysis and scenarios the code will be generalized to only depend on the value of the variables one can choose.

D. Data requirements (input)

In order to implement the various case scenarios, there are some input variables the user may experiment with:

- Boarding method to use;
- Percentage of passengers with luggage;
- Family size between 1 and 3. This input is only applicable in boarding methods that take into consideration families or groups like Kautzka 3;
- Toggle human factor. This toggle – when turned on –, is important for testing more realistic case scenarios, as the input variables mentioned below are applicable only if this toggle is turned on.
  - Luggage speed. When a passenger carries luggage it walks slower, at the speed defined by this input;
  - Distributed passenger speed. Toggle which prevents all passengers from walking at the same speed, making their speed dependent on a distribution.

E. Data requirements (output)

For measuring performance, the team idealized the following variables:

- Number of interferences for each type:
  - Aisle interferences;
  - Seat interferences.
- Total time boarding time, expressed in ticks;
- Total time a passenger takes to go to his seat;
- Total time a passenger wastes during aisle interferences;
- Total time a passenger wastes during seat interferences;
- Median dissatisfaction of all passengers;
- Maximum and minimum dissatisfaction of all passengers.

All of the parameters stated are important in order to better analyse the quality of each boarding method for all the case scenarios tested.

F. Simulation scenarios

The team agreed on implementing and analysing the boarding methods below because of their wide use, optimal results and/or ease of implementation:

- **Random**
  Considered the easiest to implement by airlines because there's no need to organize the passengers.
  Passengers board without any order although their seats are already pre-assigned. This way, a passenger doesn't choose its seat when inside the aircraft, but instead simply has to get to it.

- **Back-to-front (block)**
  Divides the passengers in 5 evenly distributed groups based on their seating rows range. So passengers whose seat lies between the 1st and 6th row board on a different group than others whose seat is within the 7th to 12th range.

  Groups further back on the aircraft board first and passengers inside it board randomly.

- **Back-to-front (row)**
  Similar to the method above, but grouping is discarded. Instead, rows further back board first and passengers on each row board randomly.

- **Front-to-back (block)**
  The same as Back-to-front (block), but reversed. As in, blocks closest to the airplane's entrance board first.

- **Front-to-back (row)**
  The same as Back-to-front (row), but reversed. As in, rows closest to the airplane's entrance board first.

- **Wilma (Window-to-aisle)**
  On Wilma, passengers whose seat is closest to the window board first. Then follow the middle seats. Then, finally, the aisle seats.

- **Steffen perfect**
  A method coined by Jason Steffen which is widely considered to be the optimal solution to the boarding issue as it minimizes boarding time whilst also minimizing passenger interferences.

  This solution requires passengers to board in an absolute optimal order. Any mismatch would disrupt the boarding process. Because of the organizational aspects of this method, it's considered unfeasible to implement in real life scenarios.

- **Kautzka 3 (for groups of 2 and 3)**
  A fairly unknown boarding method that aims to minimize the organizational issues presented by Steffen by boarding people in duos or trios. A better explanation of the method can be found on [Cimler et al., 2012].

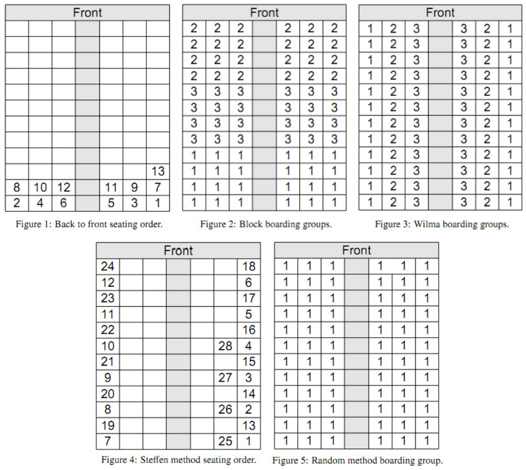

Fig. 3. Visual representation of a few boarding methods described above taken from [Anthony, 2011]

Besides each method and in order to be able to analyse how each method performs in a real case scenario we also implemented what we call the human factors. These factors are some decisions and behaviours that passengers must take when interacting with each other while boarding.

In fact, in order to simulate real scenarios we used metrics collected from a study [Kierzkowski and Kisiel, 2017] that was performed with humans in 2017 and we tried to apply them with the minimum changes possible so we could keep the simulation as realistic as possible. Although this study was done just for one specific boarding method, it shows good conclusions regarding the way people move inside a plane and how they react to interferences, so we decided to use these metrics as a base for all the boarding methods. Since this study considers a lot of empiric cumulative distributions, which are not easily transformed to functions, we decided to consider, for each distribution, multiple intervals each one of the corresponding to a probability of the CDF which naturally reduces the accuracy of the method but the errors is minimal. The following metrics were then considered and implemented in this project:

- **passenger's speed**: we considered a normal distribution of 1.3m/s with a standard deviation of 0.25m/s, having all passengers using this distribution without differentiating between the ones with and without luggage since passengers are different from each other not only because of the luggage but also because they are in fact different people with different capacities so luggage could not be the only thing that affects their speed;
- **subsequent entrances rate**: we considered an empiric cumulative distribution function, in which each passenger can take a different amount of time to enter the airplane following the distributed probability presented on Fig.7;
- **let other passenger to pass while stowing**: when a passenger is preparing his luggage to stow or while it's stowing it, if there is someone after him waiting for him to finish this task, one can let the passenger pass in order to stop being the reason for so much *trouble*. In fact, the study concluded that if a passenger is stowing there's a probability of 53% to let the passenger who is waiting to pass, while if there's an aisle seat available on the passenger's row this probability goes up to 93%. This is an important metric since human passengers can feel pressured when they are making others wait for them;
- **stowing time**: we considered an empiric cumulative distribution function, which splits stowing in 4 different scenarios. In fact, [Kierzkowski and Kisiel, 2017] concluded that the time a passenger takes to stow his luggage in the overhead bin (box) depends on if there's an aisle seat available in its row as well as if the overhead bin of the adjacent rows (own_row - 1, own_row, own_row + 1) is filled less then 50%

Scenario	Availability of the aisle seat	Filling of the box less than 50%
1	+	+
2	+	–
3	–	+
4	–	–

Fig. 4. Stowing scenarios. Taken from [Kierzkowski and Kisiel, 2017]

The study found 4 different CDF (cumulative distribution functions), presented on Fig. 8, for the time a passenger needs to stow his luggage regarding these 4 scenarios. This analysis is also important to be included in our project since, although many simulation studies have already included variable amount time for a passenger to stow his luggage, almost none of them consider different scenarios for when there's an available seat on the aisle. This can be an important factor because when there's an aisle seat available one can take more time preparing himself to stow since he is not causing any trouble to other passengers who are moving on the aisle.
- **deal with seat interference**: When a passenger is ready to take his seat on his row (right after stowing his luggage), if there's anyone between him (on corridor) and his seat (middle seat or window seat), he must ask the other(s) passenger(s) to move away so that he can take his place. This kind of interaction has been analysed in many researches which can summarize them and classify them in 4 different interferences as referenced by [Delcea et al., 2018b].

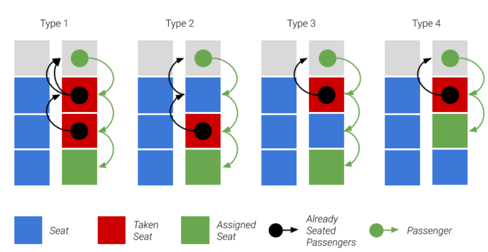

Fig. 5. Types of seat interferences

Although not being totally accurate with the reality, this way of modeling this situation is one of the best to test

in simulation since it tries to show all the movements and interactions passengers do while they are solving the interference. We can observe that the first type makes 3 passengers to move while the other 3 types only happen with 2 passengers.
- **avoid seat interferences**: when a passenger is preparing itself to seat and in order to avoid a seat interference in a short period of time, one can check if the seat of the passenger behind him will cause a seat interference where he is involved. In that case he should let the other passenger pass just before him. In other words, if passenger A is the passenger just behind B, A has no luggage to stow, and his seat belongs to the same row of B and is nearer the window, then A should let B pass to his seat just before moving himself. It allows a passenger to avoid seating and getting up in no time.

1) Simulation plan: In order to evaluate each method's performance, we ran 2 different kind of experiments each one of them with 100 simulations for each boarding method. Each simulation finishes when all the passengers are seated and their luggage is stowed.

The following experiments will be tested:

- The first one is comprised of tests made using the default characteristics where passengers can either have or not luggage. For the ones who have luggage, we set a fixed amount of time needed for stowing and well as walking speed
- The second group of tests aim for verifying how each method works regarding the human factors aforementioned.

For the both segments of experiences, we considered the following tests:

- No passengers carrying luggage;
- 50% of the passengers carrying luggage;

2) Expected Results: For the first experience we expect to be able to confirm what we found in the literature for both the tests with and without luggage. In fact, we expect to find Steffen to be the best method in both tests followed by Kautzka 3. Wilma should be a little worse followed by random and back-to-front and finally front-to-back being the worst since it is counterproductive causing a lot of waiting time as well as interferences.

Regarding the tests considering human behaviours we expect to get worse results than those without, although the best methods should keep being the best since they try to minimize the number of both types of interferences aisle and seat.

V. Implementation

In order to make the model generic it only depends on some variables which can be controlled so that different tests could be executed using the implementation. These variables are the ones mentioned on section IV-D.

A top-down aircraft model with 30 rows was designed using *NetLogo*. Each row is comprised of six seats, three to each side with an aisle divisor in the middle.

As mentioned above the system was modelled as having 31 rows (30 rows of seats plus 1 for entrance), each one of them composed by 7 patches (6 for seats divided in the middle by 1 for the corridor which the passengers use for moving along the aircraft). Each passenger is modelled as a turtle which can only be in one patch at a time moving in just 3 directions (heading to 90 while on the corridor and heading to 0/180 while on his row).

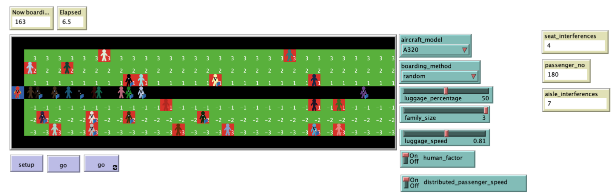

Fig. 6. Netlogo simulation running

A. No Human Factor

While not considering the human factor the system keeps each passenger moving at 1 patch/tick and at any time only one passenger per patch is allowed, so if the next patch on the desired direction is occupied then the passenger must wait it to get freed so that he can move again. There is an exception for situations where a passenger is in a seat interference where more than 1 could be in the same patch at a time. Furthermore, each passenger enters the aircraft when he has free space to do it and it takes just him 1 tick for him to enter.

Regarding seat interferences, as mentioned on IV-F, they can be of four different types. For each one of them the passenger who wants to move to his seat should ask the ones who are causing the interference to move. In this case the ones who have to move should place themselves on the aisle so that the new passenger could move towards his seat.

Furthermore, for luggage stowing, the system is modelled in the way that a passenger just keeps himself on the aisle during the time he needs to stow his luggage. This is a way to easily simulate the impact of this action without having to move the passengers.

B. Human Factor

While considering human factor, the system enforces more interaction between turtles. In fact, the system was modelled trying to apply all the metrics mentioned on section IV-F related to the human factor. Keeping in consideration that it is also based on discrete events for mapping real continuous scenarios to this approach we map the time in the real scenario to ticks on *NetLogo*. So, we considered 1 tick as 0.63 seconds due to the fact that the average length of the aisle of an aircraft A320 is 24.6m (as referenced in [mkv1109, 2014]) and each passenger moves at an average speed of 1.3m/s [Kierzkowski and Kisiel, 2017].

Having said that, the empiric cumulative distributions related to luggage stowing were used as a range of additive probabilities divided by 238 ticks since analysing the distributions from [Kierzkowski and Kisiel, 2017] demonstrated we could verify that these distributions have a cumulative probability of 1 when the time is 150s. In other words, for stowing luggage a passenger can take between 1 and 238 ticks to perform this action. Following the same idea a passenger can take between 1 and 38 ticks to enter the aircraft when it is his turn.

Finally, regarding the capacity of letting other passengers pass, each passenger can set himself as transparent allowing others to pass sharing the same patch for some moments. Although being able to do this each passenger should only use this property whenever deemed necessary as mentioned on section IV-F.

VI. Results and discussion

After testing each case scenario numerous times, we were able to gather enough data to make some conclusions in which method is better and why. We divided the results in two, one for the tests without the human factor taken into account, and another with it turned on. As such, the results are as follows:

1) No Human Factor: In these tests, we mostly tried to verify if our model was correct according to the literature. In fact, we looked at the time the boarding methods take to complete and the total number of each interference. As the scenarios section suggested, we looked into the cases where no passenger brought luggage and where half of the passengers did bring luggage.

Analysing Figure 9, we can confirm what we were expecting. The fastest boarding methods in these situations are the Steffen, Kautzka and the Wilma methods because these are the only ones that reduce the number of seat interferences. Seems that ordering people randomly works better than some methods. On a scenario where passengers travel without luggage, the time wasted can be more dependent on seat interference than in aisle interference because there is less chance that a passenger will block other passengers' paths.

Since there is no luggage into consideration, all aisle interferences are strictly dependent on seat interference. In other words, one just has to wait on the aisle before reaching his row if there is someone who can't seat because there's a seat interference and he must wait for the other to move away before seating. Therefore, the methods that avoid seat interferences (Kautzka, Steffen and Wilma) are objectively better than the others.

No luggage scenarios are completely unrealistic since normally when travelling, people take some luggage with them. Therefore, we also did test with half of the passengers bringing luggage so that we could observe if the best methods on the previous scenario stay on top.

Overall the best methods are still the same, however this time, Steffen boarding tops all of them because of the way it orders people, avoiding the necessity for one passenger to wait for another one who is stowing his luggage. For example in Kautzka for 2 and 3 people if more than 1 passenger per group have luggage the second/third one have to wait the first one to stow his luggage generating an aisle interference.

2) Human Factor: Since people do not behave as machines and each person behaviour is not 100% predictable, in order to confirm which methods are better in the most possible realistic scenarios, we tested all boarding methods with the human factor into consideration. The data gathered here will be the most important to verify which method actually is the most suited in real life.

With the human factor turned on, the data gathered has way higher values since the real world is chaotic and boarding hundreds of passengers can not be as fast as concluded in the test without human factor. However the best methods obtained in the previous scenarios still prevail. From the best methods mentioned, this time, not all of the them are able to entirely avoid interferences even without any luggage, because of the human natural behaviour, such as different walking speed and entrance rate. As such Steffen method appears to be the one which avoids these interferences more efficiently. but in this case also WILMA and Kautzka 2 and 3 come really efficient on this matter, as we can observe on figures Fig.16 and 17.

The story repeats itself when 50% of the passengers carry luggage. As we can verify on figures Fig.18, 19 and 20 the methods that were good at avoiding interferences such as Kautzka, Steffen and Wilma are beginning to struggle. However, Steffen method is still the one that stays on top by delivering the lowest values overall, and still maintaining seat interferences close to null.

Having lower boarding times and interferences, does not mean that those interferences are evenly distributed for every passenger so it's highly important to take into consideration a happiness level of each passenger boarding the plane, in order to check if the boarding method is even for every person boarding. Therefore we did calculate the dissatisfaction of each passenger (calculated by the boarding time, and time wasted in each type of interferences), and gather the average of the means of that same dissatisfaction over 100 runs as well as the maximum and minimum values. As we can observe on figure Fig. 21, dissatisfaction does not take real effect for scenarios without luggage. It can happen due to the fact that for this case almost every passenger takes the same time to board and seat. Now looking at Fig.22 we can see that in a more realistic scenario, Steffen, Kautzka, Wilma and Random methods are the best at satisfying the passengers, since we can see the mean of dissatisfaction and disparity of the max and minimum dissatisfaction with lower values than others. The other methods may show an acceptable dissatisfaction mean, however the difference between the maximum and minimum is too high compared to the better ones, meaning that not all people are keen to be equally happy/sad.

Overall, these values still prove that, despite everything, although not with a high margin, Steffen method is still better overall. So why isn't it being implemented in real life applications? Maybe evaluating the difficulty of ordering people in the order demanded by each methods will help us answer this question.

Finally it is also important to analyse how possible is a real implementation of each boarding method. As mentioned on [Kierzkowski and Kisiel, 2017], sometimes the number of divisions needed for each boarding method to work properly make it unfeasible for real scenarios. In fact, a lot of people travel together with their families and children and are emotionally affected by the fact of being in such an unusual situation which makes some pre-ordering division impossible in real case scenarios as referenced by [Delcea et al., 2018b]. Considering the boarding methods used in this study we can also split them into 2 types, the ones which allow people on the same row to board together and the ones which don't allow this situation. This division is important due to the fact that normally people who travel in group have seats next to each other, on the same row, so it is important for them to board with their families/colleagues. As we can see on table III a lot of boarding methods allow row groups to board together but almost all of them have a big overhead due to the pre-ordering need, which make them not feasible to be used on a real airport.

TABLE III
GROUP DIVISIONS OF BOARDING METHODS

Boarding Method	Divisions	Allows row passenger to board together
Random	1	yes
Block back to front	5	yes
Block front to back	5	yes
WILMA	6	no
Row back to front	30	yes
Row front to back	30	yes
Kautzka - groups of 3	60	yes
Kautzka - groups of 2	90	yes
Steffen Perfect	180	no

CONCLUSION AND FUTURE WORK

Considering all the tests and data gathered, we were able to gather a few concrete conclusions. In a real life scenario where no people bring luggage, the performance of all the methods tested are so close to each other that any method is good enough to be implemented. However, it might be better to use a method that is easier to implement and allows, for example, family groups. Therefore, the Random method is the best to be used in cases without luggage because there is no need to organize people before boarding the plane, and if people want/need they can enter in group.

Looking at the cases with luggage into consideration, we can clearly see there are boarding methods that are way better than other. The methods that shine in these situations are Kautzka, Steffen and Wilma (Random is not as close but it still pretty close, and better than front-to-back and back-to-front). From these best methods, we can see that theoretically Steffen, although by a low margin, is the best method. Nonetheless, Kautzka and Wilma are so close to Steffen that we might conclude that airline companies should implement any of these three methods, but they shouldn't. Steffen is a method that requires a lot of precision, meaning people ought to be ordered in a fashion that sounds too absurd to be implemented, consequently Steffen seems impossible to be done. Kautzka follows the same principle as Steffen but groups people in groups of two or 3 individuals, this means that the difficulty of ordering people is lowered by half and more. It still is too hard, instead of ordering people 180 people, we order 60 groups of 2 people. Then, Wilma seems to be the next perfect candidate, you only need to divide people in 6 groups (which is pretty feasible) and it performs fantastic. But there is a problem, Wilma does not take into consideration families, this means that people who come together (this is more important when we are talking about parents and kids) will not enter the plane together.

In conclusion we can see that maybe not implementing any method is better overall. Distributing people randomly seems the best way to board the passengers. It allows people that want to enter together to do it, there is no need for ordering passengers a priori and it still performs pretty well taking less than 23 minutes to board all the passengers.

Although believing our study can help to have a more realistic thought on this matter, there is still room for a wider study and further investigation on how people really behave while boarding on an airplane. In fact, it could also be important to try to model the time needed to solve seat interferences as well as understanding what people really care in this process, whether they consider more relevant boarding in less time or on the other hand they prefer not having so many interferences during their boarding.

ACKNOWLEDGMENT

This study was developed in the course of modulation and simulation of the Faculty of Engineering of the University of Porto and supervised by professor Rosaldo Rossetti.

REFERENCES

[Anthony, 2011] Anthony, S. (2011). Astrophysicist devises super-fast but dehumanizing airplane boarding. https://www.extremetech.com/extreme/94492-astrophysicist-devises-dehumanizing-but-super-fast-airplane-boarding-method. [Online; accessed 26-June-2019].

[Cimler et al., 2012] Cimler, R., Kautzká, E., Olševičová, K., and Gavalec, M. (2012). Agent-based model for comparison of aircraft boarding methods.

[Delcea et al., 2018a] Delcea, C., Cotfas, L.-A., and Paun, R. (2018a). Agent-based evaluation of the airplane boarding strategies efficiency and sustainability. *Sustainability*, 10:1879.

[Delcea et al., 2018b] Delcea, C., Cotfas, L.-A., Salari, M., and Milne, R. (2018b). Investigating the random seat boarding method without seat assignments with common boarding practices using an agent-based modeling. *Sustainability*, 10(12):4623.

[Kalic et al., 2013] Kalic, M., Markovic, B., and Kuljanin, J. (2013). The airline boarding problem: Simulation based approach from different players perspective. In *1st Logistics International Conference. Belgrade, Serbia*, pages 28–30.

[Kierzkowski and Kisiel, 2017] Kierzkowski, A. and Kisiel, T. (2017). The human factor in the passenger boarding process at the airport. *Procedia Engineering*, 187:348–355.

[Mas et al., 2013] Mas, S., Juan, A. A., Arias, P., and Fonseca, P. (2013). A simulation study regarding different aircraft boarding strategies. In Fernández-Izquierdo, M. Á., Muñoz-Torres, M. J., and León, R., editors, *Modeling and Simulation in Engineering, Economics, and Management*, pages 145–152, Berlin, Heidelberg. Springer Berlin Heidelberg.

[mkv1109, 2014] mkv1109 (2014). AirAsia A320: The Incident, The Aircraft and Theories. https://m11k09v.wordpress.com/2014/12/29/airasia-a320-the-incident-the-aircraft-and-theories/. [Online; accessed 24-June-2019].

[Steffen and Hotchkiss, 2012] Steffen, J. H. and Hotchkiss, J. (2012). Experimental test of airplane boarding methods. *Journal of Air Transport Management*, 18(1):64–67.

VII. Appendix

A. Human Factor Cumulative Distributions

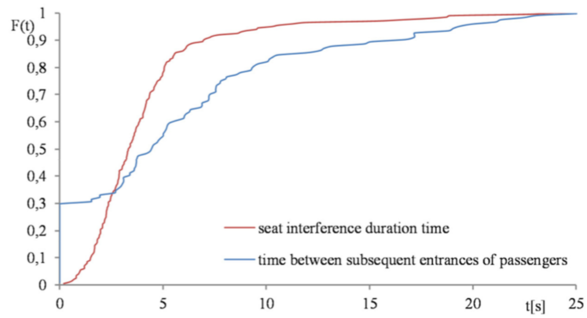

Fig. 7. Empiric cumulative distribution function of the time between subsequent entrances of passengers. Taken from [Kierzkowski and Kisiel, 2017]

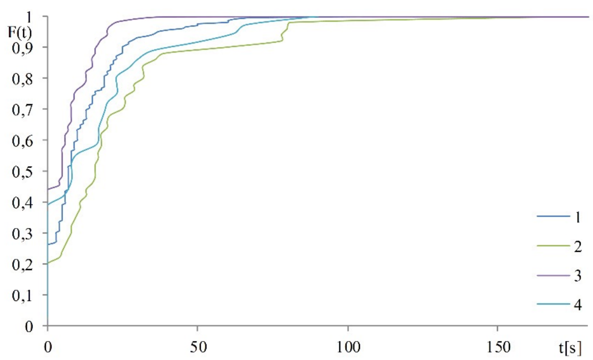

Fig. 8. Empiric cumulative distribution function of the time needed to place luggage in the overhead bin. Taken from [Kierzkowski and Kisiel, 2017]

B. Data Analysis

1) Experiments without human factor considered: Below follows data collected for situations where passengers are not affected by human factor for both situations when there are no passengers with luggage and when 50% of the passengers have luggage.

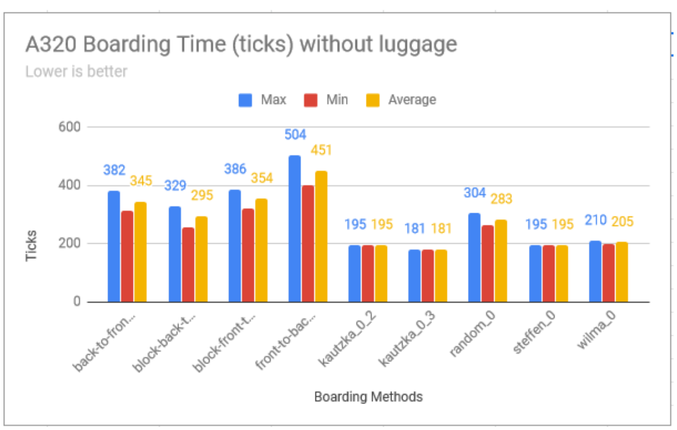

Fig. 9. Boarding times without human factor, no luggage taken into account

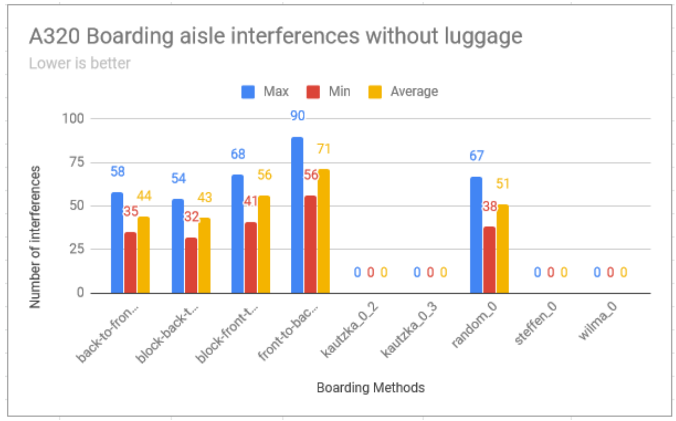

Fig. 10. Number of aisle interferences without human factor, no luggage

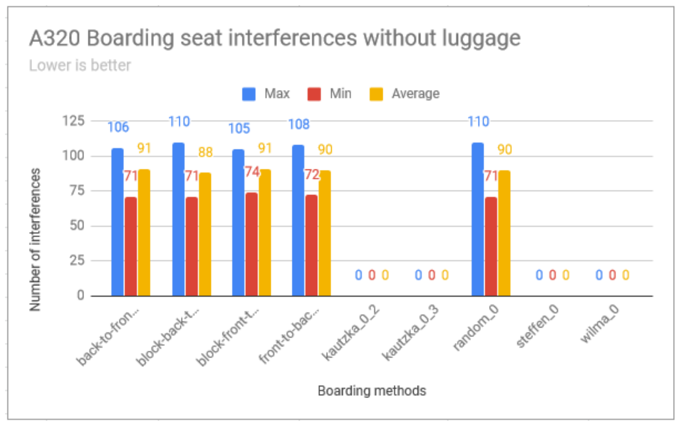

Fig. 11. Number of seat interferences without human factor, no luggage

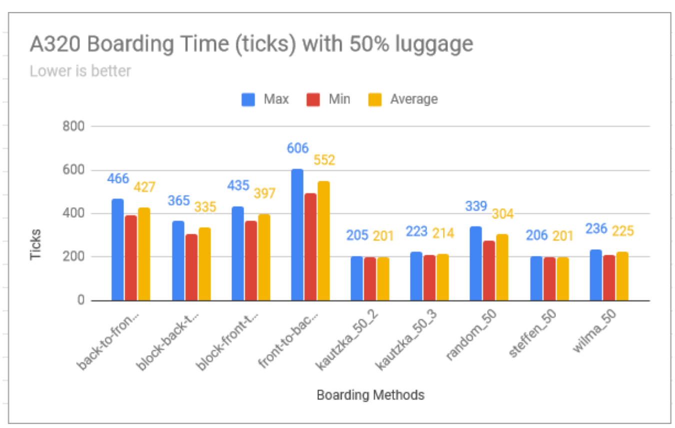

Fig. 12. Boarding times without human factor, 50% luggage

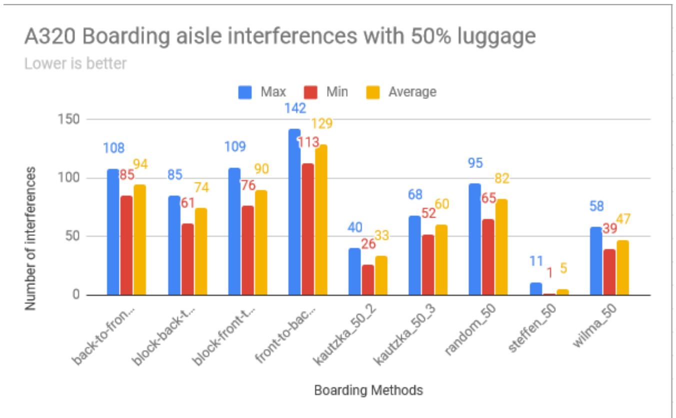

Fig. 13. Number of aisle interferences without human factor, 50% luggage

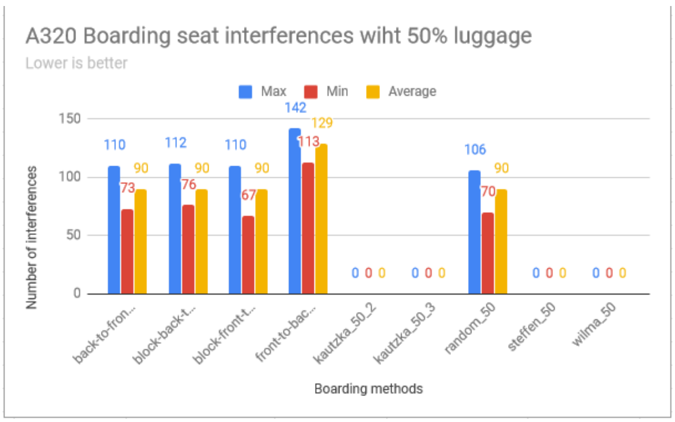

Fig. 14. Number of seat interferences without human factor, 50$ luggage

2) Experiments with human factor: On the other hand, here is the data collected for situations where passengers are affected by human factor for both situations when there are no passengers with luggage and when 50% of the passengers have luggage.

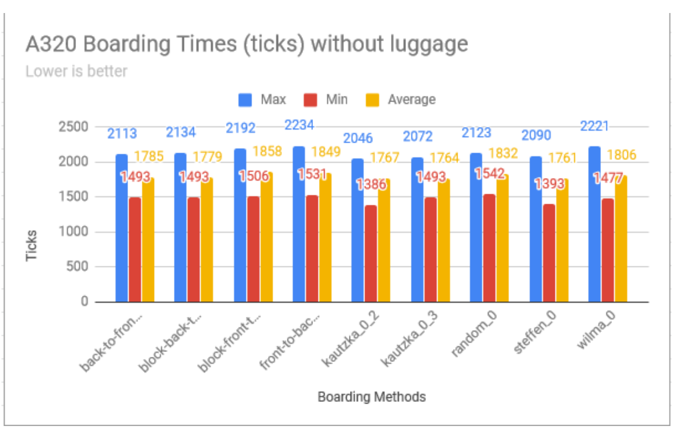

Fig. 15. Boarding times with human factor, no luggage

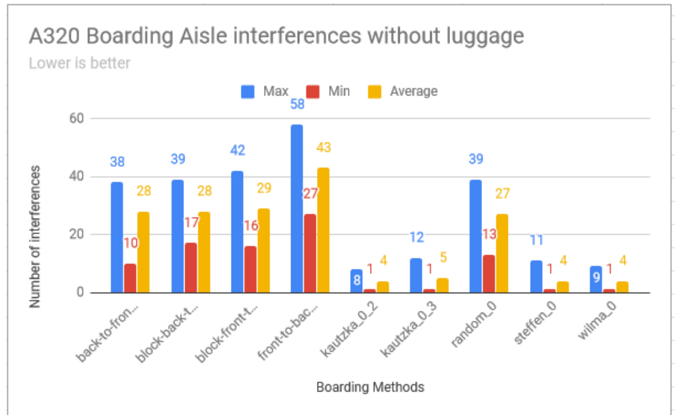

Fig. 16. Number of aisle interferences with human factor, no luggage

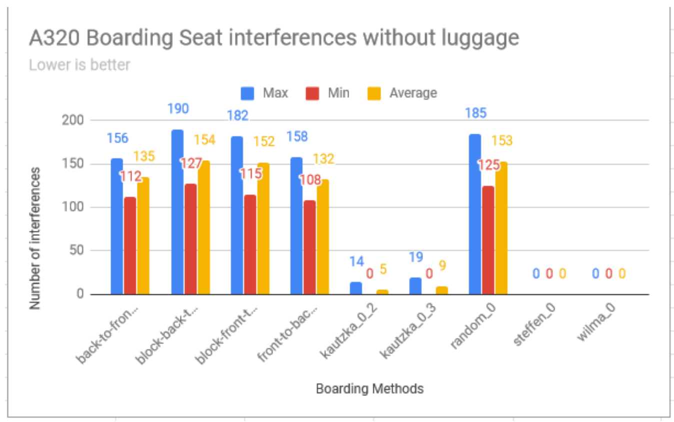

Fig. 17. Number of seat interferences with human factor, no luggage

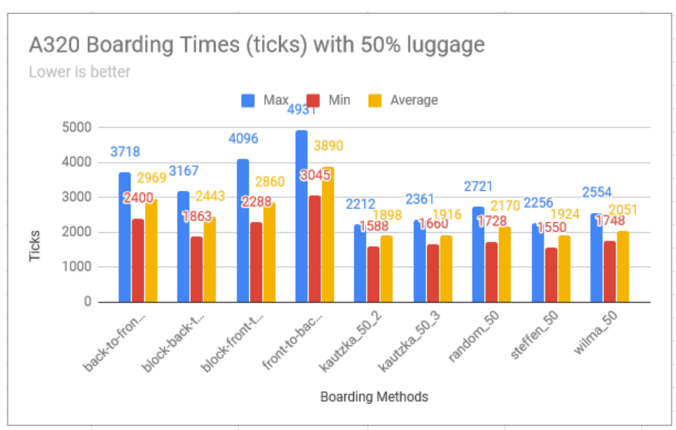

Fig. 18. Boarding times with human factor, 50% luggage

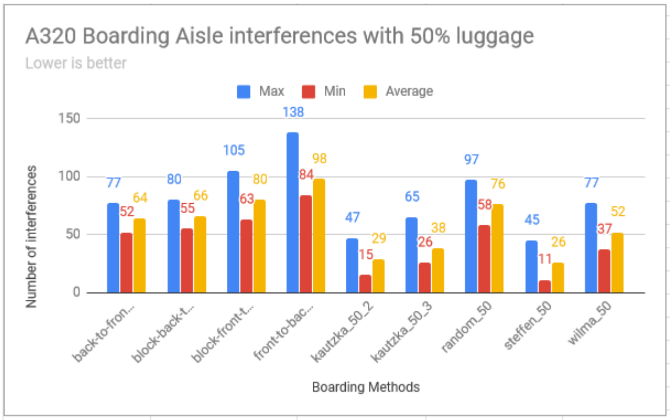

Fig. 19. Number of aisle interferences with human factor, 50% luggage

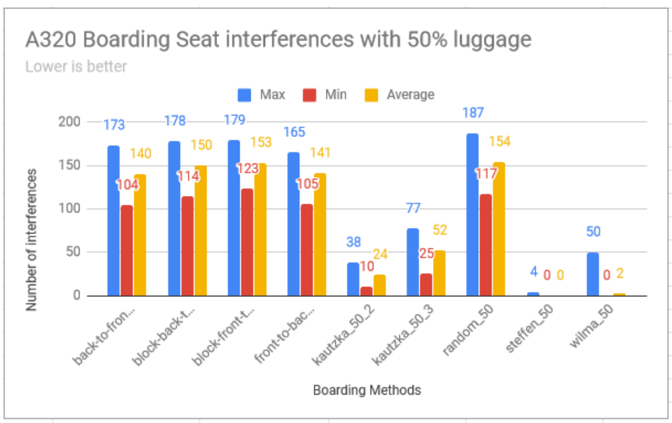

Fig. 20. Number of seat interferences with human factor, 50% luggage

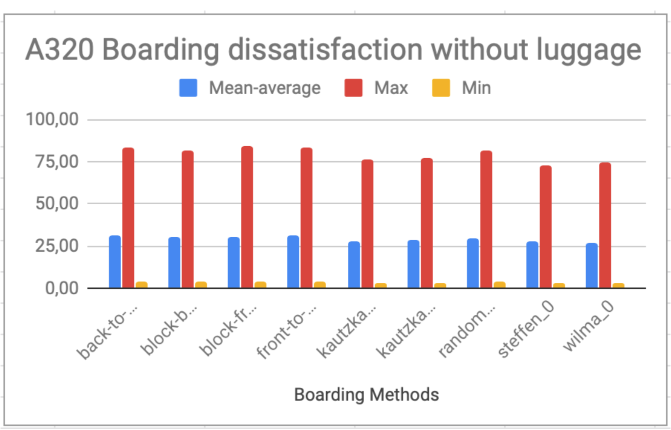

Fig. 21. Dissatisfaction of passengers with human factor and no luggage

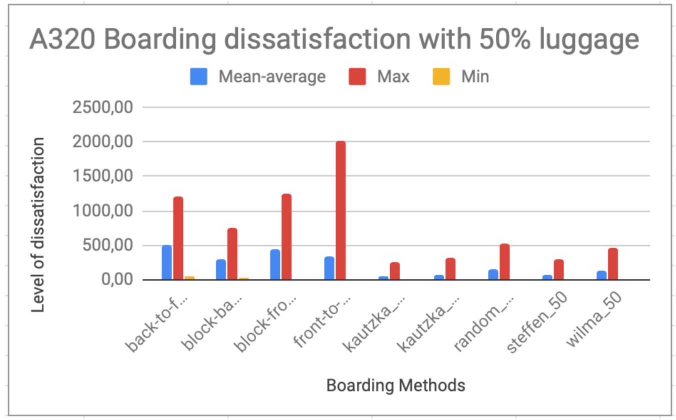

Fig. 22. Dissatisfaction of passengers with human factor and 50% of luggage