sustainability

MDPI

Article

A Two-Door Airplane Boarding Approach When Using Apron Buses

Camelia Delcea *, Liviu-Adrian Cotfas, Nora Chiriță and Ionuț Nica

Department of Economic Informatics and Cybernetics, Bucharest University of Economic Studies, 010522 Bucharest, Romania; liviu.cotfas@ase.ro (L.-A.C.); nora.chirita@softscape.ro (N.C.); ionut.nica@softscape.ro (I.N.)

* Correspondence: camelia.delcea@csie.ase.ro; Tel.: +40-769-652-813

Received: 3 September 2018; Accepted: 8 October 2018; Published: 10 October 2018

check for updates

Abstract: Boarding is one of the major processes of airplane turnaround time, with a direct influence on the airline companies' costs. From a sustainable point of view, a faster completion of the boarding process has impact not only on the airline company's long-term performance, but also on customers' satisfaction and on the airport's possibility of offering more services without additional investments in new infrastructure. Considering the airplane boarding strategies literature, it can be observed that the latest papers are dealing with developing faster boarding strategies, most of them considering boarding using just one-door of the aircraft. Even though boarding on one-door might be feasible for the airports having the needed infrastructure and sufficient jet-bridges, the situation is different in European airports, as the use of apron buses is fairly common. Moreover, some of the airline companies have adapted their boarding pass in order to reflect which door one should board once they get down from the bus. While using these buses, the boarding strategies developed in the literature are hard to find their applicability. Thus, a new method for boarding on two-door airplanes when apron buses are used is proposed and tested against the actual boarding method. A model is created in NetLogo 6.0.4, taking advantages of the agent-based modeling and used for simulations. The results show a boarding time reduction of 8.91%.

Keywords: airplane boarding strategies; agent-based modelling; NetLogo 6.0.4; efficiency evaluation; sustainability; two-door boarding

1. Introduction

The airport bus, also known as the "apron bus", is a bus with a special design which facilitates the transport of passengers and their hand luggage between the airport passenger terminals and airplanes. Considering its characteristics, it can be underlined that typically, the apron buses are wider than normal buses, mostly due to the fact that the regulations concerning the maximum vehicle width are only applicable to public ground and, as an airport represents a private ground, they do not apply in this case. Thus, the manufacturers of this type of buses can choose to increase both its width and its length. Moreover, the transfer buses are usually fitted with a reduced number of seats, with large windows, and most of the passengers standing during the journey. Driving cabs can be encountered at both ends, making their operation easier, while the maximum speed is somewhere around 40 km/h.

For the airports in Europe, it is fairly common to use two apron buses, instead of one, for transporting the travelers to their aircraft before boarding, especially for flights having 150–200 passengers. Some of the European airports that use the apron buses are: Madrid, Munich, Pisa, Frankfurt, London Luton, Amsterdam Schiphol, Kharkiv, Bucharest, Salzburg, Stuttgart, etc.

In August 2018, the COBUS Industries, which provided apron buses to the Salzburg Airport for several years, sold the first fully electric power-driven airport bus. The Salzburg Airport representatives underlined that they used the apron buses for more than 1800 h of operation and the switch to the new power-driven buses will help them save about 20,000 kilograms of carbon dioxide per year [1]. In October 2015, the fully power-driven bus was presented to the Munich Airport: the e-COBUS 3000 model. Since then, 43 busses have been sold in Europe, North America, and Asia [1].

The practice of using apron buses is widely implemented in Europe, due to the continuous increase in the number of flights while airports can provide only limited jet-bridge capacity. Moreover, in some cases, it might also happen that the airplane is too small for a jet bridge. Then, the only solution, apart from letting the passengers walk directly from the gate to the plane, is using apron buses.

Thus, the present paper analyzes the needed time to board an airplane when both doors of the airplane are used and the passengers arrive through the use of the apron buses. For this, we consider an agent-based approach in which the passengers are modeled as agents having their own set of rules and trying to find their place within the airplane as fast as possible. Moreover, as in the airplane boarding literature, a series of boarding methods have been proposed for the jet-bridge situation—as presented in the next section. We aim to determine if using the back-to-front method for the airplane passengers boarding when apron buses are employed is feasible and if the boarding time can be reduced in a significant manner. To the best of our knowledge, there are currently no other approaches for boarding using apron buses found in the published literature.

As for the simulation, an Airbus A320 aircraft configuration with 30 seat rows was used, as presented in Figure 1 with a classical grid-representation [2].

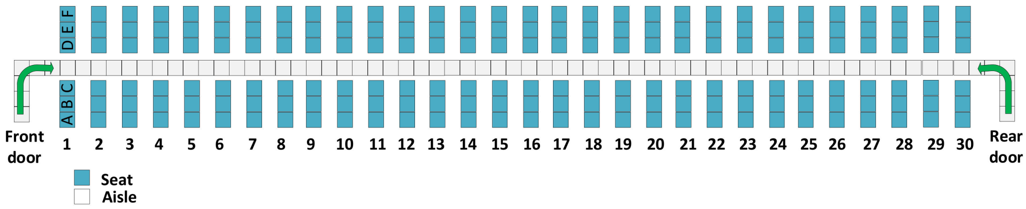

Figure 1. Airbus A320 configuration with 30 seat rows.

2. Delay Times and Boarding Methods

Eurocontrol [3] publishes yearly results regarding the airplanes delays in European countries. Comparing the results from 2017 with the ones in 2016, it can be observed that the average delay time per airplane has increased by 9.11% in 2017, reaching as much as 12.4 min of delay.

2.1. Air Transportation Delay and its Causes in European Airports

Regarding the causes that have contributed to the airplane delay, seven main causes can be underlined, three of them having a greater impact: reactionary, airline, and airport causes, as shown in Figure 2.

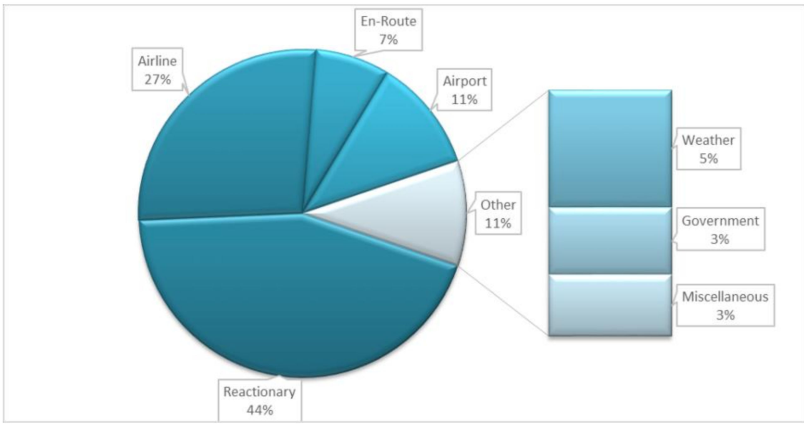

Figure 2. Delay causes in 2017 in European airports [3].

The reactionary causes include the late arrival of the aircraft, crew, passenger, or load causes. Besides the fact that it produces the greatest part of the average delay time (44.03% in 2017), it has been determined that the reactionary delay is dependent on the delays made by other airplanes in the network. For example, for all European flights in 2014, each minute of primary delay induced an average of 0.8 min of reactionary delay within the network [4].

As for the airport and airplane delay causes: together, these count as much as 38.16% of the total average delay time in 2017, being determined by delays due to passenger and luggage, flight operations and crew, or restrictions at departure airport. Figure 3 presents the average delay for each category of causes in 2017 and 2016. It can be observed that all the causes contributing to delay have increased values in 2017 as compared to 2016.

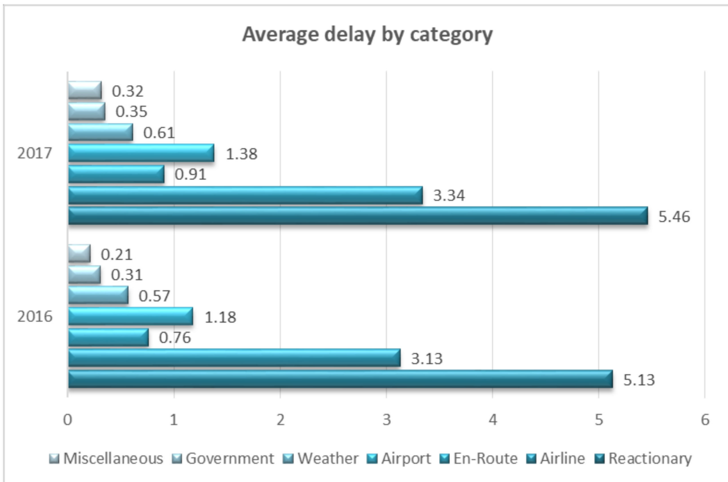

Figure 3. Average delay by category in minutes [3].

2.2. Boarding Methods

Various approaches exist related to passengers boarding into the airplane. Some of them are considering the passengers as being a compact group and decide boarding them in a random manner. From this category, one can refer to the random with or without assigned seats methods. In both methods, the passenger line up and enter one after the other in the airplane. The only difference between the two methods is that in the case of boarding without assigned seats, the passengers, once arrived in the aircraft, are free to select their own preferred seat, while in the assigned seat method, they just have to walk down the aisle and find the place stamped on their tickets [5].

Another method, which has the same characteristics once the passengers are inside of the aircraft as the random without assigned seats method, is the open seating method. The difference in this case is represented by what is happening with the passengers before entering the airplane, as they are assigned to a group based on their check-in times. Knowing the group they are assigned to the passengers align next to the column representing their group number and wait to be invited for boarding.

On the other hand, newly-developed boarding methods, all of them having an assigned seat for each passenger, have faced two main developing directions: "by group" boarding or "by seat" boarding. The "by group" boarding splits the passengers within different groups and invites them to board over a specific scheme. This method is also employed for the "by seat" methods; however, in this case, each passenger is called to enter the airplane and find their seat.

From the "by group" boarding, the following boarding methods have been developed and tested in the literature: outside-in (also known as window-middle-aisle or WilMA), reverse pyramid, back-to-front, rotating zone, modified optimal method, and the non-traditional method [6–8]. A short description of them can be found in Table 1. A series of variations of these methods have also been developed in the literature by considering half-zones or by using a row based approach [9].

Table 1. Short description of "by group" boarding methods.

Classification	Boarding Method	Main Idea
By group	Outside-in (WilMA) *	The passengers are divided into three groups depending on their seat position: near the window, middle, or aisle. The first called-in group is formed by the passengers with seats near the window, then middle, and last aisle.
	Reverse pyramid	The groups board diagonally, starting with some of the seats located near the window, then, the remaining part of the seats near the window and some of the seats in the middle, and so on, ending with the some of the seats near the aisle.
	Back-to-front	The passengers board in groups starting from the rear of the airplane and move forward about one fifth of the number of seat rows at a time.
	Rotating zone	The boarding starts with a group located in the rear, continues with a group in the front, then back in the rear again, and back to the front, while the group formed by the seats located in the middle of the airplane is boarded last.
	Modified optimal method	The even seat rows from one side of the aisle are boarded in the first group, followed by the even seat rows located on the other side of the aisle, then, the un-even rows of one side and last the un-even rows on the other side, making a total of four boarding groups.
	Non-traditional method	First, a few seat rows located in the back-middle side of the airplane are boarded, followed by the rows in the middle, the rows in the front and last the rows in the rear of the airplane. Even in this case, four boarding groups are used.

* Window-middle-aisle.

When regarding the "by seat" methods, one can say that they are created around the idea of boarding each passenger individually (one-by-one) in the airplane, based on a certain set of rules. The boarding strategies belonging to this category are fewer than in the case of "by group" strategies, having the inconvenience that each passenger should be called in order to take its place in the airplane. Some of the boarding strategies from this category are: back-to-front by seating order, descending order, Steffen method, and variation in Steffen method [10–14].

All the "by seat" methods are starting from the rear of the airplane. In the case of back-to-front by seating order, the first passenger takes the seat near the window, the second one near the opposite window, the third one in the middle near the first one and continues in the same way until the last row is full. Then, the boarding starts from the second-back row, until all cabin rows are filled. The descending order method boards the first passenger in the last row near the window, the second passenger in front of he/she on the second-last row until all the seats near the window in one side of the aisle are completed. The middle seats (near the ones occupied) are then boarded, and finally, the aisle seats. Having the half-aisle of the aircraft boarded, the other half-aisle is completed in the same way, starting with the window seats.

The two methods proposed by Steffen are based on the same idea, with few adjustments. The first boarding method by Steffen considers boarding the first passenger in the rear near to the window, while the second one is two rows apart near the window. The boarding continues until it gets to the front of the airplane, after which it moves to the other side of the aisle. Once the window seats are completed, the middle seats follow, and then aisle seats. The variation in Steffen method starts from the same idea but instead of boarding first all the rows near the window, it fills first the odd rows (window to aisle) and then the even rows.

Over time, a series of papers have been written in the area of airplane passengers' boarding, either on proposing new boarding methods, making adjustments to the already existing methods, or determining which method perform better under given conditions (number of seat rows or aircraft type description [10,14–17], passengers movement [5,13], passengers carrying hand luggage [10,12,13,18,19], seat selection [5,15], aircraft occupancy [8,10,14,18,20–22], annual cost [23], seat and aisle interference [24], etc.) As for the methods used in modeling and simulation, one can mention the following approaches: cellular Discrete-Event System Specification (Cell-DEVS) modeling [25], Discrete-Event simulation [21], cellular automata [26], stochastic approach [27–29], linear programming [30], grid based simulation model [31], computer simulation [20,21,30,32,33], Cell-based computer simulation [15], Markov Chain Monte Carlo optimization algorithm and computer simulation [13], genetic algorithm [16], critical path method and Lorentzian space-time geometry [6], and empirical tests of the performance of the considered boarding methods [14].

Based on the characteristics of the boarding methods presented above, the main observation is that all of them consider boarding passengers using only a single door of the aircraft.

As presented in the introduction, in practice, the two-door boarding is also used. Only a few studies have considered this type of boarding, as presented in the following.

A Boeing study [34] considered boarding simultaneously, using the two doors of the airplane, and compared the results in terms of boarding time with the traditional boarding methods. As a result, it was shown that boarding on two-door has the potential of reducing the boarding time by 5 min, while boarding on the two-door and considering an outside-in strategy (Figure 4) had the potential to save 17 min, for an average boarding time of 13 min.

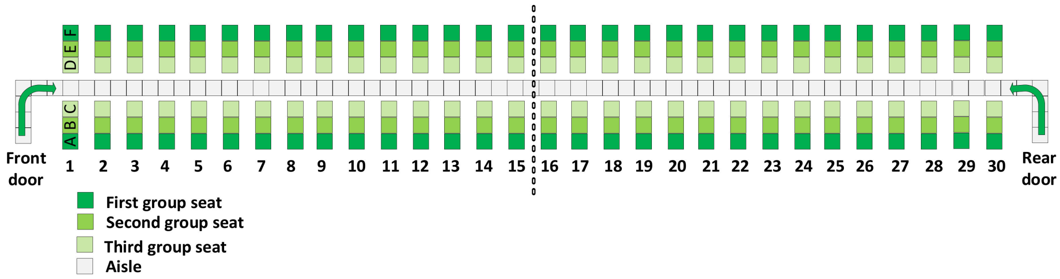

Figure 4. Boarding on two-door in an outside-in strategy.

Additionally, a comparison between different boarding methods using both one and two-door has been conducted [23]. The authors have considered the traditional boarding method and have determined that the average boarding time in minutes is 30.33. As for the non-traditional boarding method, the boarding time is smaller and has been determined to be between 8.18 and 19.58 min when boarding on a single door, depending on the fact that the passengers are carrying luggage with them or not. Considering the two-door situation, the authors found that 3.18–14.58 min are needed for boarding (depending on the presence/absence of luggage). Comparing them, it can be easily seen that the two-door approach brings better results in terms of boarding time.

Two-door boarding and four boarding sequences were also considered [35]. As a results, the authors state that the two-door approach can accelerate the boarding process by 25.9%, while showing that a proper combination between outside-in strategy and two-door configuration brings a minimum expected boarding time of 63.9% when compared to the defined reference boarding procedure [2,35,36].

None of the studies have considered the situation in which the airplane is not actually connected to the airport facilities through a jet-bridge.

Even in the two-door simulations presented above, the authors have considered that the airplane was connected to the airport using two jet-bridges which enables the use of some of the boarding methods developed for the one-door boarding in the two-door case. Thus, when the aircraft is connected to the terminal through two jet-bridges, any of the boarding methods presented above can be used, as the passengers can be called either in groups or by seat to board.

Using apron buses instead of jet-bridges makes the use of these methods harder as the passengers are randomly boarded into the buses, and when their doors open, they move towards the airplane in a random manner. In this case, no person is there to split them into groups or to call them individually for boarding.

3. Agent-Based Modeling in NetLogo

Choosing the agent-based modeling (ABM) as a tool for presenting and analyzing the human behavior has been the first choice for a series of researches in the field of transportation [37,38], emergency situations behavior and crowd movements [39,40], healthcare research [41,42], environmental sciences [43,44], social sciences [45], etc. As for the agent-based modeling tools, all the previously mentioned researches have used NetLogo (https://ccl.northwestern.edu/netlogo/), as it provides a comprehensive interface, real-time visualization of agents' actions, a good documentation, basic programming skills, integrated geographic information system (GIS) functionality, integrated graphics, and a good execution speed [46].

Thus, for modeling the passengers' behavior when boarding on two-door, NetLogo 6.0.4 was used, as described in the following.

3.1. Methodology and Model's Parameters

Knowing that the boarding takes place using two doors, some of the European companies have adapted their boarding tickets in order to help their passengers choose the door they should use for boarding once they arrive with the apron bus near the aircraft (see Figure 5). Due to this, while building the agent-based model, we have considered that there will not be situations in which the agents are choosing the wrong boarding door. Thus, all the passengers that have seats in the first-half of the airplane will choose for sure the front door, while the passengers that have seats in the second-half will choose the rear door.

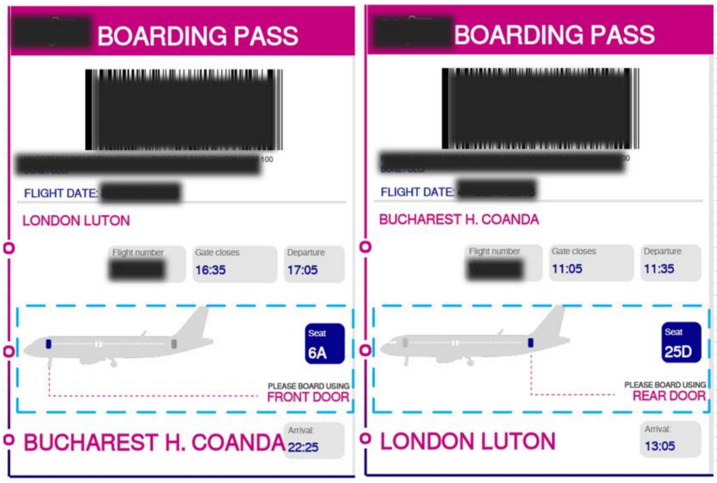

Figure 5. Example of a flying ticket.

Some of the agents' properties, such as speed, the presence of luggage, time needed for storing the luggage, the passengers is seated or not, assigned seat row, and assigned seat number, have been kept from our previous model for one-door boarding, as presented in [9]. Each tick from NetLogo, representing the unit of time, has been associated with 3.7 s in real life as recent researches suggested [27,47]. This value has been updated from 5.4 s as suggested by [10,25,48] to 3.7 s determined by field measurement in [47]. Moreover, for the current modeling, the seat interference has been considered, which will cause delay in the overall boarding time, depending on the passenger's seats and whether their neighboring seats are occupied.

Figure 6 presents the main seat interference situations considered when modeling the passengers boarding process. The highest delay interference is given by type 1, as the passenger having the seat near the window has to wait for the other two passengers to free their path, while the second highest delay interference is given by type 2. Both type 3 and 4 seat interference, produce an equal delay time.

The proposed model in NetLogo benefits from the advantages brought by the agent-based modeling, as each agent can be modeled as an individual with their own characteristics and behavior rules, which makes the agents in the model resemble real passengers. For example, each agent has their own speed which may change depending on the fact of whether they carry hand luggage or not inside the aircraft. Additionally, while walking down the aisle, the agent's speed will adapt based on the speed of the passenger in front of him. The value of the speed will be at most equal to the speed of the passenger in front of him. Once no passenger is in front of the agent, their speed changes back to the initial value. If each passenger takes hand luggage, each of them needs a particular time to store the luggage in the overhead compartment, which contributes to our effort of making the agents look similar to real passengers.

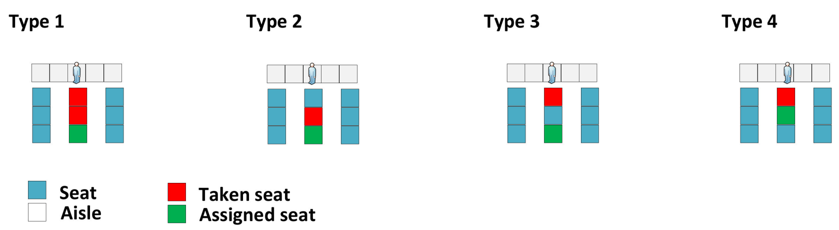

Figure 6. Types of seat interference.

3.2. Modeling the Actual Boarding Process

The actual boarding process consists of randomly filling in the first apron bus with half of the passengers travelling in a full aircraft and, when they have arrived near the airplane, the passengers with assigned seats select the boarding door (according to the boarding pass) and proceed towards it. Once they have arrived in the airplane, they will search for their seat.

Considering the randomness of the assigned seats boarding method on two-door set of rules, seat interferences, and the fact that none/some/all of the passengers are carrying hand luggage with them and the fact that storing the luggage can take time, the agents-based model was created in NetLogo 6.0.4, having the interface as in Figure 7.

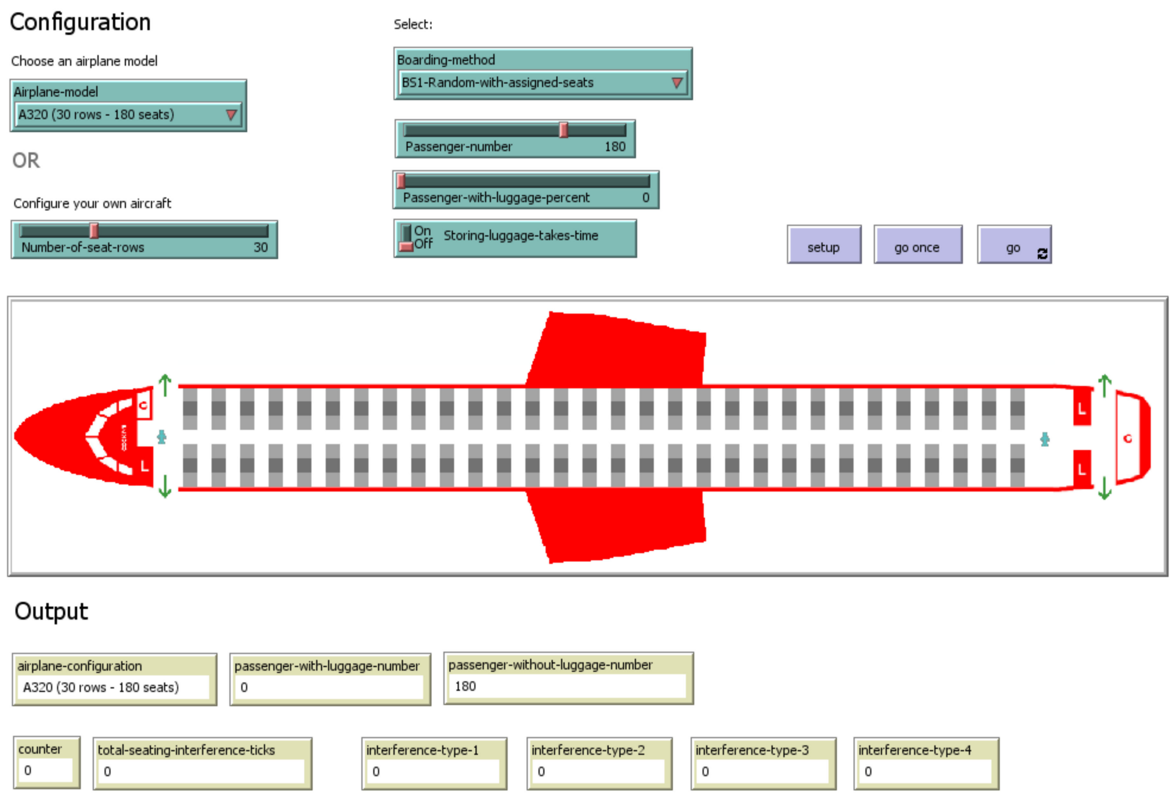

Figure 7. Agent-based model in NetLogo 6.0.4.

3.3. Modeling the Proposed Approach

In the proposed approach, in the first apron bus, the passengers from row 8 until 22 are boarded first (for an A320 configuration with 30 seat rows). On a general case, the selected rows are determined by splitting the airplane rows into four zones and selecting the two zones located in the middle of the aircraft. This is a back-to-front by group method applied twice on each half of the airplane, since the middle of the airplane, instead of rear, is considered as the starting point.

Once passengers have arrived near the airplane, they select their boarding door according to the boarding pass. Next, for the second apron bus, the passengers from the remaining seats in the front and rear (rows 1–7 and 23 to 30 in an A320 configuration) are boarded—Figure 8.

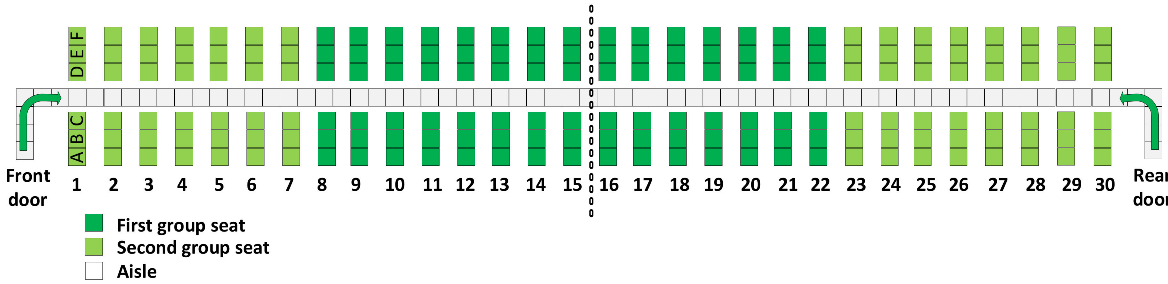

Figure 8. The proposed approach.

Thus, this proposed slight modification of boarding, where certain rows will be boarded in the first apron bus and all the others in the second one, does not require some special functionalities of the airport, as one of the crew members can simply announce this boarding rule. Moreover, as the first group of boarded passengers is a continuous group (starting from row 8 until 22), no confusion could be made here that will cause additional stress for the passengers. Additionally, considering the groups of people travelling together, this approach will not disturb them in a manner in which they will be separated as it is very likely they would be in the same bus, because they would have seats next to each other. Even in the case in which the passengers travelling together do not have the seats in the same zone of the aircraft, they can be boarded together in the first bus, as the result of this approach will be similar to the case in which they are boarded in two separate buses.

4. Data Analysis and Discussions

The simulations have considered the following situations:

- Case 1: all the passengers are travelling without hand luggage;
- Case 2-1: only half of the passengers are travelling with hand luggage;
- Case 2-2: only half of the passengers are travelling with hand luggage and they need time to store it in the overhead compartment;
- Case 3-1: all the passengers are travelling with hand luggage;
- Case 3-2: all the passengers are travelling with hand luggage and they need time to store it in the overhead compartment.

Each of the two boarding method has been run using the BehaviourSearch 1.10 tool [49], an overall number of 5000 simulations being analyzed (with each of the five cases simulated 1000 times). In each of the simulations, the sequence of passengers boarding was shuffled.

Few snapshots of the proposed approach are presented in Figure 9 below and in the Appendix A, in Figures A1 and A2.

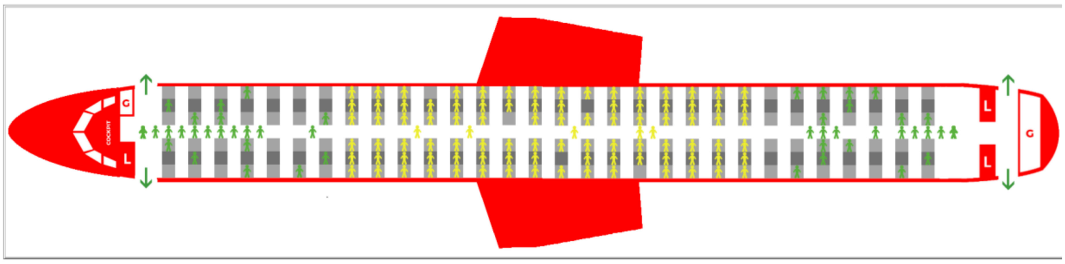

Figure 9. Snapshot of a simulation with t = 70 ticks.

4.1. Data Analysis in Terms of Interferences

Regarding the seat interferences, an average number of 261.3 individual waiting times have been recorded while the passengers were waiting to be seated in the proposed approach, with 12.5 units more than in the random with assigned seats case. This loss has just a partial impact over the total boarding time, as parallel waiting was possible.

The greatest number of interferences was from the type 4 category, followed by type 1 and lastly type 2 and 3, as shown in Table 2. Comparing the two boarding approaches, it can be said that, as expected, no seat interference difference can be encountered. Thus, the seat interference has no impact on the overall boarding results in terms of time.

Table 2. Number of seat interference situations depending on the chosen boarding method.

Issue	Resulted from:	Type 1	Type 2	Type 3	Type 4
No. of seat interference situations	Random with assigned seats	18.4	10.6	10.8	27.6
	Proposed approach	18.6	9.3	11.6	32.8

4.2. Data Analysis in Terms of Boarding Time

Considering all the cases, the data in Figure 10 was obtained. An average difference of 18.1 ticks has been determined across all the situations (equivalent to 66.97 s), with a decrease of 8.91% over the boarding time, which is equal to almost a minute and 7 s.

The smallest values have been obtained for the first case in which none of the passengers carry hand luggage with them inside the airplane. For the random with assigned seats situation, an average boarding time of 128 ticks (473.6 s) was determined, while the rest of the values obtained ranged in the interval of 120–135 ticks (in seconds: 444–499.5). The proposed approach in this case reached an average boarding time of 111.7 ticks (413.29 s), ranging between 104 and 121 ticks (in seconds: 384.8–447.7).

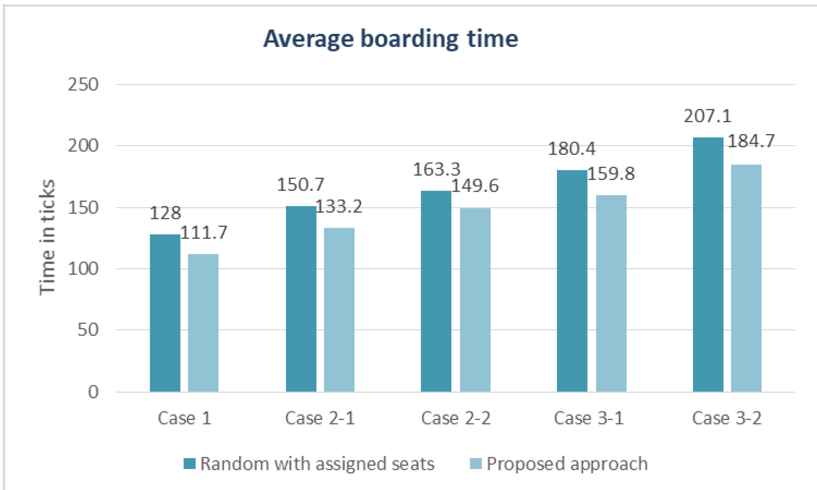

Figure 10. Average boarding time in ticks.

Among all the situations, case 3-2 seems to be the one consuming the most time for boarding, as the passengers needed additional time to store their luggage in the overhead compartment. However, it is also the one closest to the reality, as most of the passengers carry hand luggage with them. Thus, the average boarding time for the random with assigned seats was 207.1 ticks (taking values between 200 and 218 ticks), while for the proposed method, it was only 184.7 ticks (between 180 and 198 ticks). Translated into seconds, the random with assigned seats needed 746.29 s, while the proposed method needed merely 683.39 s.

Comparing the results from case 3-2, a decrease of 8.91% of the boarding time can be observed, namely 22.4 ticks. As each tick counts for 3.7 s, the time economy in this case would be 82.88 s, which is nearly 1 min and a half.

Even thought it might not seem much, the reduced amount of time when considering the number of flights per day in Europe in 2016 (27,844 flights) counts for almost 31,555 min.

Translated into costs ($ 53.5 per minute as reported by [23,32]), a saving of $73.9 is made on each flight and, considering all the flights in Europe in 2016 (10,190,903 flights according to [3]), the cost savings can be substantial.

5. Conclusions

Boarding strategies, such as the reverse pyramid, Steffen, non-traditional, modified optimal method, etc., have been developed and tested against airplanes boarded using a single-door. Some of these strategies may also work well when used on two-door boarding in an airport where two jet-bridges are available. Studies have shown that the use of some of these methods, and two jet-bridges instead of one, could reduce the boarding time with 5 min.

When one is facing boarding using apron buses, the situation is no longer the same: in most cases, two buses are available for an airplane boarding, making it difficult to divide the passengers in more than two groups. From here, it is quite clear that all the "by seat" methods cannot be applied to the apron buses case. Thus, the airline companies board passengers using the random with assigned seats methods, half of them in each apron bus.

As a result, the analysis in the present paper offers the possibility of dividing the passengers into two groups in an "orderly" manner. For this, we proposed that the airplane should be divided into four equal zones. The passengers of two of them, namely, the ones located in the middle of the aircraft, board in the first apron bus. This enables them to be the first ones who arrive inside of the aircraft. As airline companies have added a drawing on their boarding passes which emphasizes the door one should board depending on one's seat row and number, no passengers missing their assigned door have been considered. The second bus contains the passengers that board in the zones located in the front and rear. As boarding of the second apron bus takes time, the passengers from the first group have already entered into the airplane when the second groups arrived.

An agent-based model has been developed in NetLogo 6.0.4 in order to better shape the passengers behavior using agents. A series of elements have been considered, such as: whether the passengers carry hand luggage or not, whether they need time to store it in the overhead compartment, and the amount of seat interference, which takes time depending on the interference type.

The model has been used to simulate the actual boarding method using a two-door airplane and two apron buses, namely, the random boarding with assigned seats, with the proposed method.

The results have shown that no significant differences have been encountered between the two methods in terms of seat interferences, which was according to our expectations. As for the boarding time, an improvement of 8.91% was determined, which, in terms of minutes for a full-flight in which all the passengers carry hand luggage, and where its storing takes time, is about a 1 min and a half reduction on each flight. Compared with other methods employed in the field, boarding on two doors back-to-front seems to have a significant influence on the overall boarding time, which is in line with the studies showing that boarding back-to-front on just one door overpass the random boarding techniques [8,50]. Additionally, it might happen as shown by [50] that different boarding techniques perform better on certain aircraft configurations, which we aim to study in a future research.

Considering the higher number of flights in Europe, adopting this boarding method can lead to a significant reduction of the overall boarding time in a year. Additionally, as the passengers are boarded using four groups (two groups for each of the two buses), the persons travelling together are not affected by the separation among these groups, as, in most of the cases, these persons have seats on the same row.

The NetLogo 6.0.4 model can be accessed at the following address: https://github.com/liviucotfas/ase-2018-sustainability-airplane-boarding-two-door.

Author Contributions: Conceptualization, C.D. and L.-A.C.; Methodology, C.D.; Software, L.-A.C.; Validation, C.D. and N.C.; Formal Analysis, C.D. and I.N.; Investigation, N.C. and I.N.; Data Curation, L.-A.C. and N.C.; Writing-Original Draft Preparation, C.D.; Writing-Review & Editing, L.-A.C. and I.N.; Visualization, N.C. and I.N.; Supervision, C.D.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Simulation of the proposed boarding method

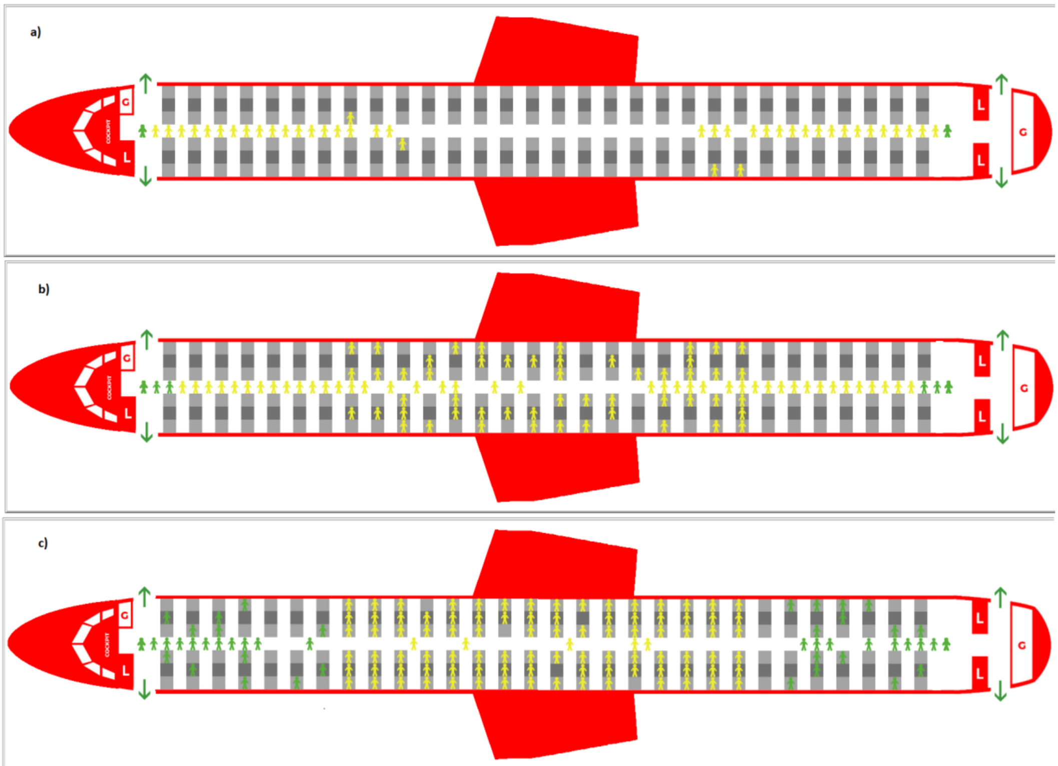

Figure A1. Snapshots of a simulation at different times with (**a**) t = 20, (**b**) t = 50, (**c**) t = 70.

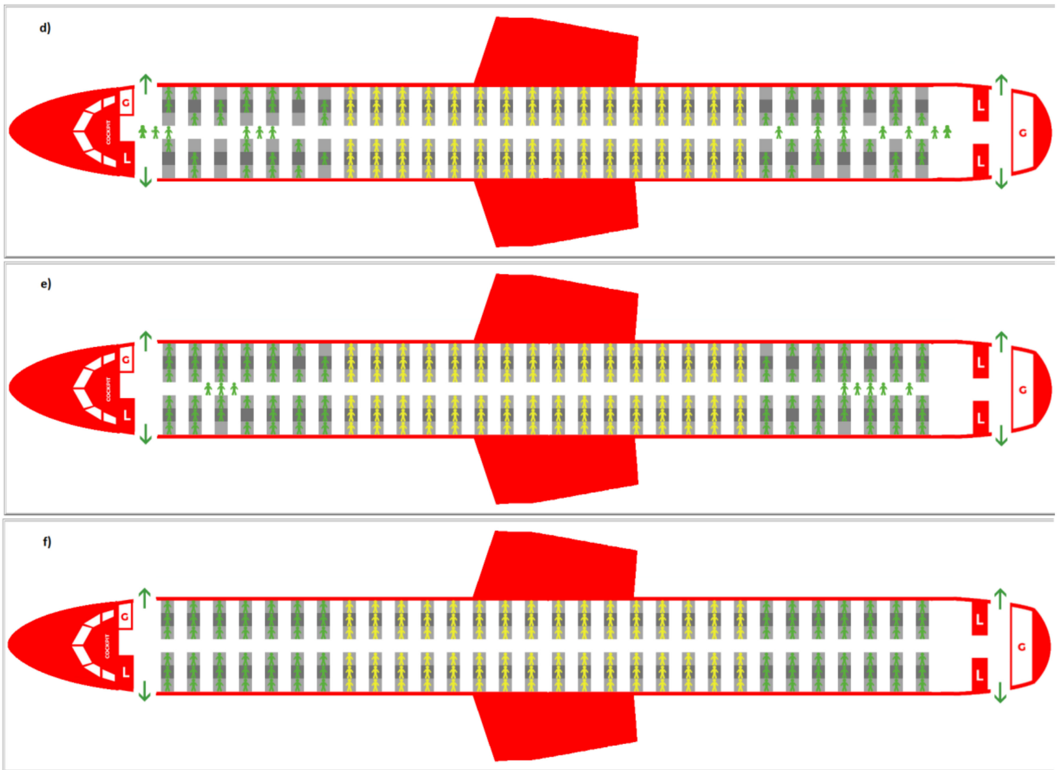

Figure A2. Snapshots of a simulation at different times with (**d**) t = 80, (**e**) t = 105, (**f**) t = 119.

References

1. Salzburg Airport Press. *First Electric Airport Bus in Salzburg 2018*; Salzburg Airport Press: Salzburg, Austria, 2018.
2. Schultz, M. Implementation and application of a stochastic aircraft boarding model. *Transp. Res. Part C Emerg. Technol.* **2018**, *90*, 334–349. [CrossRef]
3. Eurocontrol. *All-Causes Delay and Cancellations to Air Transport in Europe-2017*; Eurocontrol: Brussels, Belgium, 2018.
4. Cook, A.; Tanner, G. *European Airline Delay Cost Reference Values 2015*; Eurocontrol: Brussels, Belgium, 2015.
5. Steffen, J.H. A statistical mechanics model for free-for-all airplane passenger boarding. *Am. J. Phys.* **2008**, *76*, 1114–1119. [CrossRef]
6. Bachmat, E.; Berend, D.; Sapir, L.; Skiena, S.; Stolyarov, N. Analysis of Airplane Boarding Times. *Oper. Res.* **2009**, *57*, 499–513. [CrossRef]
7. Bidanda, R.; Winakor, J.; Geng, Z.; Vidic, N. A Review of Optimization Models for Boarding a Commercial Airplane. In Proceedings of the 24th International Conference on Production Research, Poznan, Poland, 30 July–3 August 2017; pp. 1–6.
8. Kierzkowski, A.; Kisiel, T. The Human Factor in the Passenger Boarding Process at the Airport. *Procedia Eng.* **2017**, *187*, 348–355. [CrossRef]
9. Delcea, C.; Cotfas, L.-A.; Paun, R. Agent-Based Evaluation of the Airplane Boarding Strategies' Efficiency and Sustainability. *Sustainability* **2018**, *10*, 1879. [CrossRef]
10. Milne, R.J.; Kelly, A.R. A new method for boarding passengers onto an airplane. *J. Air Transp. Manag.* **2014**, *34*, 93–100. [CrossRef]
11. Milne, R.J.; Salari, M. Optimization of assigning passengers to seats on airplanes based on their carry-on luggage. *J. Air Transp. Manag.* **2016**, *54*, 104–110. [CrossRef]
12. Milne, R.; Salari, M.; Kattan, L. Robust Optimization of Airplane Passenger Seating Assignments. *Aerospace* **2018**, *5*, 80. [CrossRef]
13. Steffen, J.H. Optimal boarding method for airline passengers. *J. Air Transp. Manag.* **2008**, *14*, 146–150. [CrossRef]
14. Steffen, J.H.; Hotchkiss, J. Experimental test of airplane boarding methods. *J. Air Transp. Manag.* **2012**, *18*, 64–67. [CrossRef]

15. Ferrari, P.; Nagel, K. Robustness of Efficient Passenger Boarding Strategies for Airplanes. *Transp. Res. Rec. J. Transp. Res. Board* **2005**, *1915*, 44–54. [CrossRef]
16. Soolaki, M.; Mahdavi, I.; Mahdavi-Amiri, N.; Hassanzadeh, R.; Aghajani, A. A new linear programming approach and genetic algorithm for solving airline boarding problem. *Appl. Math. Model.* **2012**, *36*, 4060–4072. [CrossRef]
17. Hutter, L.; Jaehn, F.; Neumann, S. Influencing Factors on Airplane Boarding Times. *Omega* **2018**. [CrossRef]
18. Qiang, S.-J.; Jia, B.; Xie, D.-F.; Gao, Z.-Y. Reducing airplane boarding time by accounting for passengers' individual properties: A simulation based on cellular automaton. *J. Air Transp. Manag.* **2014**, *40*, 42–47. [CrossRef]
19. Tang, T.-Q.; Yang, S.-P.; Ou, H.; Chen, L.; Huang, H.-J. An aircraft boarding model with the group behavior and the quantity of luggage. *Transp. Res. Part C Emerg. Technol.* **2018**, *93*, 115–127. [CrossRef]
20. Van Landeghem, H.; Beuselinck, A. Reducing passenger boarding time in airplanes: A simulation based approach. *Eur. J. Oper. Res.* **2002**, *142*, 294–308. [CrossRef]
21. Van den Briel, M.H.L.; Villalobos, J.R.; Hogg, G.L.; Lindemann, T.; Mulé, A.V. America West Airlines Develops Efficient Boarding Strategies. *Interfaces* **2005**, *35*, 191–201. [CrossRef]
22. Notomista, G.; Selvaggio, M.; Sbrizzi, F.; Di Maio, G.; Grazioso, S.; Botsch, M. A fast airplane boarding strategy using online seat assignment based on passenger classification. *J. Air Transp. Manag.* **2016**, *53*, 140–149. [CrossRef]
23. Nyquist, D.C.; McFadden, K.L. A study of the airline boarding problem. *J. Air Transp. Manag.* **2008**, *14*, 197–204. [CrossRef]
24. Ren, X.; Xu, X. Experimental analyses of airplane boarding based on interference classification. *J. Air Transp. Manag.* **2018**, *71*, 55–63. [CrossRef]
25. Jafer, S.; Mi, W. Comparative Study of Aircraft Boarding Strategies Using Cellular Discrete Event Simulation. *Aerospace* **2017**, *4*, 57. [CrossRef]
26. Airplane Turn Time. Available online: http://www.boeing.com/commercial/aeromagazine/aero_01/textonly/t01txt.html (accessed on 30 May 2018).
27. Schultz, M. Fast Aircraft Turnaround Enabled by Reliable Passenger Boarding. *Aerospace* **2018**, *5*, 8. [CrossRef]
28. Schultz, M. A metric for the real-time evaluation of the aircraft boarding progress. *Transp. Res. Part C Emerg. Technol.* **2018**, *86*, 467–487. [CrossRef]
29. Schultz, M. Dynamic change of aircraft seat condition for fast boarding. *Transp. Res. Part C Emerg. Technol.* **2017**, *85*, 131–147. [CrossRef]
30. Bazargan, M. A linear programming approach for aircraft boarding strategy. *Eur. J. Oper. Res.* **2007**, *183*, 394–411. [CrossRef]
31. Schultz, M. *The Seat Interference Potential as an Indicator for the Aircraft Boarding Progress*; SAE International: Warrendale, PA, USA, 2017.
32. Steiner, A.; Philipp, M. Speeding up the airplane boarding process by using pre-boarding areas. In Proceedings of the 9th Swiss Transport Research Conference, Ascona, Switzerland, 9–11 September 2009.
33. Tang, T.-Q.; Wu, Y.-H.; Huang, H.-J.; Caccetta, L. An aircraft boarding model accounting for passengers' individual properties. *Transp. Res. Part C Emerg. Technol.* **2012**, *22*, 1–16. [CrossRef]
34. Jaehn, F.; Neumann, S. Airplane boarding. *Eur. J. Oper. Res.* **2015**, *244*, 339–359. [CrossRef]
35. Schultz, M.; Kunze, T.; Fricke, H. Boarding on the critical path of the turnaround. In Proceedings of the Tenth USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL, USA, 10–13 June 2013; pp. 1–10.
36. Schultz, M.; Schulz, C.; Fricke, H. Efficiency of Aircraft Boarding Procedures. In Proceedings of the 3rd International Conference on Research in Airport Transportation, Fairfax, VA, USA, 1–4 June 2008; Volume 371–391.
37. Gao, M.; Zhou, L.; Chen, Y. An Alternative Approach for High Speed Railway Carrying Capacity Calculation Based on Multiagent Simulation. *Discret. Dyn. Nat. Soc.* **2016**, *2016*, e4278073. [CrossRef]
38. Riaz, F.; Jabbar, S.; Sajid, M.; Ahmad, M.; Naseer, K.; Ali, N. A collision avoidance scheme for autonomous vehicles inspired by human social norms. *Comput. Electr. Eng.* **2018**. [CrossRef]
39. Dossetti, V.; Bouzat, S.; Kuperman, M.N. Behavioral effects in room evacuation models. *Phys. A Stat. Mech. Appl.* **2017**, *479*, 193–202. [CrossRef]

40. Delcea, C.; Cotfas, L.-A.; Paun, R. Agent-Based Optimization of the Emergency Exits and Desks Placement in Classrooms. In *Computational Collective Intelligence*; Nguyen, N.T., Pimenidis, E., Khan, Z., Trawiński, B., Eds.; Springer International Publishing: Cham, Switzerland, 2018; Volume 11055, pp. 340–348. ISBN 978-3-319-98442-1.
41. Prachai, S. The Design of Diabetes Simulation System using Multi-Agent. *Procedia Soc. Behav. Sci.* **2012**, *40*, 146–151. [CrossRef]
42. Pardo, M.; Coronado, W.F. Agent-based Modeling and Simulation to Adoption Process of Information Technologies in Health Systems. *IEEE Latin Am. Trans.* **2016**, *14*, 3358–3363. [CrossRef]
43. Castilla-Rho, J.C.; Mariethoz, G.; Rojas, R.; Andersen, M.S.; Kelly, B.F.J. An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems. *Environ. Model. Softw.* **2015**, *73*, 305–323. [CrossRef]
44. West, T.A.P.; Grogan, K.A.; Swisher, M.E.; Caviglia-Harris, J.L.; Sills, E.; Harris, D.; Roberts, D.; Putz, F.E. A hybrid optimization-agent-based model of REDD+ payments to households on an old deforestation frontier in the Brazilian Amazon. *Environ. Model. Softw.* **2018**, *100*, 159–174. [CrossRef]
45. Delcea, C.; Bradea, I.A.; Cotfas, L.A.; Scarlat, E. Opinion influence in online social media environments—U grey system theory and agent-based modeling approach. In Proceedings of the 2017 International Conference on Grey Systems and Intelligent Services (GSIS), Stockholm, Sweden, 8–11 August 2017; pp. 349–355.
46. Delcea, C.; Cotfas, L.-A.; Paun, R. Airplane Boarding Strategies Using Agent-Based Modeling and Grey Analysis. In *Computational Collective Intelligence*; Nguyen, N.T., Pimenidis, E., Khan, Z., Trawiński, B., Eds.; Springer International Publishing: Cham, Switzerland, 2018; Volume 11055, pp. 329–339. ISBN 978-3-319-98442-1.
47. Schultz, M. Field Trial Measurements to Validate a Stochastic Aircraft Boarding Model. *Aerospace* **2018**, *5*, 27. [CrossRef]
48. Delcea, C.; Bradea, I.A. *Economic Cybernetics: An Equation-Based Modeling and Agent-Based Modeling Approach*; Editura Universitara: București, Romania, 2017; ISBN 978-606-28-0629-3.
49. Wilensky, U.; Rand, W. *An introduction to Agent-Based Modeling: Modeling Natural, Social, and Engineered Complex Systems with NetLogo*; The MIT Press: Cambridge, MA, USA, 2015; ISBN 978-0-262-73189-8.
50. Iyigunlu, S.; Fookes, C.; Yarlagadda, P. Agent-based Modelling of Aircraft Boarding Methods. In *Proceedings of the 4th International Conference on Simulation and Modeling Methodologies, Technologies and Applications*; SCITEPRESS—Science and Technology Publications: Vienna, Austria, 2014; pp. 148–154.