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MEASURING PROXIMITY OF INDIVIDUALS DURING AIRCRAFT BOARDING PROCESS WITH ELDERLY PASSENGERS THROUGH AGENT-BASED SIMULATION

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ABSTRACT

The COVID-19 pandemic imposed severe restrictions to the mobility of people worldwide, bringing as a consequent great losses to the air transportation industry. The evaluation of biosafety risk has never been more critical for the recovery of transport and economic activity. Elderly passengers constitute a specially vulnerable population to infectious diseases. The main objective of the present study was to investigate the factors that lead to increased proximity of individuals during the boarding process when elderly passengers are present. In order to do so, an agent-based simulation model was built to represent the boarding process in a Boeing 737 aircraft. The simulated results indicate that elderly passengers are less exposed to contact with other individuals during boarding process when they are the last passengers to come onboard and social distancing actions are taken, although this strategy may increase total boarding time.

1 INTRODUCTION

In 2020, the world was stricken by the COVID-19 pandemic. First identified in December 2019 in Wuhan, China, the virus rapidly spread across the world, accounting for more than 128 million confirmed cases and 2.8 million deaths by the end of March, 2021 (WHO 2021). In the beginning of the pandemic, the majority of deaths happened among elderly population: in March 2020, Italy witnessed a fatality rate of 20.2% in its population of 80+ (Onder et al. 2020); in the United States, 80.47% of all deaths were of individuals of 65 years or older (Centers for Disease Control and Prevention 2021). As the disease spread worldwide, social distancing and severe travel restrictions were issued globally, leading to an unheard drop in transport activity; the aviation sector has estimated net loss of US$118.5 billion in 2020 (IATA 2020).

The COVID-19 pandemic represents the first major global infectious disease outbreak since the 1918 influenza pandemic. Previous disruptions of aeronautical operations are related to regional epidemics, such as SARS or MERS. As there is no precedent to the COVID-19 pandemic impact on the global transportation, enormous concern over the safety of commercial air travel are raised. The literature reports cases in which infected passengers may have spread disease to others during flights in other epidemics such as SARS (Olsen et al. 2003; Choi et al. 2020), tuberculosis (Centers for Disease Control and Prevention 1995; Kenyon et al. 1996) and influeza (Moser et al. 1979; Baker et al. 2010; Kim et al. 2010). Following the SARS epidemic, some studies have applied transmission models to investigate the risk of infection in air travel for the entirety duration of flight (Ko et al. 2004; Smieszek 2009; Sze To et al. 2009). While the risk of transmission of COVID-19 during air travel is considered low (Pombal et al. 2020) because of how air is circulated and filtered in modern aircraft cabins, air travel involves various operations in which it may be difficult to implement social distancing measures, such as when passengers wait in airport terminals, or pass through security check points. The boarding process is also characterized by close contact with other

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individuals and recent studies have addressed the risk of exposure to the virus (Cotfas et al. 2020; Schultz and Fuchte 2020).

However, these studies have considered homogeneous passenger populations, i.e., passengers are considered to have equal characteristics and no parameters differ them from one another. In the present effort, we propose a simulation-based study in which the proximity of passengers during boarding process is addressed for a heterogenous population, i.e., to each passenger is attributed an age group and a walking speed. Therefore, we consider a measure of social distancing during boarding processes in which elderly passengers are present.

2 METHODOLOGY

An agent-based model (ABM) was adopted for boarding simulation. In the ABM approach, the system is comprised of a set of independent entities (called agents) that may interact with one another. As each agent has its own characteristics and makes its own decisions based on a given set of rules, ABM is able to capture the random nature associated to the aircraft boarding process, regarding both the environment conditions (airplane infrastructure) and the passengers' (physical, behavioral) characteristics. The simulation model was implemented in the open agent-based modeling environment NetLogo (Wilensky 1999) to simulate various boarding scenarios. The use of computer simulations offers the benefits of (i) low cost, (ii) safety, as well as the (iii) possibility of representing various scenarios. An agent-based simulation approach allows the modeling of a heterogeneous population whose behavior evolves with time and according to interactions with other agents (Bonabeau 2002).

In all of the following discussions the characteristics of a Boeing 737 aircraft will be used as an example. The process is general, though, and can be applied to any aircraft configuration. The Boeing 737 cabin layout has seat configuration 3-3, and maximum capacity of 186 passengers. The single aisle aircraft accommodates a total of 31 rows and 8 exits. The cabin is discretized into 0.5 m x 0.5 m nodes, classified as structures (seats, toilet, and fuselage) or open spaces (aisles, legroom and exits), as illustrated in Figure 1. The simulation time is set so that 20 ticks correspond to 1 second.

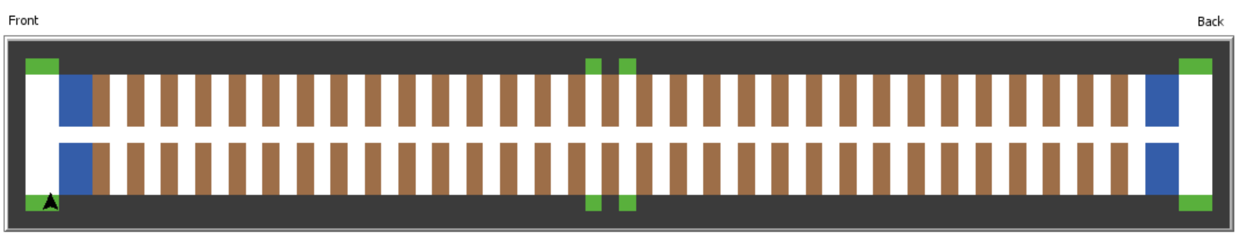

Figure 1: Example of boarding simulation for the Boeing 737 aircraft. Arrows correspond to passengers and their facing directions; white cells represent open spaces where passengers can walk freely, such as aisles and legroom; brown cells represent seats; blue cells represent aircraft internal structures; and green cells represent doors and emergency exits.

2.1 Passenger's Characteristics

There are four characteristics that differentiate passengers from each other: (i) age and, consequently, walking speed; (ii) seat ticket assignment; (iii) possession of carry-on luggage; and (iv) time needed to store luggage at overhead bin. The model incorporates different age groups, following the Brazilian population distribution from 15 to 74 years of age (IBGE 2010): (i) 15-16, (ii) 17-25, (iii) 26-50, (iv) 51-64, and (v) 65-75 years; for each age group, a particular walking speed is defined as follows.

Most of the studies addressing walking dynamics are set in open spaces, characterized by free flow of people. In the literature Willis et al. (2004), pedestrians are observed on a street, and their walking speeds, which depend on their ages, are modeled as a random variable with normal distribution with mean of 1.47 m/s and standard deviation of 0.299 m/s. A previous study (Mas et al. 2013), based on empirical observation of a real life aircraft boarding process, determined a mean walking speed of 0.5 m/s, when all passengers are considered equally. In order to model different walking speeds for agents within the aircraft cabin, the strategy adopted in the present investigation consists in applying for each age interval a correction of the reference speed value (0.5 m/s) according to free flow walking speed distribution. For example, Willis et al. (2004) state that the population mean walking speed is 1.47m/s and, for individuals older than 64 years old, their mean walking speed is 1.16m/s; thus applying the corresponding correction, the elder walking speed inside the aircraft is about 0.39m/s.

Seat tickets are randomly distributed among passengers, and all seats inside the airplane are available. Moreover, all passengers are assumed to be traveling alone, i.e., there is no group formation. Therefore, passengers enter the cabin one at a time, with a destination seat, since there is no free or preferred seating.

Each passenger is allowed to have at most one carry-on luggage and there is no physical limitation to the overhead bin. The possession of a carry-on luggage is determined randomly, with probability 80%; it means that each simulated passenger has 80% chance of carrying a piece of luggage.

Lastly, each passenger is assigned a time needed to store the luggage at the overhead bin. This storing time is modelled as a random variable that follows a Weibull distribution, defined from field trial measurements (Schultz 2018). This distribution is independent of the passenger's age. In the present simulation study, if an agent is flagged as an elder, his or her luggage storing time is increased in 20%.

2.2 Scenarios Setup

The different simulated scenarios are determined by the combinations of levels of the following factors:

1. the order in which elders get onboard the aircraft (PRI):
   i. they embark first (On);
   ii. they are the last to embark (OnLast);
   iii. the age of the passenger is not taken into account during the boarding procedure (Off).

   When elders have priority boarding, it means that they get onboard before other passengers, regardless of ticket class, loyalty program or boarding group. After all elders have boarded, the other passengers may enter, according to the determined boarding strategy. When elders are the last to come onboard, the reverse situation happens. If no priority boarding happens, it means that all passengers embark according solely to the boarding strategy.

2. boarding strategy (STR):
   i. random (Random);
   ii. back to front, by blocks (Back-to-front).

   If random boarding strategy is adopted, no order is defined, and passengers come onboard according to a first-come first-serve (FCFS) fashion. In back-to-front by-blocks strategy, three boarding groups with equal number of passengers are defined based on their seating location (front group, middle group, and back-group); the first passengers to get into the cabin are those in the back group (passengers whose tickets are near the rear of the airplane), followed by those in the middle group and, finally, those in the front group (passengers whose tickets are near the front of the airplane).

3. social distancing policy (DIS):
   i. none, representing a pre-pandemic situation, in which passengers are allowed to stay arbitrarily close to others (0m);
   ii. passengers keep a minimum distance of 1m from others at all times (1m).

There is a total of 12 possible combinations of factors levels, or simulation scenarios.

2.3 Other Simulation Parameters

There are two additional simulation parameters which are fixed values and cannot be controlled from the simulation interface: (i) passenger flow rate, and (ii) seat shuffle time.

Passenger flow rate is the time gap between successive passengers entering the aircraft. The value of this rate depends on the gate control, which is the point where the airline company employees check the passenger's identification and travel ticket. It is understood that this rate, in real situations, varies throughout the boarding process, and may be modeled as a random variable: at the beginning of the boarding process, a higher flow may be observed, and as more passengers are already inside the cabin, the rate decreases. In the present study, the fixed value of 14.1 pax/min is used (Schultz 2017), representing the situation in which passengers enter the cabin uniformly, one at a time, at constant that rate.

Seat shuffle time is the time needed for a seat interference to be resolved. For example, a passenger assigned to a window seat may be blocked by a passenger already accommodated at the aisle seat. It is possible to define different shuffle time values, depending on the interference situation underway. The simulation model assumes that all seat shuffles take 10 seconds (Schultz 2018), a time during which the passenger who wishes to seat, stays in the aisle blocking the other passengers that come in.

2.4 Measure of Proximity

At the beginning of the COVID-19 pandemic, several airline companies blocked the middle seats, in order to promote social distancing (Thomas Pallini 2020). However, this method is not economically viable in the long run (Dawn Gilbertson 2020). Thus, in the current investigation it is assumed that the aircraft operates with full capacity of passengers, which is the scenario with highest possible passenger density.

The World Health Organization (WHO) suggests the use of face masks and social distancing of at least 1 meter (WHO 2021), when keeping greater distances is not possible. The virus that causes COVID-19 seems to spread easily from person to person and more commonly than through airborne transmission (when the virus is present in small droplets that can linger in the air for a long time, having the potential of infecting people at distances above 2 meters) (Centers for Disease Control and Prevention 2020). Thus, social distancing helps decreasing the probability of disease transmission.

In this study, disease transmission models or use of face masks are not considered. As cotton handmade masks, the most common type used by general public, offer a effective reduction in droplet disperson (Verma et al. 2020), it is expected that the probability of transmission reduces when using face maks. In this study, the impact of social distancing during the boarding process is addressed by monitoring the time during which a passenger is within a distance of 1m from another person. This is done by defining for each passenger a measure of proximity given by a 1m radius that determines the social distancing boundary, and a timer is set to zero at the beginning of the boarding process. If an individual comes close enough to another, invading the social distancing boundary, both passengers' timers are started and stop counting time only when they are no longer physically close enough. If two passengers are seated next to each other, the timer of each passenger continues to operate throughout the boarding process, because both passengers are within each other's social distancing boundaries. This dynamic is illustrated in Figure 2. The measure of proximity consists of the cumulative time a passenger is within the social distancing boundary of others. When social distacing is installed, the proximity measure basically counts two situatios: (i) when a passenger is already seating and others are passing by he or she in the aisle or row, and (ii) when two passengers are seating next to each other.

2.5 Simulation Process

At the beginning of the simulation, all passengers are placed at the front door, and they stay at that position until it is their turn to get onboard, according to the flow rate with which passengers enter the aircraft.

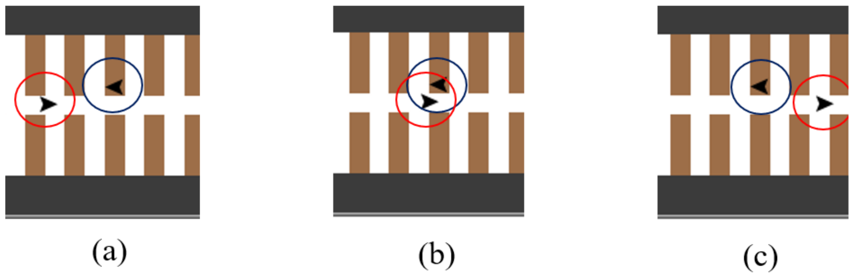

Figure 2: Measure of proximity. (a) Timer is off, because circled passengers are off social distancing boudaries of others; (b) Timer is on, because circled passengers are within each other's social distancing boundaries; (c) Timer is off.

Regardless of the scenario being simulated, the simulation model does not admit the occurrence of late comers. It is important to stress that while walking, passengers cannot pass one another, i.e, if there is a slow moving passenger ahead, or if there is an aisle interference, passengers behind are not able to move freely and overtake the slow passenger. In those cases, they must wait until the former passenger takes a seat, so they be allowed to resume his or her normal speed.

With a seat ticket in hands, and assuming that there is a crew member assisting the passenger in identifying the assigned seat with no mistakes, he or she walks until reaching the seat row. There are no lost individuals in the process. When the passenger reaches the destined position, he or she first checks if there is no seat interference, i.e., if there is no other agent seating at the same row and blocking his or her way. If that is the case, a time delay of 10s (seat shuffle time) will be added to represent the time needed to resolve the interference. Then, if the passenger is carrying luggage, another time delay will be added, representing the time needed to store it in the bin. In this case, the delay will be determined according to the Weibull distribution, as previously described; for elderly passengers, the time needed to store luggage is increased in 20% on top of that. As elderly passengers not only may need more time to storage the luggage in the overhead bin, but they may also need assist in doing so, it is expected that the proximity increases. Nonetheless, this assumption is not modeled in the present simulation. During these delays, a passenger will be in the aisle, blocking other passengers who need to proceed. After that passenger takes the seat, the previously blocked agents in the aisle resume movement.

The simulation starts when the first passenger enters the airplane and ends when all passengers are seated and then total boarding time is computed. Although we understand that the boarding process is only a fraction of the travel and other steps should also be tackled, such as arriving at the airport, checking-in, waiting at gate, flying, disembarking, baggage claiming, among others, because these also contribute to transmission, the scope of the present study is limited to the boarding process, so that other travel phases are not considered in the simulations.

3 RESULTS AND DICUSSION

The following results were obtained from 100 replicates of all simulation scenarios, consisting of 1200 simulation runs. It is important to underline that these results are not expected to be interpreted as "true" values, in the sense that no validation with real data was performed. However, care was taken in building a realistic simulation model, and several tests have been conducted in order to verify whether the simulation model performs as designed, and that the simulation model is relevant. Therefore, these results are valuable for gaining insights in terms of relative comparisons, and reaching qualitative conclusions.

In order to facilitate the understanding of the differences in the boarding processes for pre- and pandemic scenarios, the results are presented for each social distancing setting. For pre-pandemic situations, it is assumed that passengers can stay as close as physically possible to other individuals, since no social distancing actions are prescribed. In pandemic situations, it is assumed that social distancing actions are enforced so that passengers will try to keep a minimum distance of 1m from other individuals at all times. Then, the measure of proximity is analyzed for each simulated scenario, in order to evaluate the situations in which passengers stay further apart for longer periods of time.

Figure 3 shows the simulated results for the total boarding times observed for different scenarios, each is a combination of the levels of factors studied (priority setting, boarding strategy and social distacing settings).

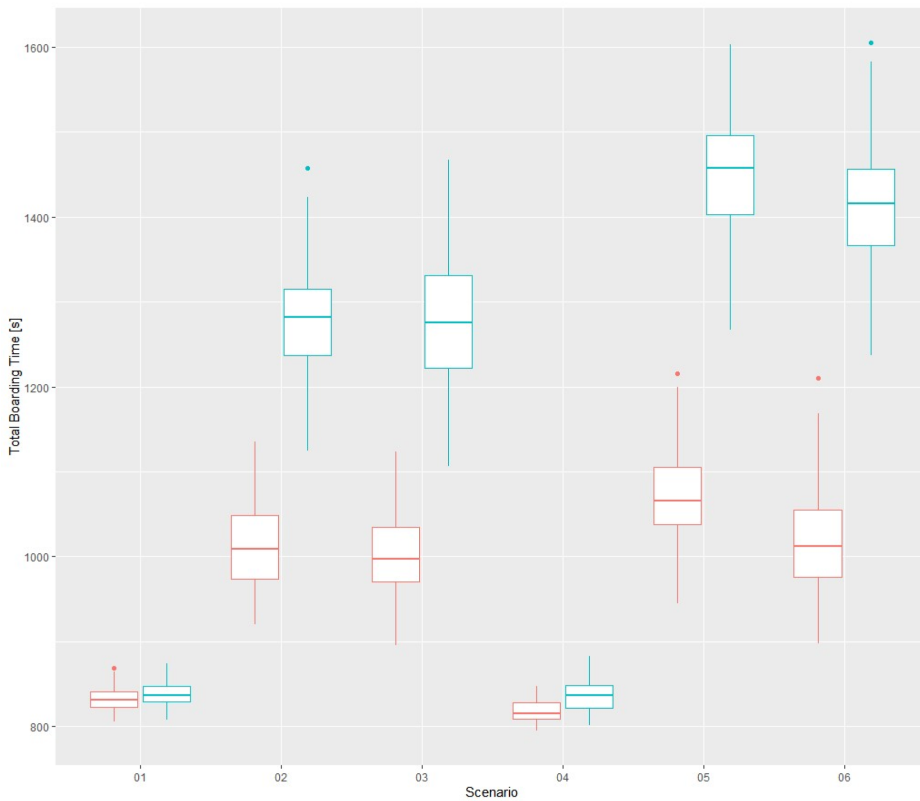

Figure 3: Boxplots for total boarding time for the different simulated scenarios (01: PRI = On, STR = Random; 02: PRI = OnLast, STR = Random; 03: PRI = Off, STR = Random; 04: PRI = On, STR = Back-to-front; 05: PRI = OnLast, STR = Back-to-front; 06: PRI = Off, STR = Back-to-front). The colors of boxplots represent different social distancing situations: red corresponds to pre-pandemic situation (no social distancing); cyan, to pandemic situation (with 1m social distancing).

The plot suggest that scenarios in which elders board first (scenarios 01 and 04) have the lowest boarding time, in both situations pre- and during pandemic. Therefore, in terms of the process time, this setting indicates significant advantage over the other situations. Another suggestion is that the boarding time is not significantly influenced by when elders board last (scenarios 02 and 04) or there is no priority boarding (scenarios 03 and 06), i.e., both settings produced similar results. Yet, in terms of the boarding strategy, there is a small difference in time when random (scenarios 01, 02 and 03) or back-to-front (scenarios 04, 05 and 06) strategy is applied. Overall, back-to-front scenarios appear to have a bigger median, except in scenario 04 without social distancing. Also, the times for when social distancing measures are applied (cyan color) demonstrate an increase in boarding times, which is expected. This increase is significantly sharper in scenarios which elders board last (scenarios 02 an 05) and priority boarding is not present (scenarios 03 and 06).

Figure 4 presents the results for the measure of proximity for pre- and pandemic situations. The proximity measure corresponds to the total time passengers are in close contact (i.e., within the 1m social distancing boundary) with other individuals during the boarding process. In pre-pandemic situation there is no restrictions on a passenger's distance to others, whereas when social distancing measures are enforced, a minimum distance of 1m from other passengers is required.

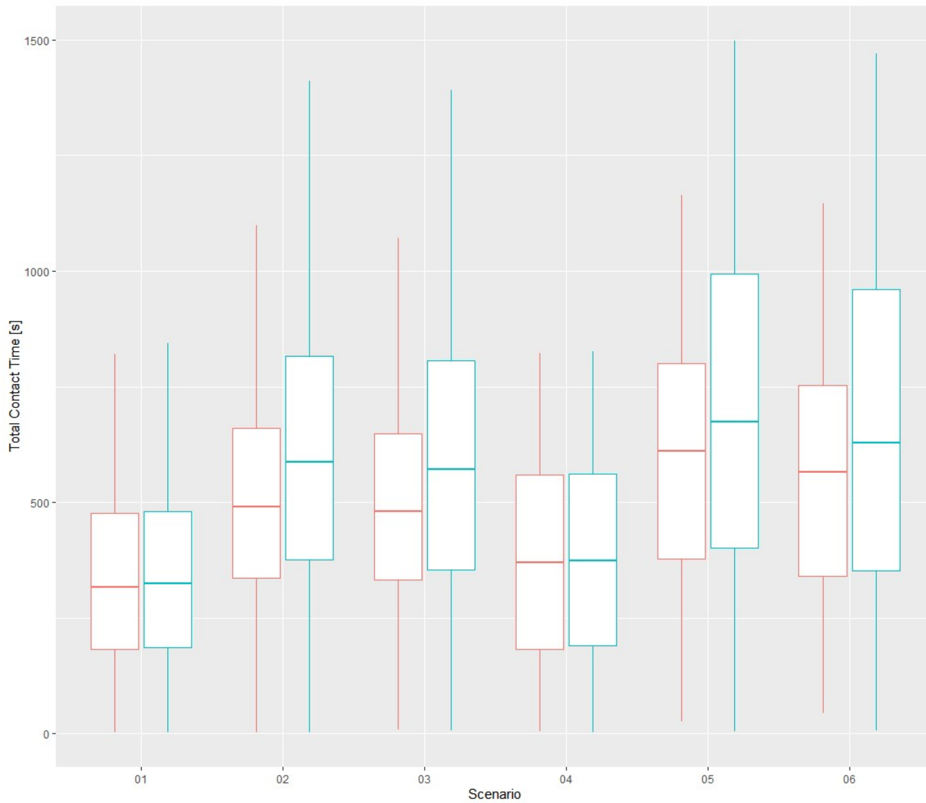

Figure 4: Boxplots for total contact time (proximity measure) for the different simulated scenarios (01: PRI = On, STR = Random; 02: PRI = OnLast, STR = Random; 03: PRI = Off, STR = Random; 04: PRI = On, STR = Back-to-front; 05: PRI = OnLast, STR = Back-to-front; 06: PRI = Off, STR = Back-to-front). The colors of boxplots represent different social distancing situations: red corresponds to pre-pandemic situation (no social distancing); cyan, to pandemic situation (with 1m social distancing).

The plot suggests that the distributions obtained for each scenario somewhat overlap and have a high variability. Therefore, results should not be taken as a deterministic, but as an overall behavior. In a pre-pandemic situation, when elderly passengers board first (scenarios 01 and 04), the average total contact time for passengers of all ages seems to be shorter in comparison to other settings. This happens mainly because the boarding process with priority embarking is significantly faster, resulting in less close contact among passengers. The random boarding strategy (scenarios 01, 02 and 03) shows an decrease in total contact time if compared to the alternative back-to-front strategy (scenarios 04, 05 and 06), which means that close contact among passengers is avoided that way. This may sound counterintuitive but is a direct result of the way the proximity measure is defined: when passengers assigned to seats close to each other board together (back-to-front strategy), they have to stay close together for longer periods of time, whereas in random boarding, the chance of being close to each other increases as the process is prolongued. A former study that adopts pedestrian-dynamics reached a similar conclusion (Islam et al. 2020). However, other studies consider the number of contacts between individuals (Cotfas et al. 2020; Schultz and Fuchte

2020) and report that adopting back-to-front strategy may be a better solution since fewer interferences are likely take place among passengers.

When social distancing is enforced, the average total contact time is increased in all scenarios, except for scenarios 01 and 04, in which those times stay fairly similar. This variation happens because, even though there's a larger distance separating individuals, the average boarding time is much longer, as seen in Figure 3. This means that two passengers seating next to each other are likely to stay in close contact for longer periods of time, while other passengers are still embarking. The increase in total contact time is not as steep as the increase in total boarding time, but still significant. The simulated maximum values for total contact times are also generally higher with social distancing, except for scenarios 01 and 04, which represent the fastest boarding scenarios in this investigation. In this case, average total boarding time and average total contact time do not differ significantly when comparing the situations pre- and pandemic. Thus, when social distancing actions are taken, the total contact time among individuals tends to increase. It is important to notice that no assessment of the infection risk was conducted; the only evaluation performed is with respect to the duration of close contact among passengers during the boarding process.

A similar analysis is performed considering the elderly passengers separately. The simulated results are presented in Figure 5. Regardless of social distancing, the results indicate that when elders are the last to go onboard (scenarios 02 and 05), although the boarding takes considerably time, they are less time in proximity to other passengers, according to the proximity measure studied. Thus, it is suggested that this priority boarding is applied in order to protect this population, who is usually more susceptible to infectious diseases. When elders embark first or no priority is established, the average total contact times are rather close to each other.

If social distancing actions are taken, similar conclusions follow with respect to elderly passengers: they should embark after all other passengers, because it appears to have a decrease in total contact time compared to other scenarios in pandemic situation. As expected, the last passengers to go onboard the aircraft are those less subjected to proximity with others. If boarding first, elders are susceptible to all other passengers passing by them when walking the aisle. In an extreme case, for example, an elder passenger seats in the fist row in the aisle seat; all passengers will have to pass closely to he or she, increasing the proximity measure. Thus, it is recommended that passengers susceptible to infectious diseases should board last.

4 CONCLUDING REMARKS

The main objective of the present study was to investigate the factors that lead to increased proximity of individuals during the boarding process when elderly passengers are present. In order to do so, an agent-based simulation model was built to represent the boarding process in a Boeing 737 aircraft; 100 replicates of a total of 12 scenarios (equivalent of 1200 simulation runs) were performed. The considered factors were priority boarding for elderly passengers, boarding strategy and the application of social distancing actions. A proximity measure that represents the amount of time that passengers stay close to other individuals during the boarding process was computed. As already stated, these results should be taken as a qualitative suggestion, and further studies should be made to confirm the findings in this study.

Simulation scenarios in which elderly passengers are given priority and are the firsts to embark result in a boarding process significantly faster. When elders board last or have no special order of boarding, the boarding time does not show significant differences. If social distancing is enforced, as expected, boarding times increase for all situations. Nonetheless, if elders boards first, even with social distancing, boarding time is consistently shorter compared to other situations.

In terms of the proximity measure, it is more likely that the elderly passengers are exposed to a higher degree of contact with other individuals when they board first, since other passengers must pass by them during boarding. Since it is important to reduce the exposition of this vulnerable population to infectious agents, the simulation results suggest that elderly passengers should be the last to go onboard, even though the boarding process can take longer.

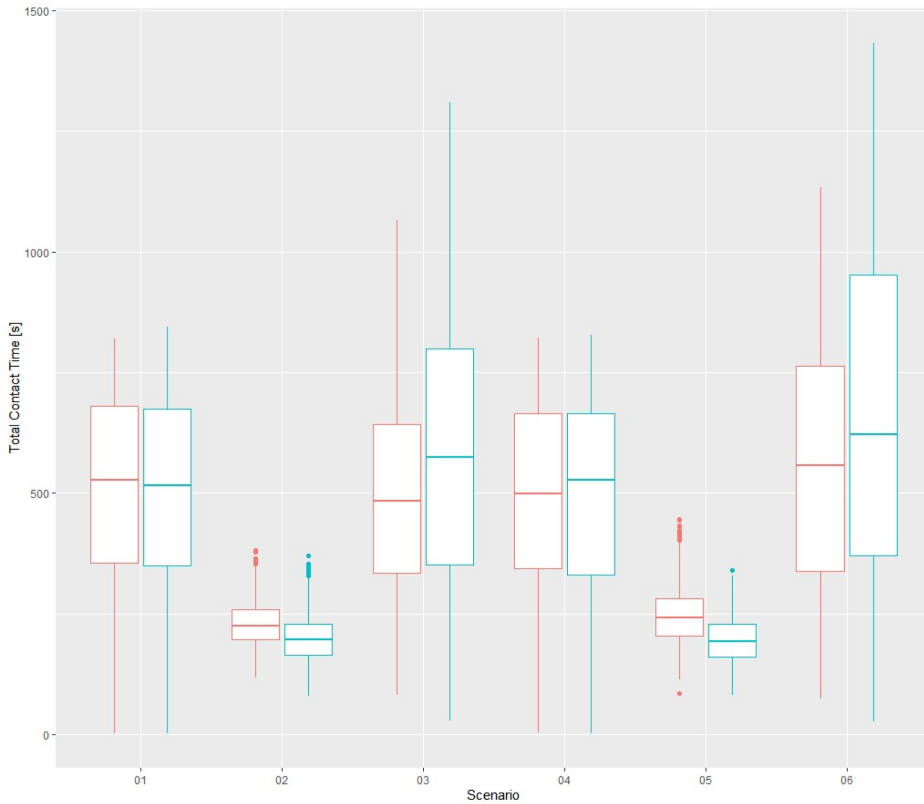

Figure 5: Boxplots for total contact time (proximity measure) for elderly passengers for the different simulated scenarios (01: PRI = On, STR = Random; 02: PRI = OnLast, STR = Random; 03: PRI = Off, STR = Random; 04: PRI = On, STR = Back-to-front; 05: PRI = OnLast, STR = Back-to-front; 06: PRI = Off, STR = Back-to-front). The colors of boxplots represent different social distancing situations: red corresponds to pre-pandemic situation (no social distancing); cyan, to pandemic situation (with 1m social distancing).

The proposed work was a preliminary study that can be easily generalized in order to include new features that confer more realism to infectious disease transmission during an airplane boarding process. Some of the adopted parameters were set as fixed values; in a future effort, sensitivity analysis should be conducted in order to evaluate the variability in response when, for example, passengers enter the airplane in a faster pace. Also, the assumption that all passengers travel alone does not necessarily reflect reality, thus group formation is another suggestion for further improvement of the simulation.

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REFERENCES

Baker, M. G., C. N. Thornley, C. Mills, S. Roberts, S. Perera, J. Peters, A. Kelso, I. Barr, and N. Wilson. 2010. “Transmission of pandemic A/H1N1 2009 influenza on passenger aircraft: retrospective cohort study”. *Bmj* 340.

Bonabeau, E. 2002. “Agent-based modeling: Methods and techniques for simulating human systems”. *Proceedings of the national academy of sciences* 99(suppl 3):7280–7287.

Centers for Disease Control and Prevention 1995. “Exposure of passengers and flight crew to Mycobacterium tuberculosis on commercial aircraft, 1992-1995”. *MMWR. Morbidity and mortality weekly report* 44(8):137–140.

Centers for Disease Control and Prevention 2020. "How COVID-19 Spreads". at https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html, accessed 17th April 2021.

Centers for Disease Control and Prevention 2021. "Weekly Updates by Select Demographic and Geographic Characteristics". at https://www.cdc.gov/nchs/nvss/vsrr/covid_weekly/index.htm, accessed 10th July 2021.

Choi, E. M., D. K. Chu, P. K. Cheng, D. N. Tsang, M. Peiris, D. G. Bausch, L. L. Poon, and D. Watson-Jones. 2020. "In-flight transmission of SARS-CoV-2". *Emerging infectious diseases* 26(11):2713.

Cotfas, L.-A., C. Delcea, R. J. Milne, and M. Salari. 2020. "Evaluating classical airplane boarding methods considering COVID-19 flying restrictions". *Symmetry* 12(7):1087.

Dawn Gilbertson 2020. "Airline middle seats won't stay empty forever in the name of social distancing. Here's why". https://www.usatoday.com/story/travel/airline-news/2020/05/08/social-distancing-flights-empty-middle-seats-would-raise-airfares/3049821001/, accessed 14th June 2021.

IATA 2020. "Annual Review 2020". https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2020.pdf, accessed 08th April 2021.

IBGE 2010. "Censo 2010".

Islam, T., M. S. Lahijani, A. Srinivasan, S. Namilae, A. Mubayi, and M. Scotch. 2020. "From Bad to Worse: Airline Boarding Changes in Response to COVID-19". *arXiv preprint arXiv:2006.06403*.

Kenyon, T. A., S. E. Valway, W. W. Ihle, I. M. Onorato, and K. G. Castro. 1996. "Transmission of multidrug-resistant Mycobacterium tuberculosis during a long airplane flight". *New England Journal of Medicine* 334(15):933–938.

Kim, J. H., D.-H. Lee, S.-S. Shin, C. Kang, J. S. Kim, B. Y. Jun, and J.-K. Lee. 2010. "In-flight transmission of novel influenza A (H1N1)". *Epidemiology and health* 32.

Ko, G., K. M. Thompson, and E. A. Nardell. 2004. "Estimation of tuberculosis risk on a commercial airliner". *Risk Analysis: An International Journal* 24(2):379–388.

Mas, S., A. A. Juan, P. Arias, and P. Fonseca. 2013. "A simulation study regarding different aircraft boarding strategies". In *International Conference on Modeling and Simulation in Engineering, Economics and Management*, 145–152. Springer.

Moser, M. R., T. R. Bender, H. S. Margolis, G. R. Noble, A. P. Kendal, and D. G. Ritter. 1979. "An outbreak of influenza aboard a commercial airliner". *American journal of epidemiology* 110(1):1–6.

Olsen, S. J., H.-L. Chang, T. Y.-Y. Cheung, A. F.-Y. Tang, T. L. Fisk, S. P.-L. Ooi, H.-W. Kuo, D. D.-S. Jiang, K.-T. Chen, J. Lando, K.-H. Hsu, T.-J. Chen, and S. F. Dowell. 2003. "Transmission of the Severe Acute Respiratory Syndrome on Aircraft". *New England Journal of Medicine* 349(25):2416–2422. PMID: 14681507.

Onder, G., G. Rezza, and S. Brusaferro. 2020, 05. "Case-Fatality Rate and Characteristics of Patients Dying in Relation to COVID-19 in Italy". *JAMA* 323(18):1775–1776.

Pombal, R., I. Hosegood, and D. Powell. 2020. "Risk of COVID-19 During Air Travel". *JAMA* 324(17):1798.

Schultz, M. 2017. "Aircraft boarding-data, validation, analysis". In *Proceedings of the 12th USA/Europe Air Traffic Management Research and Development Seminar, Seattle, WA, USA*, 26–30.

Schultz, M. 2018. "Field trial measurements to validate a stochastic aircraft boarding model". *Aerospace* 5(1):27.

Schultz, M., and J. Fuchte. 2020. "Evaluation of aircraft boarding scenarios considering reduced transmissions risks". *Sustainability* 12(13):5329.

Smieszek, T. 2009. "A mechanistic model of infection: why duration and intensity of contacts should be included in models of disease spread". *Theoretical Biology and Medical Modelling* 6(1):1–10.

Sze To, G. N., M. P. Wan, C. Y. H. Chao, L. Fang, and A. Melikov. 2009. "Experimental study of dispersion and deposition of expiratory aerosols in aircraft cabins and impact on infectious disease transmission". *Aerosol Science and Technology* 43(5):466–485.

Thomas Pallini 2020. "I flew on the 4 biggest US airlines during the pandemic to see which is handling it best, and found one blew the rest out of the water". https://www.businessinsider.com/what-to-expect-when-flying-on-united-american-delta-southwest-during-pandemic-comparison-2020-7?op=1, accessed 04th April 2021.

Verma, S., M. Dhanak, and J. Frankenfield. 2020. "Visualizing the effectiveness of face masks in obstructing respiratory jets". *Physics of Fluids* 32(6):061708.

WHO 2021. "Coronavirus disease (COVID-19) advice for the public". https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public, accessed 04th April 2021.

WHO 2021. "Coronavirus disease (COVID-19) pandemic". https://www.who.int/emergencies/diseases/novel-coronavirus-2019, accessed 01st April 2021.

Wilensky, U. 1999. "NetLogo itself". Technical report, Northwestern University.

Willis, A., N. Gjersoe, C. Havard, J. Kerridge, and R. Kukla. 2004. "Human movement behaviour in urban spaces: Implications for the design and modelling of effective pedestrian environments". *Environment and Planning B: Planning and Design* 31(6):805–828.

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