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REDUCED TRANSMISSION RISKS FOR PASSENGER OPERATIONS DURING COVID-19 PANDEMIC

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Abstract

In the aircraft cabin, passengers must share a confined environment with other passengers during boarding, flight, and disembarkation, which poses a risk for virus transmission and requires risk-appropriate mitigation strategies. Spacing between passenger groups during boarding and disembarkation reduces the risk of transmission, and optimized sequencing of passenger groups helps to significantly reduce boarding and disembarkation time. We considered passenger groups to be an important factor in overall operational efficiency. The basic idea of our concept is that the members of a group should not be separated, since they were already traveling as a group before entering the aircraft. However, to comply with COVID-19 regulations, different passenger groups should be separated spatially. For the particular challenge of disembarkation, we assume that passenger groups will be informed directly when they are allowed to leave for disembarkation. Today, cabin lighting could be used for this information process, but in a future digitally connected cabin, passengers could be informed directly via their personal devices. These devices could also be used to check the required distances between passengers. The implementation of optimized group sequencing has the potential to significantly reduce boarding and disembarkation times, taking into account COVID-19 constraints.

Keywords: COVID-19, passenger operations, aircraft cabin, virus transmission risk, optimization

1. Introduction

The COVID-19 pandemic will have a lasting impact on air transportation in general and on airport operations (aircraft handling) and passenger handling in particular. The current pandemic situation requires two major changes to normal aircraft handling procedures: (a) passengers must maintain a certain distance when boarding and disembarking, and (b) in addition to normal cleaning procedures, the aircraft cabin must be disinfected. The required process changes will have a significant impact on aircraft turnaround time, as these processes are part of the critical operating path. Airliners tried to establish several infrastructural changes in the aircraft cabin to reduce transmission risks, but most of these ideas are far from being a flexible and standardized solution for the aviation industry. From an operational perspective, adapted boarding strategies are more likely to be put into practice by airlines and airports than modified cabin equipment. Disembarkation is more difficult to control by regulation, and passengers show poor discipline and limited willingness to behave in a compliant manner while disembarking from the aircraft. This is particularly noteworthy because the risk of virus transmission is much higher during uncontrolled disembarkation than during controlled boarding of the aircraft. In the context of future passenger handling in the confined aircraft environment, an efficient sensing environment (digital cabin) will help to manage these situations with an improved awareness of system conditions, e.g., by individual distance measurements, aisle occupancy monitoring, or provision of baggage compartment status.

The aircraft turnaround consists of 5 classical, major tasks: deboarding, catering, cleaning, fueling, and boarding. Where the first and the last process are driven by passenger behavior and experience, the middle processes are performed by ground handling agents. Nowadays, the understanding of appropriate catering between passengers and airlines is significantly different from each other. Especially on short- and medium-haul flights within Europe, airlines offer only a small bottle of water and a cookie. The required loading process no longer has any operational relevance in this context. A similar situation can be observed with cleaning, which is reduced to a minimum for reasons of time efficiency. However, the COVID epidemic had led to the need for additional disinfection during cleaning, making cleaning a critical process again. Figure 1 emphasizes the operational processes during the aircraft turnaround and indicates additional efforts accompanied with COVID regulations [1]. Disruptions along the critical path lead to significant effects on the aircraft turnaround (e.g., extended ground times), airport operations (e.g., missed slots), or network impacts (e.g., rotational delays).

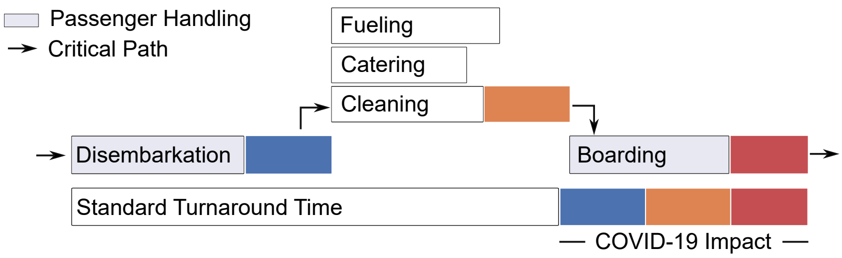

Figure 1 – Impact of COVID-19 regulations on aircraft turnaround operations, in particular during disembarkation, cleaning, boarding.

While a suitable database increasingly exists for the process outside the aircraft cabin, the processes inside the cabin are not covered and documented today. The confined cabin environment is not the only challenge for the sensor technology required for this purpose. It must also be possible to coordinate the large number of people involved in the process (crew (experts), passengers (non-experts)) in a coordinated manner to ensure an optimized workflow. Digitalization provides fundamental tools for state detection and monitoring within the cabin. Thus, the connected aircraft cabin is a mandatory infrastructure to facilitate efficient cabin operations and significantly support effective passenger management [2, 3]. This includes a communication network connecting different devices in the cabin, ranging from passenger mobile devices, crew member controlling devices, in-flight entertainment systems, or maintenance sensors [4]. Required sensors are already used in various fields and could be adapted for the aircraft environment (see Figure 2). Given the capabilities of today's technologies, the use of integrated wireless sensor networks in the connected aircraft cabin holds significant operational potential for dynamic control of passenger boarding and deplaning processes, even taking pandemic scenarios into account [5, 6].

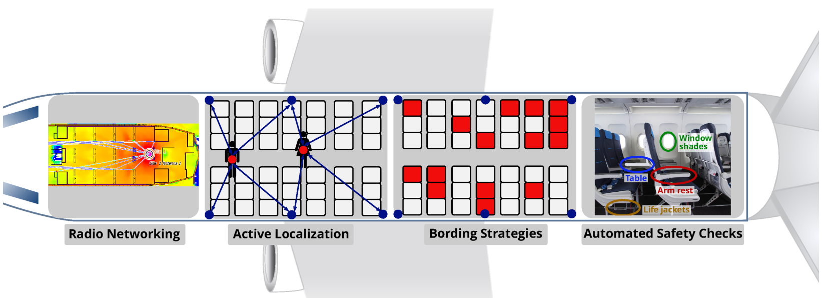

Figure 2 – Potentials of integrated communication, localization and sensing for connected cabins [4].

1.1 Literature review

Researchers have been studying the impact of the coronavirus pandemic from the beginning to better understand its consequences. Concerning coronavirus related studies in the aviation industry, the focus was set on the collapse in air travel demand and airport charges [7], global airline industry [8] and airlines' employment [9], and estimation and projection of air traffic evolution and its socio-economic impact [10]. The pandemic has significant implications for airport capacity and service levels [11], and in particular for the future of aircraft handling operations due to (post-)pandemic requirements [1].

In this context, new technologies are needed to efficiently determine passenger locations in indoor environments and confined aircraft cabins [3]. As physical distancing measure exhibits a great opportunity to reduce the spread of coronavirus among people [12], this measure has been studied in a broad range of scientific works including political, economic, and social challenges [13], and ethical aspects of physical distancing [14, 15].
The aircraft boarding studies focuses on minimizing the boarding time of passengers to decrease airline operation cost incurred by aircraft turnaround time [1, 16]. This research direction can be classified concerning the boarding assumptions and modeling techniques. There are studies that assume that the jet bridges are used to transfer passengers from the boarding gate to aircraft [17–24] while others consider apron buses for passengers commuting to aircraft [25–27]. Studies address this problem (a) under different level of seat occupancy [24, 28–31], (b) with the assumption of passengers boarding through one door or both front and rears doors of an aircraft [27, 32–34], (c) concerning individual characteristics of passengers including walking time and number of carry-on bags [16, 19, 28, 35], (d) assuming passengers traveling in groups [5, 36–38], and (e) considering seating assignment [22, 31, 39].
The pandemic requirements, in particular the requirement for sufficient distances between passengers or groups of passengers, have a lasting effect on the process flows and times for boarding and disembarking. The primary objective is to minimize the risk of transmission as far as possible and to develop appropriately adapted processes [15, 40, 41]. To address the situation where passengers travel in groups, a new analytical approach was designed to optimize the seating layout of passengers to minimize the spread of virus [5]. The approach was also used to study an optimized passenger disembarkation process considering COVID-19 regulations [6]. In this context, the developed model not only optimizes the boarding and disembarkation time but also minimizes the risk of virus transmission.

1.2 Scope and structure of the document

This document provides an overview of passenger boarding and disembarkation research in consideration of COVID requirements. After the introduction and a brief literature overview given in Section 1., the approaches for passenger movements, transmission risk, and seat allocation in the confined aircraft cabin are described (Section 2.). The approaches have been implemented (Section 3.) and the optimizations show significant improvement in boarding and disembarkation time while reducing transmission risk. The document finishes with a conclusion (Section 4.).

2. Model approach

The individual movement behavior of passengers in the aircraft cabin is modeled by a cellular automaton approach, which covers short (e.g. avoid collisions, group behavior) and long-range interactions (e.g. tactical wayfinding). The cellular automaton is based on an individual transition matrix for each passenger (agent), which contains transition probabilities to move to adjacent positions around the current passenger position [24]. This agent-based model considers operational conditions of aircraft and airlines (e.g. seat load factor, conformance to the boarding procedure) as well as the non-deterministic nature of the underlying passenger processes (e.g. hand luggage storage) and was calibrated with data from the field. Each boarding scenario is simulated 125,000 times, to achieve statistically relevant results.
We optimize the passenger boarding process and seat allocation, taking into account the boarding time and the virus transmission risk associated with passenger interaction during movements in the aisle, storing luggage in the overhead compartment, and seating. Transmission risk can be defined by proximity to the index case and duration of contact time. Our approach is based on a transmission model [42], which defines the spread of SARS-CoV2 coronavirus as a function of (continuous) distance, using different distance measures [43]. This initial approach was adapted and calibrated based on the transmission events of an actual flight [40]. To provide an appropriate seat allocation we define specific shedding rates, according to the transmission model, to determine the individual transmission risk for the passengers seated in the vicinity (adjacent seats and rows).
To address the seat assignment problem, a mixed-integer approach considering the COVID-19 requirements is defined and solved. Additionally, a genetic algorithm has to be designed to solve this

NP-hard problem achieving an optimized seat allocation in a reasonable time. This allocation ensures minimized transmission risks by maximizing the distances between passengers/ passenger groups. The seat allocation is then used as an input constraint for the agent-based simulation, which covers passenger behaviors and interactions in the aircraft cabin. In the simulation, different boarding and disembarkation sequences are evaluated according to the time needed and the transmission risk associated with them.

2.1 Passenger movements

The implemented cellular automaton model considers operational conditions of aircraft and airlines (e.g. seat load factor, conformance to the boarding procedure) as well as the non-deterministic nature of the underlying passenger processes (e.g. hand luggage storage) and was calibrated with data from the field [23]. The cellular automaton for aircraft boarding and disembarkation is based on a regular grid (Figure 3), which consists of equal cells with a size of 0.4 x 0.4 m, where a cell can either be empty or contain exactly one passenger. Passengers can only move one cell per timestep or must stop if the cell in the direction of movement is occupied.

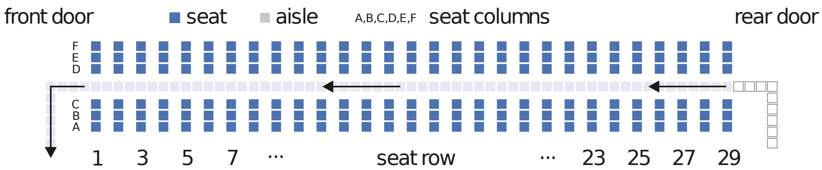

Figure 3 – Grid-based aircraft model with 29 seat rows and 6 seats per row (reference layout for single-aisle, narrow-body configurations). Layout shows one door in use for disembarkation.

The boarding progress consists of a simple set of rules for the passenger movement: (a) enter the aircraft at the assigned door (based on the current boarding scenario), (b) move forward from cell to cell along the aisle until reaching the assigned seat row, and (c) store the luggage (aisle is blocked for other passengers) and take the seat. The storage time for the hand luggage depends on the individual number of hand luggage items. The seating process depends on the constellation of already used seats in the corresponding row. The agents are sequenced concerning the active boarding sequence. From this sequence, a given percentage of agents are taken out of the sequence (non-conforming behavior) and inserted into a position, which contradicts the current sequence (e.g. inserted into a different boarding block).

For the disembarkation the movement rules are: (a) all passengers are seated in the aircraft according to an initial seat configuration, (b) passengers could enter the aisle if the seats at their corresponding row are free and the aisle is not blocked by other passengers, (c) if passengers enter the aisle, they take their hand luggage items out of the overhead compartment and block the corresponding aisle cell, (d) if all hand luggage items are taken, passengers move in the direction of the assigned aircraft door by entering empty aisle cells in front of them.

The maximum, free walking speed in the aisle is 0.8 m/s [2], so a simulation timestep is 0.5 s. In each simulation step, the list of passengers to be updated is randomly shuffled to emulate a parallel update behavior for the discrete time dynamics (random-sequential update) [44, 45]. Each boarding and disembarkation scenario is simulated 125,000 times, to achieve statistically relevant results defined by the average boarding/disembarkation time. Further details regarding the general model, parameter setups, and the simulation environment are provided in [24].

For the COVID-19 scenarios, an additional assumption is that a cell is blocked if entering or moving in the aisle would violate the separation distance between passengers or groups of passengers (e.g., families or couples). In the context of physical separation, the International Aviation Transport Association (IATA) requires a minimum separation distance of 1 m [46] and the Federal Aviation Administration (FAA) requires a minimum separation distance of 6 feet (2 meters) [47]. Considering the cellular automaton model with its regular grid structure (cell spacing of 0.4 m) and to maintain comparability with our previous results [1, 5, 40], the minimum physical spacing was set at 1.6 m (4 cells). At this point, we assume that passengers are informed that a distance of 1.6 m corresponds to the distance between 2 rows of seats, which provides sufficient visual orientation for the passengers.

2.2 Transmission model

Transmission risk can be defined by proximity to the index case and duration of contact time. Our approach is based on a transmission model [42], which defines the spread of SARS-CoV2 coronavirus as a function of (continuous) distance, using different distance measures [43]. Here, the probability of a person n being infected by a person m is described by (1).

$$P_n = 1 - exp\left(-\theta \sum_m \sum_t SR_{m,t} \quad i_{nm,t} \quad t_{nm,t}\right) \tag{1}$$

defined by:

- P_n Probability of person n to receive an infectious dose. Not “infection probability”, which depends highly on the immune response of the affected person.
- θ Calibration factor for the specific disease.
- $SR_{m,t}$ Shedding rate, the amount of virus the person m spreads during timestep t.
- $i_{nm,t}$ Intensity of the contact between n and m during the timestep t, which corresponds to their distance.
- $t_{nm,t}$ Time person n interacts with person m at timestep t.

Considering this idea, we define the shedding rate *SR* as a normalized bell-shaped function (2) with $z \in (x,y)$ for both longitudinal and lateral dimensions, respectively. The parameters are a (scaling factor), b (slope of leading and falling edge), and c (offset) to determine curve shape.

$$\text{SR}_{xy} = \prod_{z \in (x,y)} \left(1 + \frac{|z - c_z|}{a_z}^{2b_z}\right)^{-1} \tag{2}$$

SR was calibrated in a prior study [40] based on the transmission events of an actual flight [48]. We have applied the corresponding parameter setting with $a_x = 0.6$, $b_x = 2.5$, $c_x = 0.25$, $a_y = 0.65$, $b_y = 2.7$, and $c_y = 0$. This causes the footprint in the y-direction (lateral to the direction of motion) to be smaller than in the x-direction (in the direction of motion). When passengers reach their seat row and start to store the hand luggage or enter the seat row, the direction of movement is changed by 90°, heading to the aircraft window. Finally, the individual probability for virus transmission P_n corresponds to Θ, the specific intensity per timestep (3).

$$P_n = \Theta\, \text{SR}_{xy}\, \alpha \tag{3}$$

In accordance with [40], Θ is set to $\frac{1}{20}$, which means a passenger reaches the maximum probability of $P_n = 1$ after standing 20 s in closest distance in front of an infected passenger ($\text{SR}_{xy} = 1$). The parameter $\alpha \in \{1,2\}$ is 1 and changed to 2 when the passenger stores the luggage or enters the seat row. This doubled shedding rate reflects the higher physical activities within a short distance to surrounding passengers. Since the probability P_n is limited to 100%, it is set to this value if the value determined by (3) is greater than 1.

2.3 Optimized seat allocation

Following the transmission model for passengers, a mathematical model to determine an optimal strategy for assigning seats in the cabin was developed and implemented [5]. In the context of virus transmission, the objective of the seat allocation is to minimize the virus transmission risk. Figure 5 exhibits an appropriate solution for assuming a seat load of 50%. Maximizing the distances between all passengers is, of course, equivalent to decreasing the probability of transmission. At this point, however, it is necessary to question the best sequence in which passengers board and disembark to keep individual contact times as short as possible.

In addition, passengers often travel in groups (e.g., families, couples), which will have a significant impact on seat assignments and sequencing. Since group members are already in close contact

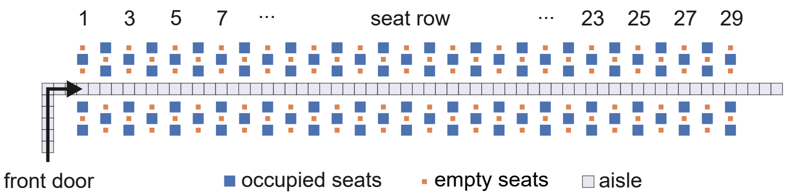

Figure 4 – Fifty percent of the seats will be allocated to passengers during the pandemic situation according to a ’next seat free’ pattern with maximum physical separation.

with each other before entering the aircraft, they should not be subject to spatial spacing rules. The general solution derived in Figure 4 must be improved when groups are considered. The model of virus transmission (shedding rates) introduced previously can also be applied, slightly modified, to the seat assignment problem.
Figure 5 shows different shedding rates assuming an infected passenger was assigned to different seat columns (window, middle, aisle seat) and rows. For example, if a passenger is sitting in row 21 and column C (aisle seat), passengers from other groups are affected if they are sitting in the same row or the previous row. The corresponding shedding rates (indexed from 1 to 6, see light oranges seats in rows 20 and 21 in Figure 5) are calculated around each passenger.

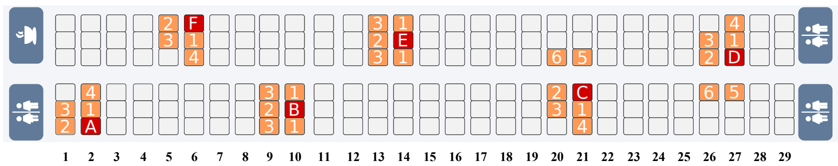

Figure 5 – Types of passenger interactions (orange) in the aircraft cabin around the infected passengers (red) considering different seat positions: besides (1 and 4), in front (2), diagonally in front (3), and across the aisle (5 and 6).

Based on the assumptions of the problem description, an optimization model for the boarding [5] and disembarkation case [6] was set up. Solving these mathematical models for a medium-sized problem (e.g. 10 groups, 10 rows of seats) led to significantly high execution times and the optimization software used (GAMS with CPLEX solver) could not find an optimal solution in a reasonable time (10 hours). Thus, a Genetic Algorithm (GA) was designed and used for the real-sized use cases for the A320 cabin. The problems were solved on a computer with AMD Ryzen 7, 3700U, 2.30GHz CPU, 16 GB RAM, and Matlab 2013 software. Figure 6 exhibits a seat allocation with a minimized virus transmission risk considering 87 passengers traveling in 31 groups.

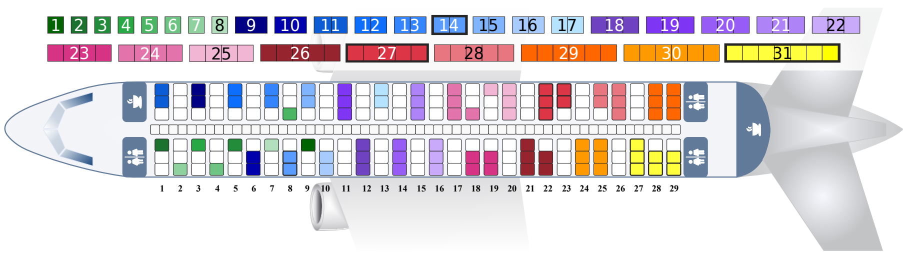

Figure 6 – Optimized boarding of 31 groups considering a physical distance of 1.6 m between passengers of different groups.

3. Implementation and results

Boarding scenarios are derived from three major approaches: boarding per rows (aggregated to blocks), boarding per seat (window, middle, aisle), and sequences of specific seats. Figure 7 depicts how the boarding strategies and operational constraints are implemented in the boarding model. The seats are color-coded to emphasize the order of aircraft seats in the boarding sequence. Six different boarding strategies are generally considered: random, back-to-front (based on 2 blocks), optimized block (based on 6 blocks), outside-in (window seats first, aisle seats last), reverse pyramid (back-to-front plus outside-in with 6 blocks), and individual seating.

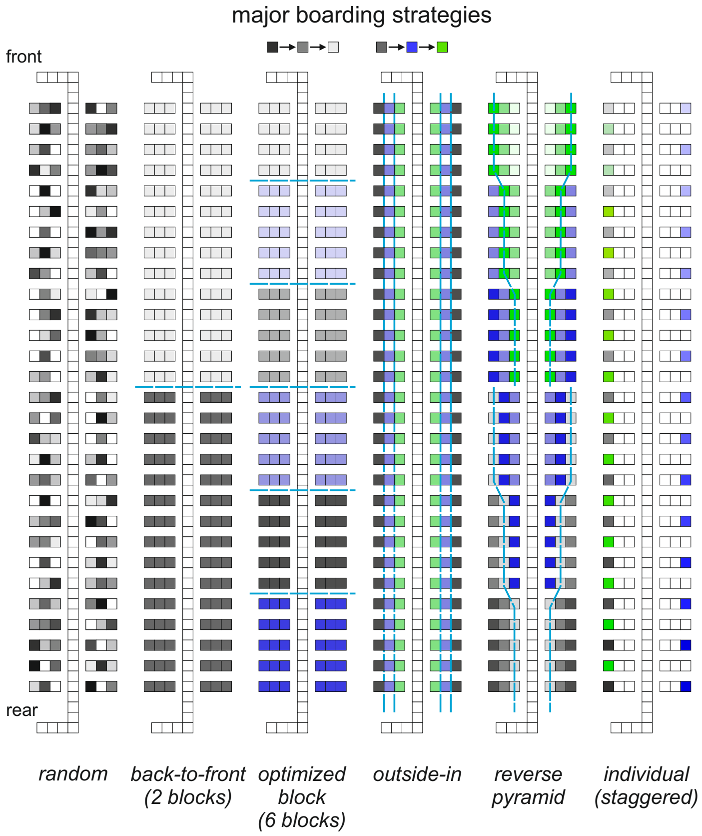

Figure 7 – Overview of different boarding strategies: black before blue, followed by green and the darker seats are boarded first (cf. [24]).

These six major boarding scenarios are used as a reference to assess transmission risks during boarding when COVID regulations, such as physical distances, are active or not. Disembarkation was also considered by assuming that passengers first get up from their seats and enter the aisle as soon as the opportunity arises, without any special rules. In these initial simulations, 148 passengers (85% seat load of Airbus 320 with 20 seat rows) were modeled without group membership, which allows for a comparison to prior studies (cf. [24]).
Table 1 shows the evaluation of the transmissions risk value considering one infected passenger, which is randomly seated in the aircraft cabin. Two different scenarios are evaluated against the reference implementation (R) [24] of the boarding strategies: (A) applying a minimum physical distance between two passengers of 1.6 m, and (B) additionally to the physical distance, the number of hand luggage items is reduced by 50% (implemented by reducing the storing time by 50%). Scenarios A and B are additionally extended by the use of two aircraft doors (one in the front and at the rear) during boarding, scenarios A2 and B2. The transmission risk and the boarding time are used as evaluation criteria [40]. The analysis points out that, in particular, the back-to-front sequence (2 blocks: front block with rows 1-15, rear block with rows 16-29) exhibits lower values for the transmission probability than the optimized block sequence (using 6 blocks of aggregated seat rows). When passengers board (block-wise) from the back to the front, the chance to pass an infected person is reduced to a minimum, which is confirmed by the reduced transmission probability exhibited in Table 1. This effect is also the reason for the low transmission risks of the outside-in, reverse pyramid, and individual boarding sequence.
If the physical distance between passengers is taken into account, the time for boarding and disembarking increases significantly. Without countermeasures (scenario A), the times double in almost all scenarios. Using the rear door for boarding and disembarking mitigates this effect, and the times of

reference scenario R could be achieved if the number of carry-on bags is additionally reduced.

Table 1 – Transmission risk assessment assuming one SARS-CoV2 infected passenger in the cabin, graded by four sequences: random, block-based, row- and individual-based, and disembarkation.

boarding scenarios:	R	A	B	A2	B2	R	A	B	A2	B2
boarding sequence	Transmission risk (a.u.)					Boarding time (%)				
Random	5.9	1.6	1.1	1.4	1.0	100	198	154	133	103
Back-to-front (2 blocks)	5.6	1.4	1.0	1.2	0.8	96	220	169	153	116
Optimized block (6 blocks)	6.5	2.3	1.5	1.5	1.0	95	279	210	166	125
Outside-in	3.5	0.4	0.2	0.3	0.1	80	161	116	107	77
Reverse pyramid	3.0	0.2	0.1	0.2	0.1	75	185	128	119	82
Individual	2.0	0.2	0.1	0.2	0.1	66	114	104	103	74
Disembarkation	10.0	9.7	7.8	7.6	6.0	55	97	68	52	36

The use of two aircraft doors for boarding will provide an appropriate solution for a reduced transmission risk inside and outside the cabin if near apron stands could be used and passengers could walk from the terminal to the aircraft. This kind of *walk boarding* also prevents passengers from standing in the badly ventilated jetway during the boarding. Disembarkation is difficult to control by specific procedures given that passengers demonstrated little discipline and high eagerness to leave the aircraft. More attention should be paid to this process and consideration should also be given to procedural or technical solutions to provide passengers with better guidance and control.
To emphasize the impact of passenger groups for the initial idea of a 'next seat free' pattern (see Figure 4) is used and compared against an optimized seat allocation (see Figure 6). For this, a seat load factor of 50% (87 passengers) was assumed and passengers were assigned to 31 groups. First, the baseline with single passengers and a random boarding sequence is simulated. As table 2 shows, taking groups into account leads to a reduction in boarding time with the same transmission risk if the seat allocation is optimized accordingly. This is primarily due to self-organization in groups, as group members arrange themselves appropriately in advance and take their seats in the most appropriate order. If, in addition, the boarding sequence is also optimized, both the boarding time and the transmission risk can be reduced to a minimum.

Table 2 – Evaluation of average boarding times and transmission risk during boarding assuming a randomly selected contagious passenger at 50% seat occupancy (87 passengers).

Boarding scenario	Time (%)	Transmission risk (a.u.)
single passengers, next seat free		
random boarding	100.0	0.58
groups, optimal seat allocation		
random boarding sequence	69.0	0.57
best boarding sequence	**41.1**	**0.09**

The same results can be obtained if the optimization is also applied to the case of disembarkation [6]. Figure 8 shows the optimized seat assignment and a corresponding disembarkation sequence. As mentioned in the introduction, we assume that passengers (groups of passengers) can be informed when they are allowed to enter the aisle.

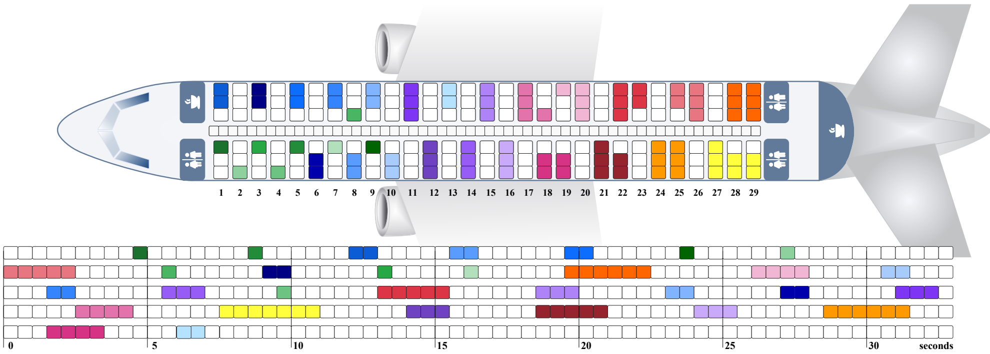

Figure 8 – Disembarkation sequence with five batches assuming 87 passenger (31 groups) at optimized seat allocation [6].

4. Conclusion

In the aircraft cabin, passengers must share a confined environment with other passengers during boarding, flight, and disembarkation, which poses a risk for virus transmission and requires risk-appropriate mitigation strategies. Spacing between passenger groups during boarding and disembarkation reduces the risk of transmission, and optimized sequencing of passenger groups helps to significantly reduce boarding and disembarkation time. A physical distance between passengers during boarding and staggered seat configurations are part of current risk mitigation strategies. However, the side effect from an operational point of view is a doubled boarding time compared to the situation before the coronavirus pandemic situation. Simulation results exhibit that optimized passenger handling (seat allocation and boarding/ disembarkation sequences) can reduce the boarding/ disembarkation times significantly (approx. 40%) at a low level of transmission risk. In the context of aircraft ground operations (turnaround), appropriately optimized passenger handling is one essential element to compensate for the extended ground times caused by the required COVID constraints.

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