BOARDING ASSESSMENT AND COVID-19 CONSIDERATIONS FOR THE AVACON AIRCRAFT CABIN CONCEPTS

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Abstract

In the German LuFo research project AVACON, the project partners jointly developed a mid-range aircraft concept for the year 2028 with an over-wing engine configuration. With every new iteration of the initial concept, an adapted cabin concept was derived. This paper introduces the different cabin concept derivatives and assesses them regarding their boarding performance. The assessment is performed using the PAXelerate open-source boarding simulation framework. The results for a random boarding simulation show a boarding time reduction potential of 3.4 percent for the adapted cabin layouts of the iterated cabin design.

The COVID-19 crisis has forced severe limitations on the international transportation market and has put a focus on the infection risk within the aircraft cabin. Thus, this paper introduces as a second aspect a new methodology that enables PAXelerate to assess the individual COVID-19 exposure risk of passengers during the boarding process. The basic model enhancement consists of the tracking of all passenger movements throughout the cabin, the determination of the proximity to other passengers as well as the monitoring of the duration of the individual contacts. This approach is similar to the frameworks introduced by Apple and Google for contact tracing on smart phones. The results highlight the overall risk for rear-to-front and front-to-rear boarding scenarios, considering the overall number of contacts as well as the proximity and duration of individual passenger contacts. Boarding scenarios such as window-to-aisle, random or the so-called Steffen procedure seem beneficial. The removal of cabin luggage has the largest effect on exposure risk mitigation. This highlights potential pathways for a future safe travel scenario with a minimized exposure risk for all passengers.

Keywords

Cabin, Boarding, Simulation, Passenger, Covid-19, Exposure Risk

Abbreviations

AVACON	Advanced aircraft concepts LuFo research project
BHL	Bauhaus Luftfahrt e.V.
ARB	AVACON research baseline
RTF	Rear-to-front boarding strategy
LF	Load factor
CPACS	Common parametric aircraft configuration schema
PAXelerate	BHL open-source boarding simulation
WTA	Window-to-aisle boarding strategy
FTR	Front-to-rear boarding strategy

1. MOTIVATION

During the course of the German LuFo research project AVACON, the consortium of German aerospace research and industry entities jointly developed a novel mid-range aircraft concept for the year 2028 with an over-wing engine configuration [1]. With every iteration of the initial aircraft concept, an adapted cabin layout has been derived. While all cabin concepts share the same overall characteristics, they differ in their detailed

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arrangement. This paper introduces the different cabin concept derivatives, explains the reasoning behind the adaptions and briefly compares them regarding their boarding performance.

In recent developments, the COVID-19 crisis has spread all over the world and forced severe limitations on the international transportation market. The aircraft cabin has thus moved more into focus as it represents an area of elevated infection risk. This is especially true for the boarding process where passengers get into close contact with each other, particularly during the queueing and luggage storing processes. Thus, this paper introduces as a second aspect a new methodology that enables PAXelerate to assess the individual COVID-19 infection risk of passengers during the boarding process.

With the introduction of this model, PAXelerate aims to contribute to the impact assessment of COVID-19 for passenger processes in the cabin and to highlight the overall risk of a given boarding scenario, considering the overall number of contacts as well as the proximity and duration of individual passenger contacts.

2. PAXELERATE

The open-source passenger flow simulation PAXelerate created by Bauhaus Luftfahrt (BHL) [2] is powered by a 2D agent-based foundation using the cheapest path A-Star algorithm. It operates in a grid based cabin representation based on nodes.

Being under development at BHL since 2014, its initial purpose was the assessment of novel cabin layouts regarding their boarding performance. It has since been expanded to assess different boarding strategies and door combinations in conventional cabin concepts as well as the impact of cabin layout changes on passenger walking behavior. [3, 4]

PAXelerate and its data structure are based on the CPACS file format. This enables a fast and simple import, export and integration of different aircraft concepts. CPACS is a common language for aircraft design that can “hold data from a variety of disciplines considered in an aircraft design process” [5] and thereby enables easy data exchange capabilities between a variety of different tools and disciplines.

3. AVACON

During the course of the AVACON project, the aircraft and fuselage geometry have been evolving constantly. Starting with the reference aircraft [1] up to the later concept stages, the fuselage and in particular the cabin have thus adapted to the new boundary conditions as well. The evolution of the AVACON reference aircraft and concepts is depicted in the following Figure 1.

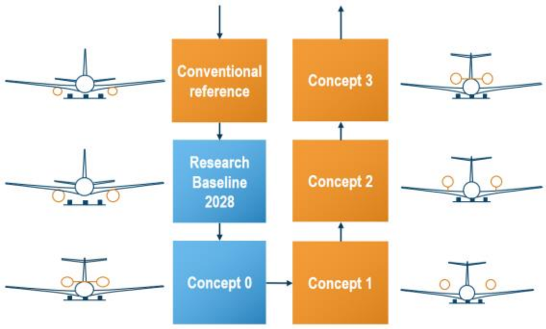

Figure 1: Overview of the AVACON aircraft concept evolution.

Regarding the effect of the fuselage geometry changes on the cabin design, only the following iterations (highlighted in blue in Figure 1) are relevant for cabin design adaptions and will be considered in the following chapters:

- Initial AVACON Research Baseline (ARB)
- Research Baseline Loop 2
- Concept 0

3.1. Cabin Overview

This chapter describes all changes to the cabin layout over the course of the project in the following figures and paragraphs. Figure 2 shows the initial cabin layout of the AVACON research baseline, which is derived from the two-class twin-aisle cabin layout of a Boeing 767.

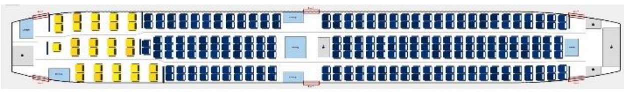

Figure 2: Initial AVACON research baseline (ARB).

In the next steps of the project, the initial cabin layout of the ARB was adapted and optimized. Due to the introduction of over-wing engines and the resulting blockage of the previous L2/R2 doors, the center doors of the initial ARB had to be removed due to engine blockage. Thus, the center doors were replaced by emergency exits, the galleys and lavatories were moved backward and an additional set of doors was added in the rear of the fuselage. Furthermore, a more uniform seating arrangement was selected for the ARB loop 2. All changes are shown in Figure 3.

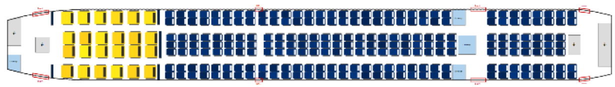

Figure 3: ARB Loop 2 with an adapted cabin design for the over-wing engines.

During the development of the concept 0 design, the wing of the AVACON concept moved further backward. Thus, the cabin for Concept 0 also had to be slightly adjusted to compensate for the changed wing position. In order to be positioned exaclty above the wing, the emergency exits have shifted two seat rows to the rear. This slightly adjusted layout can be seen in the following Figure 4.

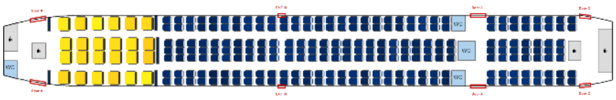

Figure 4: Concept 0 cabin with emergency exits shifted two rows back.

3.2. Boarding Assessment

As a last aspect of the AVACON project work package 4.2, the boarding performance of the different cabin iterations is briefly highlighted in the following. This is done by using PAXelerate with a random boarding scenario, default settings and 100 iterations each. The novel passenger movement model which was introduced in a previous publication is active. The results of this comparison can be seen in the following Table 1.

Table 1: Overview of the default boarding procedures for the AVACON concepts.

Concept	Average Boarding Time [min]	Standard Deviation [min]	Delta [%]
Initial ARB	21:40	00:31	-
ARB Loop 2	20:56	00:54	-3.39
Concept 0	21:05	00:48	-2.68

As visible in in delta column, the boarding time has slightly but statistically significantly decreased from the initial ARB compared to ARB loop 2. This is potentially due to the passengers travelling overall shorter distances, as the seats (especially in the rear section) are closer to the entrance door L1. However, other causes cannot be ruled out either. The next step with a shift of the emergency exit for concept 0, on the other hand, has no further significantly measurable impact on boarding times and therefore shows no change compared to the simulation of the ARB in the second loop.

A detailed assessment of various boarding strategies and door combinations has previously been performed in another publication [6] and will thus not be discussed in detail in this paper.

4. CONTACT-TRACING MODEL

As mentioned in chapter 1, a second part of this paper contains contribution to the COVID-19 impact assessment on passenger processes in the cabin and during the boarding process in particular. Hence, the following chapters introduce the newly developed contact-tracing model for PAXelerate which tries to assist in providing guidelines for a future safe travel scenario.

4.1. Motivation

To begin with, the introduction and development of a contact-tracing model in PAXelerate is based on the following research questions:

- Which parameters influence the exposure risk during boarding?
- Are there any boarding process changes that can reduce the exposure risk?
- How can the exposure risk be modelled in PAXelerate?

Regarding the term exposure risk, a brief definition and clarification is required. The term exposure represents a close contact with an infected person that has occurred within a given radius. An exposure to an infected person does however not automatically lead to an infection. For an infection, various other factors such as the type of transmission, number of transmitted viruses etc. needs to be taken into account and cannot be easily quantified analytically. Hence, for the assessments performed in the scope of this paper, the exposure and not the infection risk is the target variable.

Since the outbreak of the COVID-19 pandemic, there has been research in every aspect of COVID-19 infection risk during the passenger boarding process and within the cabin during flight. Relevant literature for the contents of this paper includes the suggestion of novel boarding strategies [7, 8], social distancing during boarding at the aisle [9] as well as de-boarding and the impact of cabin luggage [10].

4.2. Privacy Preserving Contact Tracing

As a basic concept idea for the contact-tracing model being implemented in PAXelerate, the “privacy preserving contact tracing” model by Apple and Google has been selected [11]. This model was introduced in April 2020 as a response to the quickly worsening COVID-19 pandemic and was designed as a possiblility to enable alerts on a smartphone if a contact to an infected person has occurred, all while maintaining privacy and anonymity.

The underlying model used for this contact tracing tool is based on a “exposure notification framework” [11] that takes into account the Bluetooth signal strength of other devices in proximity in order to derive the distance to the other device. Combined with the duration of the Bluetooth signal reception, the model can then evaluate if the contact to the other device can be neglected or if it should be remembered in a randomized storage for future actions. If in the future, the contact proves to be COVID-19 positive, the device detects the prior contact to this anonymized device and can warn the user via an iOS or android application. The model is anonymized and no external tracking is possible.

In order to adapt this modelling approach for PAXelerate, a small but important change can be made. As there is no privacy for passengers needed, the model can operate with a global observer and all contacts can be stored in detail.

4.3. Derived Model Parameters

Based on this modelling concept and the overall goals, the following targets have been defined. First, a reduction of the average contact / exposure time as well as the reduction of the maximum duration during a boarding process have to be achieved. To do so, the duration of contacts has to be calculated and stored.

Second, the average as well as maximum distance between two passengers during a contact has to be decreased. Thus, another model parameter has to be the distance between two passengers during a contact event.

Last, the total number of contacts has to be limited and hence represents an additional model parameter. This results in the following collection of model parameters that are incorporated into the PAXelerate contact-tracing model in the following chapters:

- Average & maximum contact duration
- Average & minimum contact distance
- Number of contacts

4.4. Theoretical Approach

The fundamental modelling idea to collect the parameter values is presented in Figure 5 below. A passenger (dark blue) is walking in the direction to the right. In its proximity, three other passengers A, B and C (orange) are acting in the cabin.

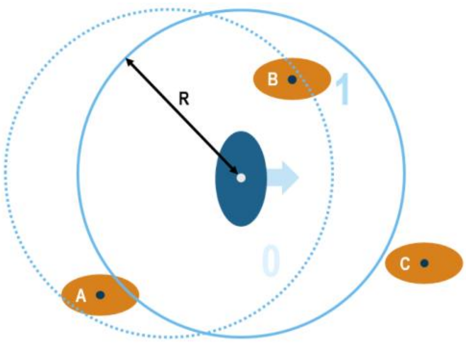

Figure 5: An abstracted passenger walking to the right. The blue circle highlights the radius in which contacts with others are considered.

At the time step 0, passengers A and B are within the predefined threshold radius of 1.75m that triggers the contact tracing. Hence, passenger A and B are added to the contact-tracing list of the main passenger seen in Table 2. Passenger A, who is already seated, is logged with a given state, the current distance $r_{0,A}$ at time step 0, while passenger B is logged with the state of luggage stowing at a distance of $r_{0,B}$.

At time step 1, the main passenger has moved further to the right and only passenger B remains within the radius. Hence, passenger B is added to the contact list again. Passenger C did not cross the threshold distance to the passenger yet and is thus ignored in the contact list up until time step 1.

Table 2: Exemplary contact tracing list of a passenger for multiple time steps according to the depiction in Figure 5.

	State	Time step	Distance	State of contact
Passenger A	WALK	[0]	[$r_{0,A}$]	SEATED
Passenger B	WALK	[0,1]	[$r_{0,B}$,$r_{1,B}$]	STOW LUG.
Passenger C	-	-	-	-

The number of contacts can be derived from this list by means of counting the number of passengers within the list. The distance can read out using the radius of the contact and the duration of the contacts can be calculated by using the different time stamps and the time between these steps.

4.5. Distance Calculation Challenges

Ideally, the distance between passengers has to be calculated for each time step. Every passenger has to calculate the 3D distance to every other passenger simultaneously. This leads to a high computational effort that can be reduced by introducing an additional abstraction layer.

In a previous publication, a new movement model for PAXelerate that calculates the walking speed of passengers in dependence of the 3D cabin geometry has been introduced [12]. During the development, the same issue regarding repeated 3D distance calculations occurred. The abstraction method used previously can now easily be reused.

The solution for increased calculation performance is based on the fact that the cabin area is represented by a grid of nodes within the simulation environment. The distance to other passengers can now be calculated and saved inside these nodes for other passengers to access it. Thus, every passenger just has to calculate values for itself and the surrounding nodes instead of for every passenger within the cabin.

4.6. Contact Tracing Model

Figure 6 depicts the abstracted contact-tracing model using the grid of nodes that represents the cabin layout. The passenger 0 is located in the center of the image and is represented by black nodes.

Surrounding the passenger 0 in a color gradient are nodes that have stored distance information of this passenger 0. Red represents nodes with a low distance value, whereas green nodes have high distance values. Blank nodes represent the space that lies outside of the threshold radius that triggers the contact-tracing algorithms.

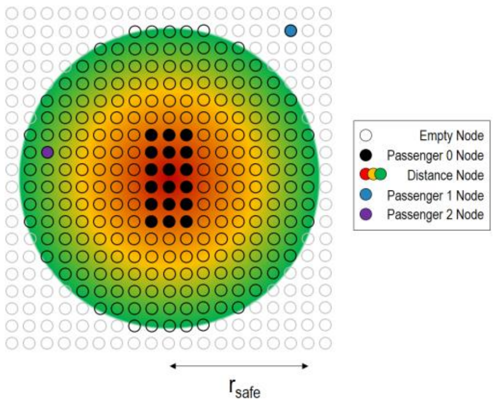

Figure 6: Node grid area in which passengers store information on their distance to surrounding nodes.

Other passengers, such as passengers 1 and 2 and represented by the blue and purple nodes, check the node at their current location for the existence of distance values of other passengers. If a value is available, the passenger knows that another passenger is located within the threshold radius.

Exemplary, passenger 1 detects no distance value at the current location and hence does not add any contact-tracing information to its contact list at this given time step.

Passenger 2 on the other hand is located in the green area and thus detects a distance value of passenger 0 of roughly 0.8 times the threshold radius of 1.75 meters. The contact-storing algorithm is then triggered and passenger 2 stores this contact event together with additional information on passenger 0, the distance value and the current time stamp in the contact list.

4.7. Model Structure

Figure 7 below depicts the overall model structure of the contact tracing algorithm during runtime. Beginning with each passenger from 0 to n, the distance to surrounding nodes is stored in the contact-tracing map and is updated for each step. All passengers request information on distance values of other passengers at their current location and save this information for post processing purposes.

This process of storing the distance values and reading information of the contact-tracing map is repeated throughout the simulation sequence. When every passenger is seated, the tool then post-processes all information gathered and calculates the average and extrema values including the total contact count, the duration and distance, the state of the passenger and contact as well as a unique timestamp.

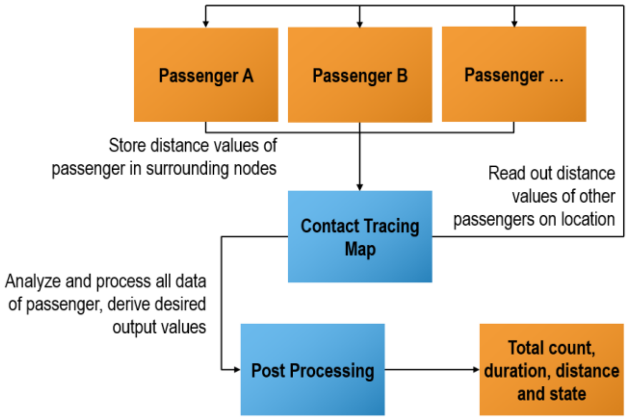

Figure 7. Diagram showing the logic behind the contact-tracing model and data processing during runtime.

5. APPLICATION

In this chapter, PAXelerate and the new model are applied to different boarding strategies and a variation in the load factor using the AVACON concept 0.

First, the graphs in Figure 8 show the distribution of the different model parameters consisting of the number of contacts, the average contact distance and the average contact duration. It can be seen that the histograms do not depict normal distributions for a single boarding scenario.

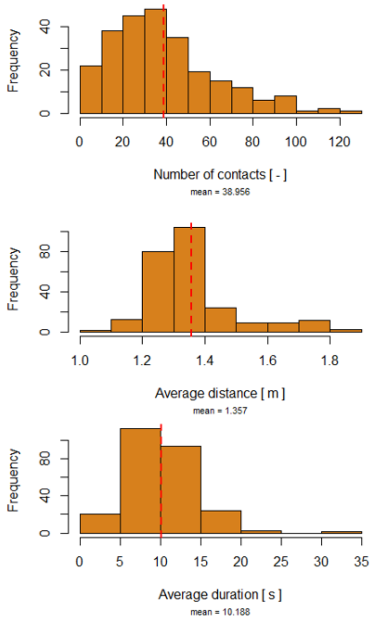

Figure 8: Histogram of amount, average distance and average duration of contacts for all 252 passengers of a single random simulation.

Second, averaging these distributions over all 252 passengers of the AVACON concept 0 and collecting those average over 50 iterations of a random boarding simulation, the following Figure 9 is produced. This time, the data adheres to a normal distribution (as determined by a Shapiro-Wilk test) for all parameters assessed.

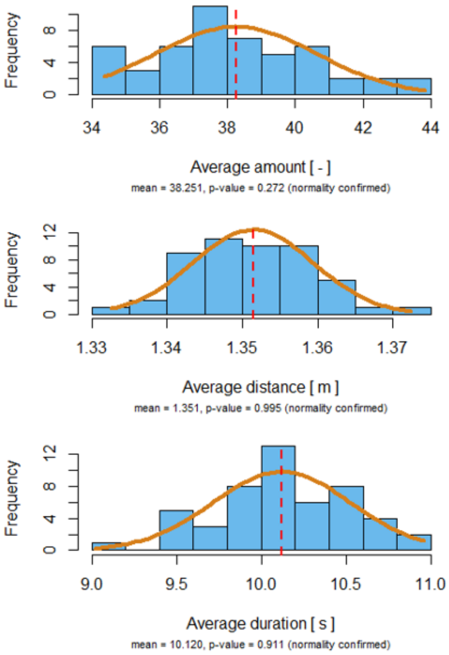

Figure 9: Histogram of average amount, distance and duration of contacts for 50 iterations of random boarding simulations.

5.1. Boarding Strategy Assessment

Figure 10 depicts the different boarding strategy options that are used in the assessment of the contact-tracing model. For each of the six strategy options, green rectangles represent the passengers boarding first, whereas red rectangles represent passengers boarding last.

Figure 10: Overview and schematic of the different boarding strategies used in the assessment of the contact-tracing model in PAXelerate.

The assessed boarding strategies comprise of a random, class-wise, rear-to-front (RTF), front-to-rear (FTR), window-to-aisle (WTA) and Steffen [13] boarding scenario. All strategies are now applied to the PAXelerate boarding simulation with default settings in 50 iterations each.

Additionally, the scenarios of no carry-on luggage during boarding, a safe distance of 1.75 meters on the aisle and a boarding using the L1 and L3 door configuration used for larger long range flights are assessed as well. The results of these simulations for the various model parameters introduced earlier are highlighted in the following Table 3.

Table 3: Overview of the boarding simulation results for the different boarding strategies (n=50).

	Total contacts [-]	Avg. contacts [-]	Avg. distance [m]	Min. distance [m]	Avg. duration [s]	Max. duration [s]	Boarding time [min]
CLASS	11416	45	1.36	0.34	10.3	33.8	21:08
RANDOM	9639	38	1.35	0.35	10.1	29.6	19:21
STEFFEN	**5922**	**23**	**1.38**	**0.38**	**7.6**	**18.0**	**17:44**
WTA	8586	34	1.35	0.35	9.0	26.2	19:56
FTR	**20461**	**81**	1.31	**0.33**	**21.0**	101.3	47:27
RTF	8239	32	**1.27**	0.34	**21.5**	**107.3**	40:41
L1 L3	5593	22	1.33	0.46	11.8	24.6	14:33
NO LUGGAGE	2944	11	1.40	0.49	1.6	5.9	14:47
SAFE DISTANCE	9737	38	1.37	0.34	9.0	24.9	24:49

Regarding the boarding strategies, the Steffen strategy delivers by far the best results for the contact reduction efforts. It provides the best parameter values in all categories and is, due to its low boarding times, the overall best option available. However, a disadvantage of this strategy is the requirement of a strict predefined boarding sequence.

Other strategies with less preparation effort are also beneficial compared to the default class-wise boarding strategy used in today's turnaround process. This includes in order of decreasing effect the window to aisle boarding and the random boarding process.

Comparing these results to the rear-to-front and front-to-rear boarding scenarios, the inferiority of those becomes visible immediately. The parameter values double or even quadruple in some cases, rendering the strategies an immense exposure risk according to the PAXelerate boarding simulation. The effect of the two strategies can be explained by the fact that at any given time, multiple passengers meet at the same row to stow their luggage and find a way to their seat, whereas the rest of the cabin remains without any significant contact activity. It is hence beneficial to distribute activity throughout the cabin to reduce the occurrence of these contact hot spots.

Taking other boarding options into account, the removal of hand luggage has the best effect of all options as it removes all interactions during the luggage stowing procedures and by this reduces the number of contacts for passengers significantly.

On the other hand, the introduction of a safe distance to other passengers of 1.75m during the boarding process barely has any effect on the parameters. The total number of contact even increases, whereas the average and maximum duration decreases slightly. This behavior can be explained by the fact that the main interactions are close to the seats during the seating and luggage stowing processes and not while walking on the aisle, where the safe distance has its biggest effect.

5.2. Seat Dependent Risk

Diving one level deeper into the boarding assessment, the following Figure 11 depicts the contact amount, average contact duration as well as the maximum contact duration per seat within the AVACON concept 0, averaged over 50 iterations each. The values represented by the same color in different boarding scenarios are not comparable. For example, the highest maximum duration value in the random scenario is significantly lower than the front-to-rear value, but they both share the red color in their respective graphs.

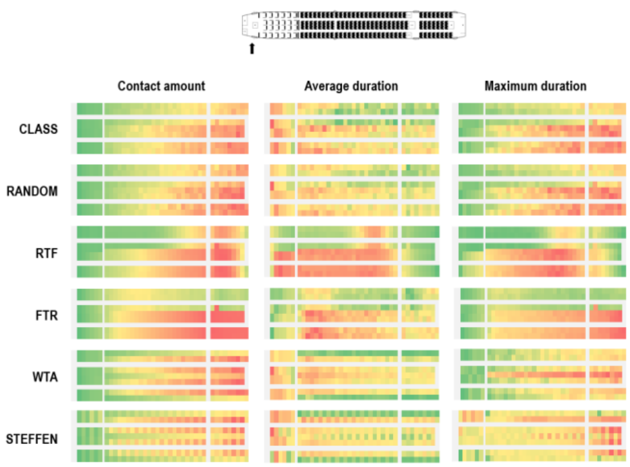

Figure 11: Seat dependent exposure risk for different boarding strategies.

Almost every boarding scenario shows a similar tendency, where the contact amount as well as the maximum duration is higher in the rear parts of the cabin, whereas the front parts have comparatively low values.

For the average duration, the trends are reversed. This reversal can be observed in all scenarios and is because passengers in the front of the cabin get into contact with fewer people no matter their position in the boarding sequence. Hence, the average is calculated using far less contact events. As passengers walking to the back pass many passengers that are already seated, those contacts count as a very short contact event into the average, thus lowering it. On the other hand, front passengers queuing in the aisle have few but longer contact events, raising the average.

Another interesting aspect of Figure 11 is the asymmetric distribution of values along the aisles. The reason for this behavior is the queue of passengers building up on the aisle closer to the boarding door first and prolonging into the gangway. This queue throttles the access to the second aisle, which remains comparatively empty throughout the boarding as passengers only reach it in a limited amount at a time. As there are no queues, less contact events due to waiting or luggage storing occur in the second aisle.

Concluding, the seat with the lowest exposure risk depends on the boarding strategy but is located in the front of the aisle further away from the boarding door. This behavior is strongly dependent on the cabin geometry and can thus not be generalized or applied to a single aisle scenario.

5.3. Load Factor Assessment

Additional to the different boarding strategies, it is important to look at the model behavior for different load factors during the boarding procedure. The following Figure 12 thus depicts various contact-tracing model parameters such as contact duration and distance for different load factors ranging from 50% up to 100%. This assessment uses the average of 50 simulations per load factor variation with a random boarding sequence and default settings.

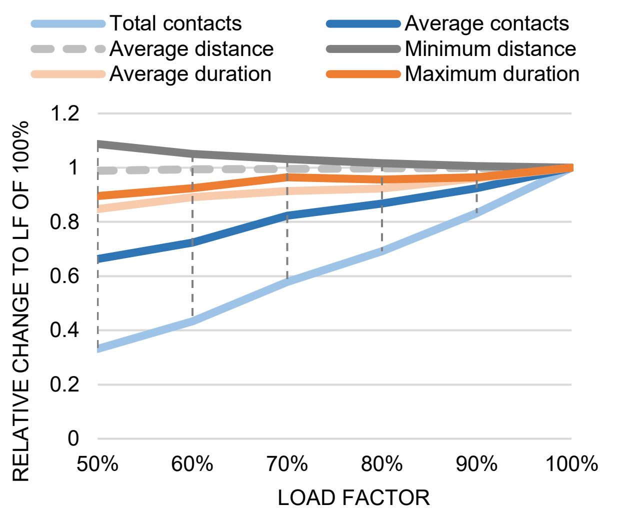

Figure 12: Various contact-tracing model parameters and their behavior for a change in the load factor (LF) during the boarding process.

Regarding the average distance between two passengers during a contact, almost no change occurs for a load factor variation. The minimum distance between contacts increases to about 1.1 times for a load factor decrease from 100% to 50%.

The average and maximum durations of a contact on the other hand decrease by 15% and 10% respectively for a load factor of 50%. Interestingly, the values first start to drop below a load factor of 70%, meaning that only after this threshold a reduction in load factor has an increased impact on exposure risk.

A significant decrease can be observed for the total and average amount of contacts for a passenger during the boarding process. At a load factor of 50%, the values drop to 0.35 times and 0.7 times respectively. In addition, the decrease occurs steadily throughout the range of load factor variations. This means that every reduction in load factor during the boarding simulation decreases the amount of different contacts for a passenger significantly.

Although the distance and duration values do not drop as much, the reduction of the contact amount can decrease the exposure risk drastically as a passenger gets into contact with fewer different people during the boarding process, thus reducing the exposure risk if only a single infected person is boarding the aircraft.

6. SUMMARY

Referring back to the research questions presented in chapter 4.1, it can be confirmed that these questions can now be answered confidently using the PAXelerate boarding simulation and the newly introduced contact-tracing model. The parameters that influence the exposure risk have been presented, the model has successfully been developed and the impact of different boarding strategies has been identified.

Regarding the boarding strategies, the rear-to-front and front-to-rear ordering have been identified to increase the exposure risk dramatically, whereas the Steffen, window-to-aisle and random boarding scenarios are beneficial in decreasing order compared to the reference class boarding. The overall best option for an exposure risk mitigation is the removal of hand luggage. The load factor on the other hand can play a crucial role in the reduction of total and average amount of contacts per passenger, whereas the average duration and distance of contacts are only weakly influenced by a load factor reduction.

7. OUTLOOK

In the future, the contact-tracing model for PAXelerate could be enhanced with multiple new features and improvements such as a contact tracing for passengers that are already seated and do not participate in the boarding simulation anymore. Furthermore, passengers that are queueing outside of the cabin in the gangway are currently neglected. As this area is a constricted space with reduced ventilation, the queueing in this area is of increased interest for the contact-tracing and exposure risk estimation algorithms.

In a further step, the exposure risk could be transformed into a real infection risk as mentioned in chapter 4.1. This could be achieved by using formulas that translate the exposure risk using various additional parameters as well as probabilities. Lastly, the contact-tracing model could be used to assess different, potentially beneficial cabin layout changes regarding their impact on the exposure risk.

8. OPEN SOURCE INFORMATION

The PAXelerate boarding simulation including the source code of the contact-tracing model introduced in this paper is available open source on GitHub.

www.paxelerate.com

Available on GitHub

9. ACKNOWLEDGEMENTS

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