BOARDING PROCESS ASSESSMENT OF NOVEL AIRCRAFT CABIN CONCEPTS

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Abstract

For airlines, an efficient aircraft turnaround is an essential element to be competitive. Passenger boarding and disembarking, as key processes of an aircraft turnaround, are often on the critical path. Hence, a passenger process time reduction would also shorten the total turnaround time. Novel cabin concepts which can be adapted during boarding, such as foldable seats, provide more space for passengers' movements and them stowing luggage. Yet, such concepts have not been investigated thoroughly, even though they promise a significant process time reduction. This paper investigates a lifting seat pan and a sideways foldable seat concept using the two-dimensional agent-based passenger flow simulation framework PAXelerate. The case studies follow the Monte Carlo approach with a probabilistic distribution of passenger anthropometrics, a variation of load factor and hand luggage to be stowed. In comparison with a reference case, a state-of-the-art short-to-medium haul aircraft with 180 seats in a six-abreast single-aisle layout, a boarding time reduction of up to 28% could be identified. This can be translated into an 11%-shorter total turnaround time, which is a significant contribution towards promoted environmental goals of international regulators.

1 Introduction

An efficient aircraft turnaround is an essential element for airlines to be competitive, especially for multiple daily occurrences during regional and short-haul operations. Usually, the passenger egress and ingress, together with refueling or cabin services, constitute the critical path, which determines the total turnaround time. Hence, a reduction of the passenger boarding and disembarking time would simultaneously shorten the overall turnaround time or could increase the buffer time between two flights, which enables the compensation of delay propagation. National and international regulators, such as the Advisory Council for Aviation Research and Innovation in Europe (ACARE) incorporated these targets in their agendas and demand a 40%-reduction of turnaround times by 2050 using novel handling concepts [1,2].

The remainder of the paper is organized as follows. The first section provides an overview of the bottleneck of passenger boarding and highlights recent research in the field of efficient passenger processes. Therefore, a review of advanced cabin concepts focusing on aisle, door and seats modifications is provided. Thereafter, characteristics of the applied agent-based framework are explained. Afterwards, the investigated concepts are presented in detail and key findings of the analyzed case studies are highlighted. The paper concludes with a discussion of the obtained results and gives key development directions towards the assessment of future aircraft concepts.

1.1 The passenger egress and ingress bottleneck

The boarding process of passenger aircraft has been an issue since the late 1970s, as stated by Marelli et al. [3]. An observed decline in the average boarding throughput results from more numerous and larger carry-on luggage and changes in airline service strategies and passenger demographics.

In general, after passengers have entered the aircraft, they search for their assigned seat and stow hand luggage under their seats or in the overhead bins. During this task, the passenger blocks the aisle. This blockage is referred to as aisle interference. Seat interference, on the other hand, occurs when a passenger has to wait for another passenger in their row to sit down before they can enter the row. Additionally, seat interferences often cause aisle interference.

Airlines have looked for alternative strategies to reduce aisle and seat interferences in an effort to increase the boarding process efficiency. Various boarding strategies have been implemented that specify a predefined sequence of passengers entering the cabin depending on their allocated seats [4,5]. Methods that parallelize the boarding process via a more efficient use of the aisle, such as having more passengers stow their luggage simultaneously, tend to quicken passenger ingress [6]. Methods with shorter total boarding times for the aircraft usually also offer reduced ingress times for each individual passenger. Unfortunately, most of the strategies tested are not practical in regular flight operation, as passengers must be grouped in a predefined way which can split individuals travelling together.

Cabins which can be adapted during boarding, such as foldable seats or movable cabin monuments, provide flexible cabin designs that can be modified depending upon flight phase requirements. They offer more space for passengers' movements and them stowing luggage. Moreover, splitting the passenger flow through optimized door positions could further contribute to reduced process times. These novel concepts under investigation could provide increased efficiency gains; however, their applicability and detailed assessment still remain unanswered.

1.2 Review of advanced cabin concepts

In literature, three general development directions for advanced aircraft cabins can be identified: aisle, door and seats modifications. An overview of the associated concepts is listed in Table 1 and key aspects are highlighted in the following.

Table 1. Overview of cabin modifications (S: simulation, E: estimation)

	Concept	Benefit	Method	Ref.
Aisle	Aisle width (0.2m)	5-7%	S	[10]
Aisle	Multi-aisle (two)	40-50%	S	[10]
Door	Quarter door	3-24%	S	[10]
Door	Quarter & Three-quarter	55%	E	[12]
Door	Door size	-	-	-
Door	Number of doors (two)	33%	S	[10]
Seat	Sideways foldable seat (SFS)	37%	E/S	[15,16] [17]
Seat	Lifting seat pan (LSP)	60%	S	[14]
Layout	Increased seat pitch	-	-	-
Layout	Multi-deck	-	E	[18]

A widening of the aisle results in a reduced seat width or in an increased aircraft cross-section diameter. The latter requires new aircraft design programs which manufactures try to avoid due to high development and certification expenses. The minimum aisle width for passenger aircraft is defined as 0.38 m (15 inches) on the floor and 0.51 m (20 inches) at 0.64 m (25 inches) above the floor level (CS/FAR 25.815) [7]. In current single-aisle configurations, the aisle width is between 19 and 25 inches (0.48-0.64 m) [8,9]. First studies of an aisle widening of 0.2 m (8 inches) show a boarding time reduction potential for common single-aisle aircraft, of 5-7%, depending on the cabin size and number of passengers [10].

Switching from a single-aisle layout to a twin-aisle configuration allows for the separation of passenger flow into two different streams. This shortens the cue lengths and number of aisle interferences. Traditional single-aisle configurations are superior in minimizing drag, weight and fuel burn from an aircraft design point of view. A patent from Boeing [11] shows a concept for around 200 passengers in a twin-aisle configuration, preferably, with a seven-abreast configuration. Fuchte [10] investigated single- and twin-aisle cabin layouts in the range from 150 to 340 seats. A seven-abreast twin-aisle out-performs a six-abreast single-aisle with 180 seats. The seven-abreast twin-aisle requires only half of the single-aisle's boarding time with hand luggage taken into account. This results from fewer seat interferences, slightly reduced walking distance and added overhead volume due to a larger cross-section. For 340 seats the boarding time difference between twin- and single-aisles reduces to 40%.

Changing the door positions along the fuselage allows splitting the passenger flow in two separate streams. For large single-aisle aircraft above 180 seats, a so-called quarter door could achieve a 3-24% boarding time reduction in correlating with the fuselage length. For smaller aircraft the limited fuselage length does not grant a sufficient margin between quarter and forward doors. This concept, however, has a substantial aircraft weight penalty below 220 seats, since then no full size exits are required [10].

Significant improvements could be made using the front and the rear door simultaneously for passenger processes. Fuchte [10] showed a 33% boarding time reduction for this scenario. Further, larger doors that allow two passengers to enter the cabin simultaneously would split the passengers into two streams within the jetway.

An enhancement of the two-door layout envisages the installation of a quarter and three-quarter door, splitting the passengers into four streams. This concept could yield an estimated boarding time reduction by 55% [12].

While being beneficial for passenger comfort, an increased seat pitch is disadvantages for airlines, since it reduces the cabin's capacity. For boarding and disembarking procedures, this enables passenger to get to their seat without other passengers needing to stand up. This eliminates seat interferences. Furthermore, passengers could stow their luggage in the overhead bins without blocking the aisle, significantly reducing aisle interferences.

On-demand adaptable cabins during boarding promise significant reductions in passenger egress and ingress times. A so-called lifting seat pan (LSP) [13] concept was part of a study conducted by Hertl [14]. The seat pan of the two-aisle seats in six-abreast single-aisle configuration could be folded upwards, enabling passengers to stand properly in the seat row while stowing their luggage. The simulation revealed a 60% time reduction compared to conventional single-class layouts. However, the applied simulation framework was lacking path-finding capabilities and could not take passenger interactions into account. A concept proposed by Isikveren et al. [15,16] enables a three-fold increase of the aisle width using a so-called sideways foldable seat (SFS). Hence, passengers can seamlessly pass other passengers stowing their hand luggage in the overhead bins. A similar concept, the side-slip seat, should enable a 37% boarding time reduction [17].

The arrangement of passengers on two decks could increase the number of seats considerably. A design study, based on a typical narrow-body aircraft, accommodates several passengers in the underfloor space, which is used today for cargo. This change would only require a slight enlargement of the fuselage diameter. Rearranging the aircraft doors enables parallel passenger boarding on the lower and upper deck, as well as, on both fuselage sides. First estimations show that current egress and ingress time could be retained despite a 20% increase in number of passengers [18].

The analysis of the passenger egress and ingress processes can benefit the development of competitive solutions when dealing with novel cabin architectures for future passenger aircraft. In particular, pragmatically adaptable cabins during boarding, such as foldable seats or movable cabin monuments, allow a flexible cabin which can be adjusted according flight phase requirements. Futuristic cabin concepts have only been addressed notionally within the aviation community and still postulate huge improvement potentials with respect to passenger egress and ingress times, as well as, the total turnaround time. Tying in with this shortfall, this paper demonstrates the application of an agent-based passenger flow simulation framework facilitating the assessment of novel seating concepts.

2 Overview of the passenger flow simulation framework - PAXelerate

In literature various microscopic passenger ingress and egress models exist [19], one approach of these models is agent-based simulation (ABS). They represent system behavior that is characterized by common actions of autonomously deciding agents. As a result, the behavior of the total system is based on the interactions of the entities as a macro phenomenon [20].

The applied two-dimensional agent-based passenger flow simulation framework PAXelerate [1] [19,21] is based upon the OpenCDT[1] [22] framework which implements the Eclipse Modelling Framework (EMF). The latter is a modelling framework and code generation facility for building tools based on a structured data model.

Fig. 1 provides an overview of the modules of PAXelerate's user interface. The general workflow is based on four steps: cabin layout definition, generation of agents, execution of the simulation and data analysis. A more detailed description of the ABS-based passenger flow framework PAXelerate can be found in [19].

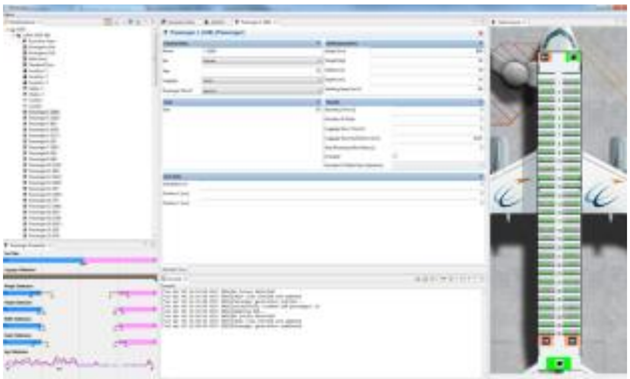

Fig. 1. Overview of the passenger flow framework PAXelerate: model explorer (top-left), property view (top-center), cabin rendering (right), passenger properties (bottom-left) and an output console (bottom-center).

[1] The PAXelerate and OpenCDT source code and any accompanying materials are available under the terms of the Eclipse Public License (EPL) v1.0. Further information can be obtained from http://www.paxelerate.com or http://www.opencdt.org.

2.1 Cabin layout definition

The initial cabin layout is generated using top-level requirements, such as overall cabin length and width, type of seating classes with assigned rows, seats and number of passengers. An integrated layout generator automatically produces a first cabin proposal under consideration of current cabin design rules and regulations. Afterwards, manual editing of the cabin monuments and doors, in terms of size and position, is possible. Simultaneous updates of the graphical cabin visualization enables short feedback loops during layout definition.

2.2 Agent builder

The virtual passengers are generated with their anthropometrics and behavior patterns taken into account.

The anthropometric properties of waist width, body depth and walking speed are determined using a Gaussian normal distribution between pre-defined minimum and maximum values. Based on the passenger's age, the appropriate walking speed is derived.

The behavior patterns, aggressive and passive, influence the simulation process in terms of agent's overtaking behavior. Optional hand luggage requires an additional stowing task to be performed before agent seating. The agent will block the aisle while stowing the luggage and cause aisle interference. In terms of luggage, small, medium and big items are distinguished with increasing stowing times. If agents approach a row with occupied seats, they block the aisle (i.e. aisle interference) for the simulated amount of time that seated agents would require for making way (i.e. seat interference). This enables to model dynamic reactions based on the agent's mood and environment and to define various passenger patterns, such as business or leisure travelers. Furthermore, a selection of predefined boarding strategies allows investigation of different airline boarding schemes.

2.3 Agent-based simulation

The two dimensional agent-based simulation module is the core of the passenger flow framework. Agents representing the passengers search for the shortest and most cost efficient path to their assigned seat using an A-Star path-finding algorithm. Applying parallel thread processing techniques renders the simulation to be non-deterministic, as every agent can react independently enabling realistic agent interaction.

The path-finding simulation is based on a node grid, enabling an agent to move in eight directions. Each node possesses properties such as location, neighbors and occupation status, as well as, distance and cost, which are important during path finding. A gradient-based potential is defined around cabin monuments and agents, avoiding agents walking to closely to the obstacles. The agents follow the calculated path and react to obstacles occurring on the way to their assigned seat. They are able to turn their two-dimensional body in 45-degree steps or can take sideways steps.

2.4 Data analysis and post-processing

Finally, results are displayed showing heat maps of passenger queuing hotspots or individual passenger walking paths and their interactions. The created data can also be exported for post processing.

3 Investigated cabin concepts studies

The case studies investigate the potential of a lifting seat pan and a sideways foldable seat concept in detail. The results are compared to a reference case: a state-of-the-art short-to-medium haul aircraft with 180 seats in a six-abreast single-aisle layout.

In total, 60 studies are performed, covering all combinations of five different load factor (LF) and four hand luggage (HL) variations. The LF is set to be within the common range of current airline operations between 60-100% [23] (see Table 2). In terms of HL, a best case scenario with no luggage, two further cases with a usual distribution and one with a higher amount of bulky items are considered (see Table 3).

Table 2. Load factor parameter variations

Load factor [%]	Passenger
60	108
70	126
80	144
90	162
100	180

Table 3. Luggage distribution parameter variations (S: small, M: medium and B: big hand luggage.)

Study	Values [%]			
	No	S	M	B
No HL	100	0	0	0
Usual HL low	10	50	30	10
Usual HL high	10	30	40	20
Bulky HL	0	20	30	50

Monto Carlo experiments are conducted in order to gain insight into the performance of the cabin concepts investigated. The passenger anthropometrics and properties, such as walking speed and type of luggage carried, are distributed among the agents using probability functions before each simulation run. The number of required runs is estimated with the approach by Byrne [24]. At least 20 simulation runs are performed for each study to determine the coefficient of variation (CV) as a measure of variability. The CV is defined as the ratio of standard deviation (σ) and median (μ). The minimum number of model runs (n) to achieve the desired confidence interval width (w) of 0.05 is estimated with Equation 1, where $z_{\alpha/2}$ is the usual value of standard normal assuming a 95% confidence level.

$$n = \left(\frac{z\frac{\alpha}{2}}{w} CV\right)^2 \tag{1}$$

The probabilistic results allow assessing the likelihood of each outcome. Table 4 exemplarily summarizes the distribution of passenger anthropometrics for 180 passengers. The input values are derived for European and US American passengers.

Table 4. Probabilistic distribution of passenger anthropometrics for a LF of 100% (M: median, CV: coefficient of variation)

Parameter	M	CV	Min	Max
Height [m]	1.71	0.05	1.51	1.93
Depth [m]	0.27	0.09	0.23	0.35
Width [m]	0.42	0.07	0.39	0.50
Walking speed [m/s]	1.18	0.36	0.60	1.60

3.1 Reference case

The reference case (RC) features 180 seats in a one-class six-abreast single-aisle layout, as depicted in Fig. 2. The passengers have randomly assigned seats and use the forward left door to enter the cabin. The values for seat pitch and width and aisle width are based on contemporary short-haul cabin layouts (see Table 5). The adaptable seating concepts are also applied to the depicted cabin configuration.

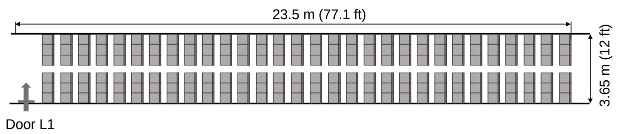

Fig. 2. Reference cabin layout with 180 seats in a one-class configuration

Table 5. Summary of the layout characteristics

Parameter	Value
Cabin layout	Single-class
Cabin width	3.65 m (12.0 ft)
Cabin length	23.50 m (77.1 ft)
Seats	180
Seat abreast	3-3
Seat pitch	0.75 m (29.6 inch)
Seat width	0.50 m (19.7 inch)
Aisle width	0.65 m (25.6 inch)
Boarding rate	18 PAX/min
Boarding strategy	Random

3.2 Lifting seat pan

The concept of a lifting seat pan (LSP), also referred to as cinema seats, was introduced by AIDA Development [13] and initially assessed by Hertl [14]. The aim is to increase the moving space of passengers in the row and enhance their access to the overhead bins. The aisle width remains unchanged during boarding. All aisle seats are folded upwards before the passengers enter the aircraft. The foldable seat pan allows passengers to step into the row, if the aisle seat is not yet occupied, and to stow their hand luggage in the overhead bin without blocking the aisle. In the case of seat interferences with occupied aisle seats, these passengers can stand up while remaining within the row, reducing the duration of aisle interferences. The unfolding of the seat and the sit down procedures of passengers are accounted for with two seconds.

The general configuration of folded and unfolded LSP is illustrated in Fig. 3. The investigated case study features the foldable seats for both sides of the aisle.

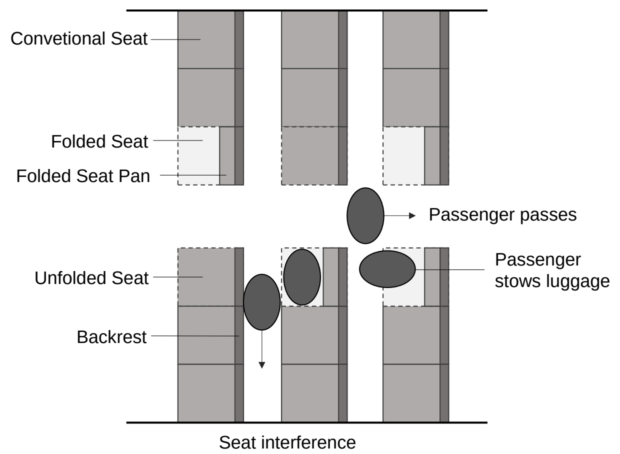

Fig. 3. Lifting seat pan (LSP) concept in a six-abreast arrangement with folded and unfolded seats

3.3 Sideways foldable seat

Two variants of sideways foldable seat (SFS) concepts exist: one model where the aisle seat is sliding over the middle seat, as proposed by Molon [17] and the other where the aisle seat sliding under the middle seat, as investigated by Isikveren et al. [15,16]. In the following the latter concept is further described, as it allows the middle seat to be occupied with the aisle seat still unfolded. The general configuration of folded and unfolded SFS is illustrated in Fig. 4. The investigated case study features the foldable seats for both sides of the aisle.

The aisle seats are folded away before the passengers enter the aircraft increasing the aisle width threefold. Still, passengers prefer to walk in the middle of the aisle, since overhead bins constrict the ease of walking on either side. However, the increased aisle width allows passengers to pass each other seamlessly while others are stowing their hand luggage in the overhead bins. Hence, aisle interferences are significantly reduced. When passengers, who seated at aisle seats, have reached their row, they pull out the folded seat; hence, decreasing that row's aisle width. The unfolding procedure is assumed to not cause any obstruction of the middle aisle and to last five seconds.

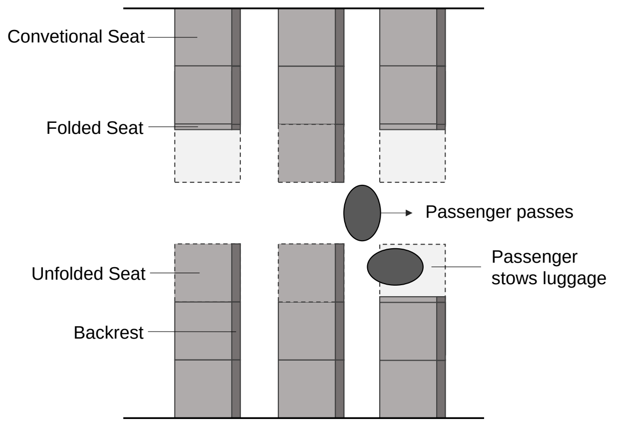

Fig. 4. Sideways foldable seat (SFS) concept in a six-abreast arrangement with folded and unfolded seats

4 Results

The seating concept assessment focused on the effect of LSP and SFS with the influence of aircraft LF and HL distribution.

4.1 Reference case

Validation for the RC is conducted on the basis of existing data from aircraft manufacturers, simulation results and empirical data obtained for current short-to-medium-haul aircraft (see [19] for a validation case). It becomes apparent that results lie in the same range as results from other available simulation frameworks, as well as, manufacturers' data with a mean boarding time of 14:27 minutes for a LF of 100% and an usually high amount of HL (CV=0.068).

Fig. 5 illustrates the results of the RC taking a 60% LF and no HL as datum. The outcome underlines the assumption of a drop in the boarding velocity with higher LF and amount of HL. An increase of the LF from 60% to 100% causes a 65%-higher boarding time, if the passengers do not have to stow any HL. The LF correlation shows an almost linear behavior, with an increasing amount of seat interferences. The amount and size of carried HL also influences the boarding time significantly. The duration increase accounts for a median of 31% for usual HL low, 41% for usual HL high and 58% for bulky HL for each investigated LF variation

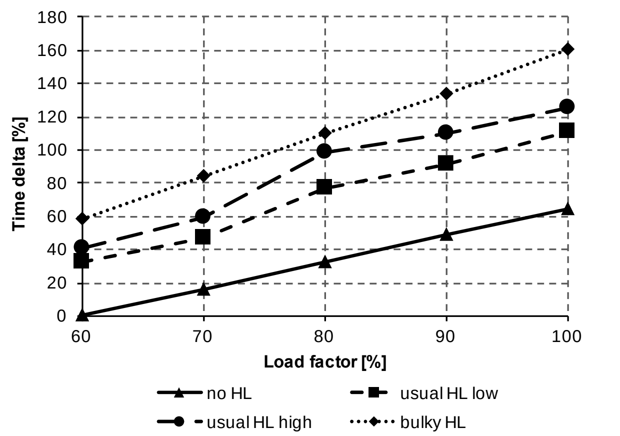

Fig. 5. Impact of the load factor and hand luggage distribution for the reference case

4.2 Adaptable seating concepts

Comparing the LSP concept with the RC reveals significant lower boarding times. The results are illustrated in Fig. 6 taking the corresponding RC result as datum.

An efficiency gain with higher LF could not be identified. The CV is in the range from 0.02 for no HL up to 0.06 for bulky HL. The highest gains appear around a LF of 80%. However, the impact of carried HL is distinct. The RC and LSP score almost identical results, if no HL has to be stowed. In this case, passengers only block the aisle when seat interferences occur. These events are slightly reduced in the case of LSP due to the increased free moving space, however their impact on the total boarding time is marginal. The potential of the LSP becomes apparent with the additional stowing of HL. The LSP shows an average of 14% reduction in ingress time with a usual HL low, 19% with a high usual amount of HL and a reduction of up to 24% for bulky luggage. The LSP allows passenger to stow their HL directly at the folded seat, if the aisle seat is not yet occupied. As a consequence, passengers do not block the aisle while stowing their hand luggage. With an increasing amount of bulky HL, the efficiency gains rise.

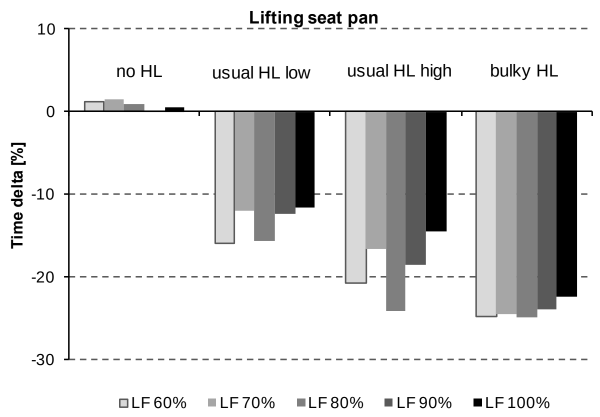

Fig. 6. Impact of the hand luggage distribution for the LSP compared to the RC

For the SFS similar trends in dependence of the LF and HL distribution can be identified compared to the RC, as depicted in Fig. 7. The SFS shows an average of 16% reduction in ingress time with a usual HL low, 22% with a high usual amount of HL and a reduction of up to 28% for bulky luggage. Same as for the LSP, no efficiency gain with higher LF could not be identified. The CV is in the range from 0.02 for no HL up to 0.05 for bulky HL. The highest gains appear at a LF of 80% for each investigated HL scenario.

Comparing the two foldable seating concepts reveals advantages for the SFS in case of higher LF and a larger amount of HL carried, as illustrated in Fig. 8. The benefit rises up to 6.3% compared to the LSP for bulky HL and a LF of 100%.

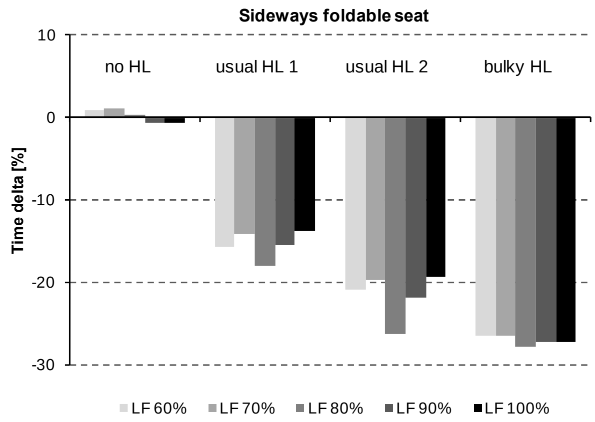

Fig. 7. Impact of the hand luggage distribution for the SFS compared to the RC

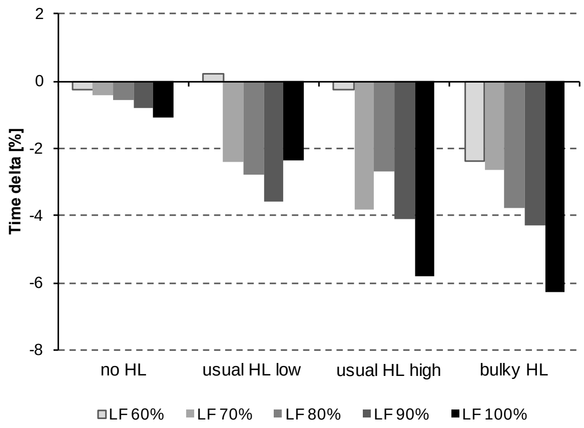

Fig. 8. Comparison of the SFS and LSP concept for different hand luggage distributions

4.3 Recommendations

The conducted case studies underline the claimed efficiency gains of adaptable seating configurations, despite previously estimated values of 60% for the LSP by Hertl [14] and 37% for the SFS by Molon [17] could not be confirmed. This might be caused by the simplified approach of the agent behavior modeling undertaken by previous studies. However, the concepts investigated show a passenger ingress time reduction potential of up to 28%, which is a significant efficiency gain. Especially when facing increasing load factors of around 85% in current operations and a shift towards an increasing amount of hand luggage. An independence of the LF is caused by the high rate of already unfolded seats at the end of the boarding process, which results in similar results compared to the RC. Thus, the aisle is blocked during HL storage and seat interferences.

The operational applicability of the concepts relies on the certification and passenger acceptance in terms of manageability and comfort. Further, from an airline perspective, the operating cost advantages have to outweigh the weight penalty due to the folding or sliding mechanism, which introduces complexity and potential robustness issues.

A more detailed modeling of the agent behavior could increase the likelihood of passing and overtaking events which could lead to even shorter boarding times. Investigating applied boarding schemes, such as group boarding, could also show large efficiency gains by optimally using the newly-created moving space in the cabin.

Since the passenger processes constitute the critical path of most turnaround processes, a reduction contributes to the fulfillment of earlier mentioned ACARE goals. Fig. 9 shows the comparison of turnaround times of a state-of-the-art single-aisle aircraft with and without the SFS concept.

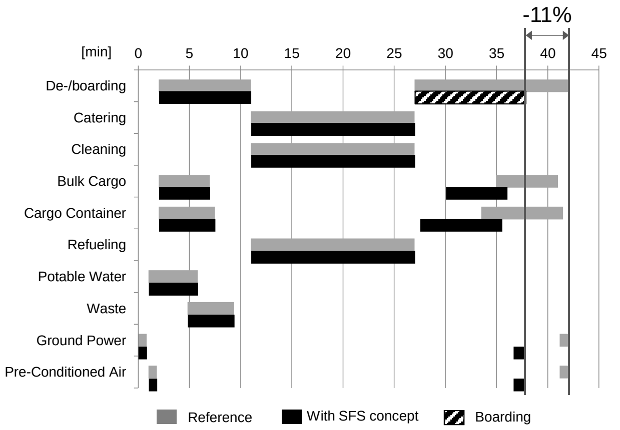

Fig. 9. Turnaround performance of a state-of-the-art single-aisle aircraft with and without the SFS concept (adapted from [8])

The installation of the SFS concept allows reducing the total turnaround time by 11%. Together with fuel burn reductions through more efficient engines and aerodynamics, which re demanded by the ACARE agenda, a significant contribution towards the promoted goals could be accomplished. This enables to free up airport capacity and to increase the buffer times between two flights, improving on-time performance.

5 Conclusion and outlook

This paper assessed the boarding time reduction potential of adaptable seating concepts, namely a lifting seat pan (LSP) and sideways foldable seat (SFS) configuration, using the two-dimensional agent-based passenger flow simulation framework PAXelerate. The conducted case studies following the Monte Carlo approach underline claimed efficiency gains, even if previous higher estimated boarding time reductions could not be confirmed. In comparison with a reference case, representing a state-of-the-art short-to-medium haul aircraft with 180 seats in a six-abreast single-aisle layout, a boarding time reduction of up to 25% for the LSP and 28% for the SFS could be identified. This can be translated into 11% reduction in total turnaround time, a significant contribution towards the promoted goals of international regulators.

In future studies, a more detailed modeling of the agent behavior could increase the likelihood of passing and overtaking events. An increase of the design space covering boarding schemes, position and number of doors used could identify integrated solutions with even more impactful benefits. Furthermore, investigations of different cabin sizes and configurations should be conducted to determine the application for regional and larger single-aisle aircraft [25].

References

[1] Advisory Council for Aviation Research and Innovation in Europe (ACARE), “Strategic Research & Innovation Agenda (SRIA) - Volume 1”, Technical report, 2012.

[2] Advisory Council for Aviation Research and Innovation in Europe (ACARE), “Strategic Research & Innovation Agenda (SRIA) - Volume 2”, Technical report, 2012.

[3] Marelli, S., Mattocks, G., Merry, R., “The role of computer simulation in reducing airplane turn time”. AERO Magazine 1, 1998.

[4] Nyquist, D. C., and McFadden, K. L., “A study of the airline boarding problem,” Journal of Air Transport Management, Volume 14, Issue 4, pp. 197–204. doi:10.1016/j.jairtraman.2008.04.004

[5] Jaehn, F., and Neumann, S., “Airplane boarding,” European Journal of Operational Research, vol. 244, 2014, pp. 339–359. doi:10.1016/j.ejor.2014.12.008

[6] Steffen, J.H. and Hotchkiss, J., “Experimental test of airplane boarding methods”. Journal of Air Transport Management, Volume 18, Issue 1, pp. 64-67, 2012. doi:10.1016/j.jairtraman.2011.10.003

[7] European Aviation Safety Agency (EASA), “Certification Specifications for Large Aeroplanes CS-25,” 2009.

[8] Airbus, “A320 - Aircraft Characteristics - Airport and Maintenance Planning,” 2015.

[9] Boeing, “B737 – Airplane Characteristics for Airport Planning,” 2013.

[10] Fuchte, J. C., “Enhancement of Aircraft Cabin Design Guidelines with Special Consideration of Aircraft Turnaround and Short Range Operations,” Technische Universität Hamburg-Harburg, PhD Thesis, 2014.

[11] Sankrithi, M. M. K. V., “Twin aisle small airplane,” US 6,834,833 B2, 2004.

[12] Schmidt, M., Nguyen, P., and Hornung, M., “Novel Aircraft Ground Operation Concepts Based on Clustering of Interfaces,” SAE Technical Paper 2015-01-2401, 2015, doi:10.4271/2015-01-2401.

[13] AIDA Development GmbH, “Foldable Passenger Seat”, http://www.sii-engineering.de/en/projects_passenger_seat

[14] Hertl, M., “Bewertung einer Klappsitzoption in Hinblick auf Bewegungsabläufe in der Fluggastkabine eines Verkehrsflugzeugs,” Term Thesis, Technische Universität Berlin, 2005.

[15] Isikveren, A. T., Seitz, A., Vratny, P. C., Pornet, C., Plötner, K. O., and Hornung, M., “Conceptual Studies of Universally-Electric Systems Architectures Suitable for Transport Aircraft,” 61th Deutscher Luft- und Raumfahrtkongress (DGLR), Berlin, 2012.

[16] Götz, M., “Engineering Concept Study of an Innovative Sideward Retractable Aircraft Seat,” Diploma Thesis, Technische Universität München, 2014.

[17] Molon Labe Designs, “Side-Slip Seat”, http://www.airlineseats.biz (accessed 15th June 2015).

[18] Bauhaus Luftfahrt e.V., “Interdisciplinary Cooperation in the Research Field of Radical Cabin Architectures and Novel Ground Handling Processes”, 2013. http://www.bauhaus-luftfahrt.net/archive/interdisziplinaere-zusammenarbeit-im-bereich-radikale-kabinenarchitekturen-und-neuartige-bodenabfertigungsprozesse?set_language=en (accessed 15th June 2015).

[19] Schmidt, M., Engelmann, M., Brügge-Zobel, T., Hornung, M., and Glas, M., “PAXelerate - An Open Source Passenger Flow Simulation Framework for Advanced Aircraft Cabin Layouts,” 54th AIAA Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, San Diego, California, USA, 2016. doi:10.2514/6.2016-1284

[20] Page, B., Knaaka, N., and Kruse, S., “A discrete event simulation framework for agent-based modelling of logistic systems,” INFORMATIK 2007: Informatik trifft Logistik, 2007, pp. 397–404.

[21] Schmidt, M., Engelmann, M., and Rothfeld, R., “PAXelerate Release Alpha 0.7, Github Repository, 2016. doi:10.5281/zenodo.56736

[22] Ziemer, S., Glas, M., and Stenz, G., “A conceptual design tool for multi-disciplinary aircraft design,” Proc Aerospace Conference, 2011, doi:10.1109/AERO.2011.5747531.

[23] MIT, “Global Airline Industry Program, Airline Data Project,” http://airlinedataproject.mit.edu/

[24] Byrne, M. D., “How many times should a stochastic model be run? An approach based on confidence intervals,” Proceedings of the 12th International Conference on Cognitive Modeling, 2013, pp. 445–450.

[25] Schmidt, M., Heinemann, P. and Hornung, M., “Progress on Single-Aisle Aircraft Cabins with Enhanced Turnaround Performance” 55th AIAA Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Dallas Fort Worth, Texas, USA, 2017. (submitted)

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