Engage 2

Passenger-centric operations - Enlighten the dark aircraft cabin

Final technical report

Engage 2 catalyst fund project

Coordinator: University of the Bundeswehr Munich

Consortium partners: Chemnitz University of Technology

Thematic challenge: TC2 Passenger-centric digital airport

Edition date: 27/03/2026

The Passenger-centric operations - Enlighten the dark aircraft cabin project has been supported by the SESAR 3 Joint Undertaking and its founding members under the Grant Agreement nr. 101114648. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or SESAR 3 JU. Neither the European Union nor the SESAR 3 JU can be held responsible for them.

SUPPORTED BY sesar JOINT UNDERTAKING

Co-funded by the European Union

Authoring & approval

Author(s) of the document

Organisation name	Date
University of the Bundeswehr Munich	05/03/2026
Chemnitz University of Technology	27/02/2026

Reviewed by

Organisation name	Date
University of the Bundeswehr Munich	05/03/2026
Engage 2 mentors, EUROCONTROL; TU Braunschweig	10/03/2026
Engage 2 Task Leader, University of Westminster	21/03/2026

Approved for submission to the SESAR 3 JU by[1]

Organisation name	Date
Micol Biscotto, Deep Blue srl	27/03/2026

Rejected by[2]

Organisation name	Date

Document history

Edition	Date	Status	Company Author	Justification
01.00	05/03/2026	Submitted to the Engage 2 consortium	University of the Bundeswehr Munich	Initial version
02.00	27/03/2026	Ready for publication	Engage 2	Final version

[1] Representatives of all the beneficiaries involved in the project

[2] Representatives of the beneficiaries involved in the project

Engage 2

THE SESAR 3 KNOWLEDGE TRANSFER NETWORK

Engage 2

This document is part of a project that has received funding from the SESAR 3 Joint Undertaking under grant agreement No 101114648 under European Union's Horizon Europe research and innovation programme.

Table of contents

List of figures

1 Introduction

1.1 Abstract

This catalyst project addressed the structural lack of real-time operational information from inside the aircraft cabin during boarding. In current turnaround management, the cabin remains a black box, limiting the reliability of boarding time prediction and dynamic process control. The project established a sensor-based laboratory cabin environment replicating a single-aisle A220 configuration and implemented a multi-sensor architecture combining LiDAR as primary detection source with Lighthouse-based tracking and wearable localization sensors to ensure spatial stability under multi-participant conditions. A coherent data acquisition and processing pipeline was developed and linked to a mixed-reality environment for validation and demonstrator purposes. Structured laboratory experiments were conducted to identify and evaluate operationally meaningful sensor-derived input variables for boarding time prediction. Aggregated hand luggage count was validated as a robust candidate feature. Model-based evaluation indicated an improvement of approximately 10% in boarding time prediction accuracy when incorporating luggage information compared to baseline configurations. The project advanced the concept from simulation-based studies to a functional laboratory demonstrator corresponding to TRL 4.

1.2 Executive summary

Aircraft boarding remains one of the least digitally observable processes within aircraft turnaround operations. While airport and airside operations are supported by structured milestone monitoring, the aircraft cabin itself provides no measurable real-time state information. As a result, boarding progress and completion times are estimated based on experience rather than data, introducing uncertainty into Target Off-Block Time (TOBT) forecasting and downstream departure sequencing within the Air Traffic Management (ATM) network.

The Engage 2 catalyst project 'Enlighten the dark aircraft cabin' addressed this structural limitation by establishing a digitally connected cabin demonstrator capable of generating sensor-based boarding state information under controlled laboratory conditions. The project transitioned from prior simulation-based boarding research toward an integrated physical and digital experimental environment.

A laboratory cabin mock-up replicating a single-aisle Airbus A220 configuration was established and equipped with a multi-sensor detection architecture. LiDAR sensors were implemented as the primary geometry-based detection source. Lighthouse ceiling tracking and wearable localization units were integrated to increase spatial robustness under multi-participant conditions. A synchronized middleware layer ensured stable real-time data acquisition across heterogeneous sensor streams.

In parallel, a parameterizable three-dimensional cabin model was developed using a Blender-to-Unity workflow and deployed on standalone extended reality (XR) hardware. Real-time sensor data were streamed into this environment, enabling spatial validation, immersive analysis, and demonstrator functionality. The mixed-reality setup served both as a validation instrument for sensor consistency and as a visualization tool for stakeholder engagement.

Co-funded by the European Union

Structured laboratory experiments evaluated which sensor-derived input variables provide measurable explanatory power for boarding time prediction. Aggregated hand luggage count was identified and validated as an operationally meaningful feature. Model-based evaluation indicated an improvement of approximately 10 percent in boarding time prediction accuracy when incorporating luggage information compared to baseline configurations without this input. This effect magnitude is comparable to structured queue-order information reflecting seat sequence dynamics.

The project therefore established two advances beyond the prior state of the art. First, it integrated real sensor feedback into a controlled cabin environment, replacing purely synthetic boarding inputs. Second, it quantified and validated a privacy-compliant, geometry-based sensor variable suitable for future boarding time prediction architectures.

From a maturity perspective, the concept advanced from simulation-based research at approximately TRL 2 to 3 toward a functional laboratory prototype at TRL 4 integrating hardware, real-time processing, and immersive validation. Although no operational field deployment was conducted within the project scope, the demonstrator provides a validated technical foundation for pilot installations, for example at boarding gates where luggage detection could be implemented without intrusive cabin modifications.

Within the SESAR context, improved boarding time predictability directly supports the performance areas of predictability and capacity. More reliable estimation of boarding completion enhances the accuracy of TOBT forecasting and reduces uncertainty in departure sequencing. By instrumenting a previously unobservable process segment at the airport–aircraft interface, the project contributes to improved decision support within Airport Collaborative Decision Making (A-CDM) processes and reduces the need for reactive rescheduling. Stabilized turnaround timelines have the potential to decrease buffer usage, mitigate knock-on delays, and indirectly reduce fuel burn associated with taxi and runway queuing.

The achieved results demonstrate that measurable cabin state information can be generated using scalable, geometry-based sensing approaches. The project establishes a structured basis for further maturation toward near-operational validation and integration into network-level ATM decision processes.

2 Overview of catalyst project

2.1 Operational/technical context

Aircraft turnaround operations represent a tightly coupled sequence of ground-handling and airside processes within A-CDM environments. Boarding is one of the final and most behavior-driven elements within this sequence and directly influences the achievement of the Target Off-Block Time. While many airport processes are digitally monitored and supported by milestone-based tracking, the aircraft cabin itself remains operationally uninstrumented. As a result, boarding progress cannot be measured in real time, and completion times are estimated based on experience rather than structured state information.

This lack of cabin transparency introduces uncertainty into A-CDM milestone coordination, particularly between Target Off-Block Time and Target Start-Up Approval Time. Deviations between forecasted and actual boarding completion may affect departure sequencing, stand utilization, and network slot adherence. At capacity-constrained airports, even minor uncertainties at the cabin level can propagate through apron operations and airspace flow management, reducing predictability and affecting overall network stability.

From a technical perspective, the aircraft cabin represents a challenging sensing environment. The confined geometry, repetitive seat structures, reflective surfaces, and dynamic passenger interactions complicate localization and object detection. Existing wired aircraft infrastructure is dedicated to certified flight-critical systems and cannot be repurposed for operational monitoring without significant regulatory implications. Therefore, nonintrusive, scalable, and privacy-compliant sensing approaches are required to enable implementation without interfering with certified avionics.

Previous research in passenger boarding has predominantly relied on simulation-based models or field trials without systematic real-time sensor integration. Although dynamic boarding strategies and boarding time prediction models have demonstrated potential efficiency gains under simulated conditions, the absence of validated cabin state data has limited their operational applicability. The aircraft cabin has therefore remained a 'black box' within otherwise increasingly digitalized airport systems.

The technical context of this project lies at the interface between sensor-based localization, data-driven process modeling, and immersive validation technologies. By establishing a sensor-equipped cabin environment and linking real-time detection data to digital models, the project addresses a previously uninstrumented segment at the airport–aircraft boundary. In doing so, it contributes to the broader objective of a passenger-centric digital airport by transforming boarding from an experience-based estimate into a measurable and model-supported process, thereby supporting improved predictability and capacity within the ATM system.

2.2 Project scope and objectives

The scope of the catalyst project was to establish a digitally connected aircraft cabin environment capable of generating measurable state information during passenger boarding. The project addressed the structural gap between simulation-based boarding research and the absence of real-time operational data from inside the aircraft cabin.

Building on prior research in dynamic boarding strategies and boarding time prediction models, the project pursued the objective of creating an experimental environment in which sensor-based cabin state information could be generated, evaluated, and linked to predictive models under controlled laboratory conditions. Rather than further refining purely algorithmic approaches, the project focused on validating which types of sensor-derived input variables are technically feasible, operationally meaningful, and scalable within the constraints of an aircraft cabin.

The project objectives were structured around three central questions:

- First, how can passengers and boarding-relevant objects be detected and localized within a confined single-aisle cabin geometry using nonintrusive and privacy-compliant sensing technologies?
- Second, which measurable cabin state variables provide explanatory power for boarding process modeling and time prediction beyond synthetic simulation inputs?
- Third, how can real-time sensor feedback be integrated into a digital representation of the cabin to enable validation, visualization, and structured experimentation?

To address these questions, the project established a laboratory cabin mock-up replicating a representative single-aisle configuration and implemented a multi-sensor detection architecture. The objective was not fully operational deployment but the creation of a coherent demonstrator that integrates sensing, data processing, and digital modeling into a consistent experimental framework.

In addition to boarding time prediction, the project considered the conceptual integration of sensor feedback into dynamic boarding logic. However, the primary focus remained on identifying validated and quantifiable input variables that could serve as a foundation for future decision-support architectures within Airport Collaborative Decision Making environments.

By concentrating on sensor feasibility, data integration, and measurable explanatory variables, the project defined a technically robust intermediate step between theoretical process optimization and future operational implementation.

2.3 Research carried out

To address the defined scope and objectives, the project established an integrated experimental platform combining a physical cabin mock-up with a synchronized digital representation. The research activities focused on generating measurable cabin state information under controlled laboratory conditions and evaluating its suitability for boarding process modeling.

Physical Cabin Environment

A laboratory cabin environment was constructed to replicate the geometry of a representative single-aisle aircraft configuration. Due to hardware procurement constraints, originally planned real aircraft cabin elements could not be installed. Instead, modular seating arrangements and aisle structures were implemented to reproduce spatial constraints representative of an Airbus A220 layout (Figure 1).

The physical setup replicated aisle width, seat spacing, and passenger movement restrictions typical of narrow-body aircraft operations. The modular configuration ensured repeatability across experimental runs while preserving operationally relevant geometry.

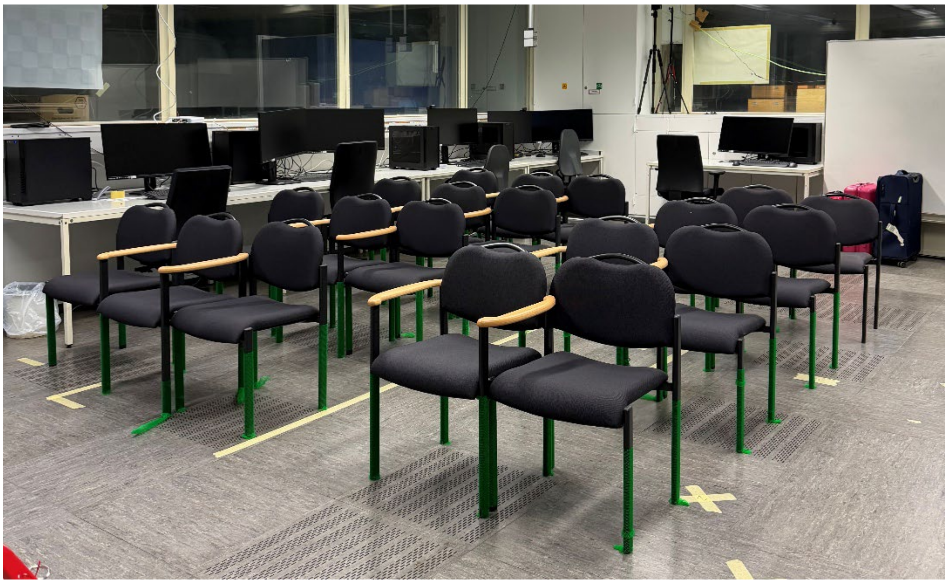

Figure 1: A220 seat configuration as lab setup.

Sensor Architecture and Detection Framework

A multi-sensor detection array was implemented within the cabin mock-up. LiDAR sensors were deployed as the primary geometry-based detection source. Filtered three-dimensional point cloud data were used to determine participant positions within the laboratory environment (Figure 2). Detection relied on geometric segmentation and clustering of point cloud structures.

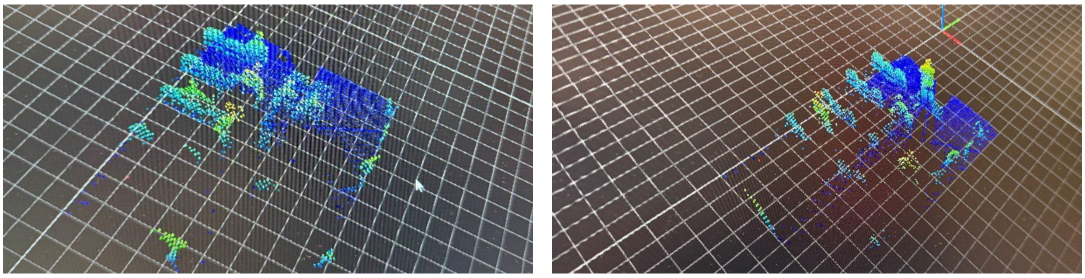

Figure 2: Filtered LiDAR point cloud data are used to determine participant positions within the laboratory environment.

To enhance spatial robustness and compensate for temporary occlusions and close-proximity effects, a ceiling-mounted Lighthouse tracking system was integrated (Figure 3). Ten wearable localization units were deployed to provide additional positional references. Each unit included onboard processing and infrared receivers to enable real-time positional updates.

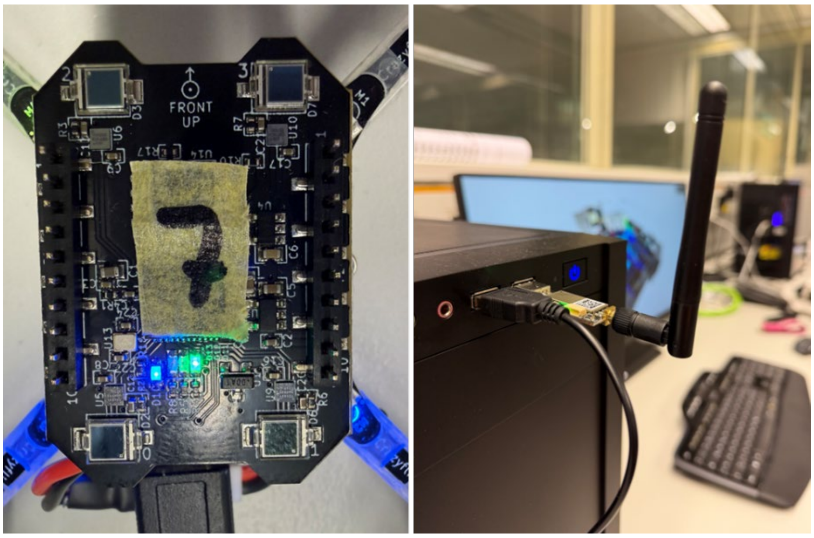

Figure 3: HTC Vive / SteamVR Lighthouse tracking system with ceiling mounted receivers. Ten localization sensors are deployed, each featuring an onboard FPGA for real time signal processing using an open-source toolchain and four TS4231 infrared receivers with UART and I2C interfaces.

A middleware layer was developed to synchronize heterogeneous data streams and align timestamps across LiDAR, Lighthouse, and wearable devices. This ensured stable real-time data acquisition and structured logging of all experimental runs.

Camera systems were installed but used exclusively as secondary reference sources. Their role was limited to plausibility checks and visual cross-validation of geometry-based detections. The core detection pipeline remained independent of image-based identification to maintain a privacy-compliant sensing architecture.

Digital Cabin and Mixed-Reality Integration

In parallel with the physical setup, a parameterizable three-dimensional cabin model was developed using a Blender-to-Unity workflow (Figure 4). The digital cabin replicated the geometry of the laboratory environment and allowed configurable seating layouts consistent with the A220-based arrangement.

Real-time positional data from the detection array were streamed into the Unity environment and rendered as dynamic entities. The immersive system was deployed on a Meta Quest 3 headset. Within the extended reality environment, tracked participants were represented as simplified virtual objects whose positions were continuously updated based on live sensor data (Figure 5).

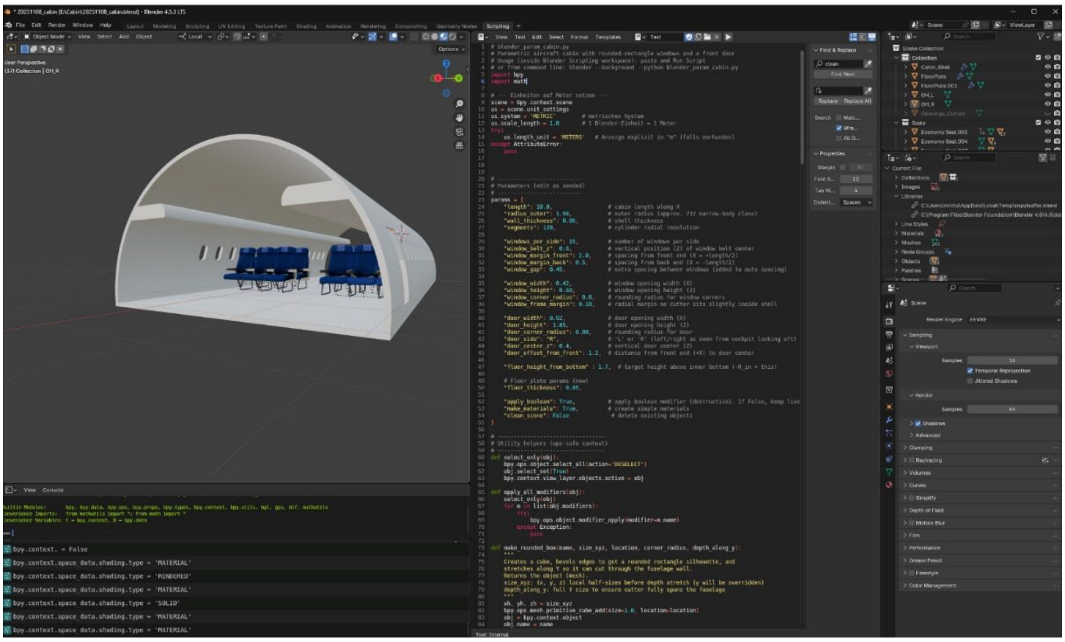

Figure 4: A parameterizable 3D cabin model was developed using Blender.

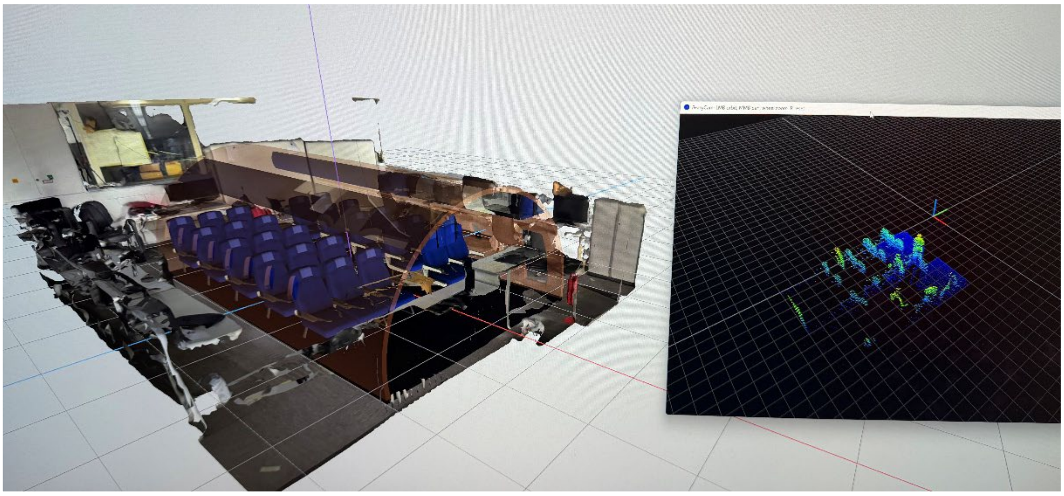

Figure 5: Linking of 3D cabin, lab environment and location data.

Pass-through mode was used to overlay virtual cabin structures onto the physical setup (Figure 6). This enabled direct comparison between real participant positions and their virtual representations and supported spatial validation of the sensing and visualization pipeline.

Figure 6: Virtual cabin in Meta Quest 3 (Unity)

Structured Experimental Design

More than thirty structured laboratory scenarios were conducted. These scenarios varied passenger density, luggage quantity, spatial distance, and partial occlusion conditions. The experimental design aimed to evaluate detection robustness under multi-participant conditions and to derive aggregated cabin state variables suitable for boarding process modeling.

The research activities concentrated on sensor feasibility, synchronization integrity, spatial validation, and structured variable derivation. The objective was not immediate operational deployment but the establishment of a technically coherent demonstrator integrating sensing, data processing, immersive validation, and controlled experimentation within a single framework.

2.4 Results

The project produced measurable results demonstrating the technical feasibility and operational relevance of sensor-based cabin state detection during passenger boarding.

In laboratory experiments, the feasibility and detection accuracy of camera-based and LiDAR-based hand luggage detection were assessed. The results show that hand luggage can be detected and counted with sufficient robustness to be considered a realistic candidate input for future prediction models (Figure 7).

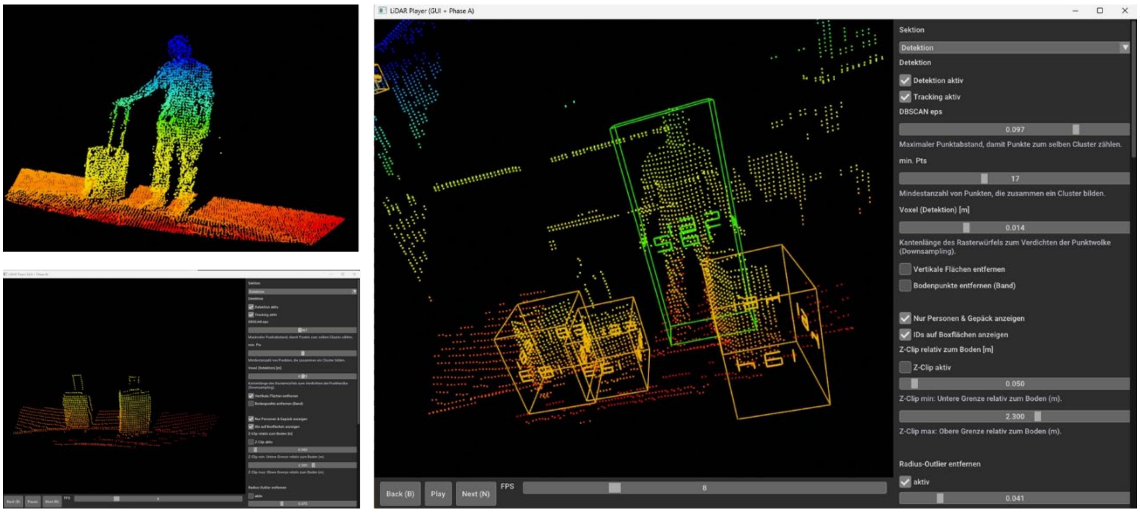

Figure 7: Detection of hand luggage.

More than 30 structured laboratory scenarios were conducted, varying passenger density, luggage quantity, spatial distance, and partial occlusions. With the camera-based setup, person detection achieved a precision of about 0.70 and a recall of about 0.83, resulting in an F1 score of approximately 0.76. Luggage detection at object level was more challenging, but aggregated luggage counts per passenger were stable.

A second implementation used LiDAR data only and therefore does not rely on image data, supporting privacy-compliant implementation. Detection was based on three-dimensional point cloud segmentation and geometric clustering. Under laboratory conditions, LiDAR-based person detection achieved precision and recall values of around 0.5, resulting in an F1 score of about 0.5. Performance was mainly limited by close object proximity and temporary occlusion. Aggregated luggage counts remained robust even when individual objects were misclassified.

Following the refinement of the project focus toward identifying and validating sensor-derived input variables, hand luggage scanning was identified as the most suitable and operationally meaningful feature. A quantitative assessment showed approximately 10% improvement in prediction accuracy when including aggregated luggage count compared to the baseline configuration.

In addition, experimental runs demonstrated reliable end-to-end integration of the cabin mock-up, the detection array, and the Unity-based XR environment (Figure 8). Multiple participants were tracked continuously and their positions were visualized in real time as simplified representations. This enabled verification that the sensor system, data pipeline, and visualization layer were spatially consistent. Pass-through mode allowed overlay of virtual cabin structures onto the physical laboratory setup and confirmed reliable operation under multi-participant conditions.

Figure 8: Experimental setup with one VR participant

Overall, by enabling measurable and quantifiable cabin process information, the project strengthens the data basis for boarding estimation and future prediction models. Improved temporal accuracy at cabin level would support more reliable TOBT forecasting and contribute to reduced uncertainty and more stable operations within the ATM system.

3 Conclusions, next steps and lessons learned

3.1 Conclusions

The project demonstrates that measurable cabin state information can be generated under controlled laboratory conditions using geometry-based sensing technologies. By integrating a physical cabin mock-up, a multi-sensor detection architecture, and a synchronized digital representation, a coherent experimental platform was established for evaluating sensor-derived input variables in the context of boarding process modeling.

A central finding is that aggregated hand luggage count represents a technically feasible and operationally meaningful cabin state variable. The experimental evaluation showed that this feature can be derived with sufficient robustness to support boarding time prediction models. Model-based analysis indicated that incorporating aggregated luggage information improves boarding time estimation compared to baseline configurations without this input.

The results further show that geometry-based detection can be implemented independently of visual passenger identification. This supports privacy-compliant sensing concepts and reduces potential regulatory constraints for future applications.

With respect to technological maturity, the project advances previous simulation-based research toward a laboratory-validated system integration. The achieved state corresponds to approximately TRL 4, characterized by validation of components and their interaction within a controlled environment.

Overall, the work provides a technical basis for further development toward applied research and potential near-operational validation. By instrumenting a previously unobservable segment of the turnaround process, the project strengthens the empirical foundation for boarding time estimation within Airport Collaborative Decision Making environments.

3.2 Next steps

The project established a laboratory-validated sensing and visualization platform. Further development will focus on extending this setup toward near-operational validation under increased environmental variability and higher participant density.

During the project, structured exchange was maintained with Munich and Cologne/Bonn Airport. In a subsequent phase, the LiDAR-based sensing approach is planned to be tested under field conditions in collaboration with these stakeholders. A staged deployment outside certified cabin infrastructure, for example at boarding gates, will allow evaluation of detection robustness under real passenger flow conditions.

A structured data exchange with the airport operator will enable incremental refinement of the boarding time prediction models. By integrating operational passenger flow data into the existing modeling framework, the prediction models can be progressively trained and evaluated under realistic conditions while maintaining methodological consistency.

The immersive validation environment will be expanded to support multiple XR devices operating simultaneously. This will allow interaction between several virtual cabin users and physically present participants, thereby increasing experimental realism and enabling more complex interaction scenarios between virtual and real entities.

The cabin mock-up will be further enhanced by integrating realistic overhead compartments and additional sensor elements. Instrumented luggage compartments will provide supplementary cabin state information related to storage behavior and compartment utilization. This extension will enable evaluation of additional aggregated state variables beyond passenger position and luggage count.

Further work will continue to assess the scalability of the sensor architecture and to identify minimal and cost-efficient configurations that preserve detection stability while reducing system complexity.

Collaboration with airport operators and airline representatives will continue to ensure operational relevance and implementation feasibility. Engagement with stakeholders responsible for turnaround coordination and digital airport integration will support alignment with existing IT infrastructures and data governance requirements.

These activities aim to transition the system from laboratory validation toward applied research and pre-operational demonstration.

3.3 Lessons learned

The execution of the project provided several practical insights regarding the development of sensor-based cabin technologies within a small-scale funding framework.

First, the laboratory-based approach proved suitable for structured experimentation and controlled validation. The modular cabin setup allowed flexible adaptation of the physical environment and enabled repeatable test scenarios. At the same time, the absence of real aircraft cabin infrastructure required technical adjustments, particularly in the design of the localization framework.

Second, the integration of heterogeneous sensing technologies highlighted the importance of synchronization and data consistency. The implementation of a middleware layer for timestamp alignment was essential to ensure reliable real-time operation. Early attention to data integrity significantly reduced integration issues in later experimental phases.

Third, the combination of physical sensing and immersive visualization supported interdisciplinary collaboration. The mixed-reality environment facilitated validation and discussion of experimental results, particularly when interacting with external stakeholders. The XR-based representation improved transparency of the sensing architecture and process dynamics.

With respect to project management, the catalyst funding format enabled rapid prototyping and focused experimentation without extensive administrative overhead. The relatively compact project structure supported iterative refinement of the technical setup. However, hardware procurement constraints and coordination across institutions required careful planning and flexibility in adapting the implementation sequence.

The structured exchange with airport stakeholders during the project was valuable in aligning experimental design with operational considerations. Early dialogue supported realistic scoping and clarified practical deployment constraints.

Overall, the project confirmed that small-scale, targeted funding can effectively support the transition from conceptual research toward validated laboratory demonstrators. At the same time, scaling toward operational environments requires early consideration of infrastructure constraints, data governance requirements, and integration with existing airport systems.

4 Dissemination

The project results are being prepared for scientific dissemination through peer-reviewed publication and conference presentation.

A conference paper related to the developed sensing architecture and its application to boarding time prediction has been submitted for presentation at the ICAS Conference 2026. In addition, a journal manuscript focusing on sensor-based cabin state detection and its implications for boarding process modeling is in preparation for submission to Transportation Research Part C: Emerging Technologies.

Dissemination activities also included structured exchange with operational stakeholders. Meetings with representatives from Munich and Cologne/Bonn Airport were conducted to discuss implementation feasibility, infrastructure constraints, and potential pathways for field validation. These discussions informed the experimental design and the planned next development phase.

The immersive visualization setup developed within the project serves not only as a validation instrument but also as a demonstrator platform for presenting the sensing architecture and experimental results to external partners.

Further dissemination will follow the consolidation of extended experimental findings and potential field validation results.

5 References

5.1 Project outputs

Conference paper submitted to the ICAS Conference 2026: *Providing sensor information for boarding time prediction*.

Journal article in preparation.

EUROPEAN PARTNERSHIP
Co-funded by the European Union

6 List of acronyms

Acronym	Description
A-CDM	Airport Collaborative Decision Making
ATM	Air Traffic Management
SESAR	Single European Sky ATM Research Programme
TOBT	Target Off-Block Time
TRL	Technology Readiness Level
VR	Virtual Reality
XR	Extended Reality

EUROPEAN PARTNERSHIP
Co-funded by the European Union