Smart and Connected Aircraft Cabin: A Balancing Act between Operational Cabin Management, Airline Business and Passenger Expectations

Ralf God, Lothar Kerschgens, Leonardo Goratti, Steven Lemaire

Abstract—Ubiquitous connectivity is a reality and a basic need for users on ground. Air travel connectivity in the cabin is also becoming increasingly important for passengers during cabin use. Wireless sensor networks that provide information to cabin management systems are being used by airlines to optimize cabin crew workload. In networked cabin systems, communications and digitally transmitted data must be managed by airlines in every direction. Security and privacy, information processing and knowledge management are the current and future requirements for a smart and connected cabin.

Keywords—Smart and connected cabin management, Internet of Things, power management, airline business.

I. Introduction

As in all other industries, the mega-trend of connectivity and digital transformation [1] is unstoppably influencing the aviation industry [2]. The so-called digital revolution [3] marks a change triggered at the end of the 20th century that increasingly connects our real world with cyberspace. Digital transformation addresses the customer- and service-driven strategic business transformation that requires organizational changes as well as the implementation of digital technologies. The implementation of digital technologies takes advantage of the digitization and digitalization process. As specified in [3], digitization focuses on converting analog information into a digital form without changing the underlying process. In contrast to digitization, the digitalization uses digital technologies to transform and integrate analog processes into a digital workflow to provide value producing opportunities. This means that it is the automated process implementation which enables digital business operation as required by the digital transformation.

An example which illustrates the differentiation between digitization, digitalization, and digital transformation in aviation industry is given by the “Electronic Technical Logbook Case Study” in [4]. Today it is state of the art that airlines work with a paper driven Logbook which is used by the flight crew and as well by the cabin crew to report issues about the technical system status within the aircraft. A photocopy of this paper version is left on ground and is physically transferred to the maintenance staff so they can take the necessary actions to resolve the issues. This way of working represents a classic analog process. Following the description in [3], the process of digitization provides an application to the crew which enables them to document issues digitally. The information is stored locally and not further processed according to digitization criteria. The automation of the maintenance workflow by forwarding the digitized information is provided by the digitalization process. Furthermore, the process in this example enables the centralized storage of all given digital information to provide the ability of a historical overview. As the digital transformation intends to pursue new revenue streams, products as well as services and business models, the implementation of predictive maintenance provides such new service within the example. Predictive maintenance intends to determine the condition of in-service equipment by using historical data and condition monitoring in order to estimate when maintenance should be performed.

Table I provides an overview about the three introduced definitions digitization, digitalization and digital transformation.

TABLE I
Digitization, Digitalization and Digital Transformation Overview Based on [3]

Item	Digitization	Digitalization	Digital Transformation
Focus	Data conversion	Information processing	Knowledge leveraging
Target	Change analog to digital format	Automate existing business operations and processes	Change company’s culture, the way it works and thinks
Activity	Convert paper documents into a digital format	Creation of completely digital work processes	Transformation to a digital company
Example	Provide an app. For aircraft TechLog entries	Complete electronic workflow for aircraft maintenance process	Implementing predictive maintenance as new service

II. The Smart and Connected Aircraft Cabin

With the beginning of the digital revolution at the end of the 20th century, the Advisory Council for Aeronautics Research

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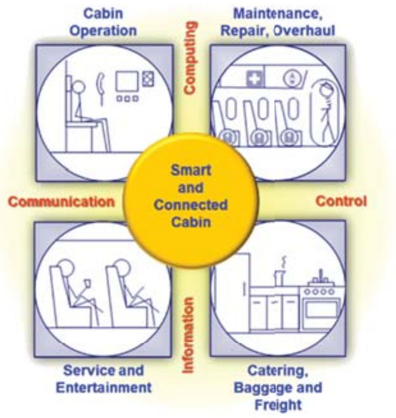

Fig. 1 Areas of interest in a smart and Connected Cabin

in Europe (ACARE) had been founded at the beginning of the 21st century [5]. In its first publication "European Aeronautics: A Vision for 2020" in January 2001 the Council addresses the five challenges for aviation in the upcoming years, i.e. 1. quality & affordability, 2. the environment, 3. safety, 4. air transport system efficiency and 5. security. Predominantly in 1. and 4. digitalization means were proposed to solve existing issues.

When focusing on the aircraft cabin four prominent areas of interest (cf. Fig. 1) are (a) safe and secure cabin operation, (b) maintenance, repair and overhaul (MRO) of the cabin, (c) catering, baggage, freight and other logistics in the cabin as well as (d) service and entertainment for the passengers.

Besides the classical systems and procedures for safe and secure cabin operations where the integration has to be certified by the authorities such as FAA and EASA, all the other areas could now benefit from ubiquitous connectivity emerging digital technologies without interfering with safety and security regulations of the authorities.

The well-known safety regulation CS-25.1309 "Equipment, systems and installations" of EASA (or FAR-25.1309 respectively) reads in parts as follows: (a) The airplane equipment and systems must be designed and installed so that: (1) Those required for type certification or by operating rules, or whose improper functioning would reduce safety, perform as intended under the airplane operating and environmental conditions. (2) Other equipment and systems are not a source of danger in themselves and do not adversely affect the proper functioning of those covered by sub-paragraph (a)(1) of this paragraph. [. . .]

The brand new security regulation CS-25.1319 "Equipment, systems and network information protection" of EASA [5] (on the FAA side there are currently only special conditions) on "airworthiness security", which was published in the middle of 2020, takes into account the new challenges of connected and digitally communicating aircraft systems and reads in part as follows: (a) Airplane equipment, systems and networks, considered separately and in relation to other systems, must be protected from intentional unauthorized electronic interactions (IUEIs) that may result in adverse effects on the safety of the airplane. Protection must be ensured by showing that the security risks have been identified, assessed and mitigated as necessary. [. . .]

The two certification specifications, CS-25.1309 and CS-25.1319, present challenges but do not stand in the way of developing a smart and connected cabin that helps solve the five ACARE challenges. Over the past two decades of this century, an extreme amount of technology has evolved and electronics have become increasingly miniaturized as part of the digital revolution. All of this can be harnessed for a smart and connected cabin, if only the two certification specifications mentioned above are considered.

The reason why this has not happened consistently to date may be that the aircraft manufacturer, i.e. the OEM, does not perceive the challenge of integrating such technology-based solutions as its core business. On the other hand, due to the complexity of such new technologies and digitally supported processes, the airlines and suppliers have not yet managed to integrate a comprehensive new platform for the smart and connected cabin, even though this would solve many of the existing challenges for the airlines' business. At the latest, however, with the current availability of Certification Specification CS-25.1319 for the security requirements, airlines and suppliers can now integrate their new business processes into the cabin and ideally support them with a digital platform solution.

Fig. 2 schematically describes such a preferred platform approach, which connects the certified systems and processes for cabin operation, i.e. safe take-off and landing, with the novel and future digitally supported business processes of the airlines. A well-known standard to assign aircraft systems to individual criticality levels is the so-called aircraft domain model which is specified in the ARINC standard ARINC 664 P5. It segregates systems for control of an aircraft in the ACD (aircraft control domain) from systems for airline operations in the AISD (aircraft information services domain). Furthermore, the systems for passenger entertainment and connectivity are assigned to the PIESD (passenger information and entertainment services domain) and the devices of the passengers themselves are summarized in the PODD (passenger owned devices domain). Typically, the systems for aircraft control have a high so-called design assurance level A (DAL A) whereas systems that are not needed for a safe flight – the in-flight entertainment (IFE) system for example – have a low level, e.g., DAL E in case of the IFE system. This aircraft domain model and the DAL classification are in line with certification requirements and serve to fulfill the CS-25.1309 and FAR-25.1309, respectively.

In Fig. 2 it is shown how the high-DAL systems which are indispensable for a safe flight must be protected against negative interference from lower DAL systems. Protective measures are typically physical isolation and measures for reliability are redundancy and dissimilarity. It is very expensive and cumbersome to develop high-DAL-systems, e.g., such as the flight control system. And Fig. 2 implicitly shows that new digital technologies and systems are only rarely developed for high DAL levels. From an architectures standpoint it therefore makes sense to safely and securely

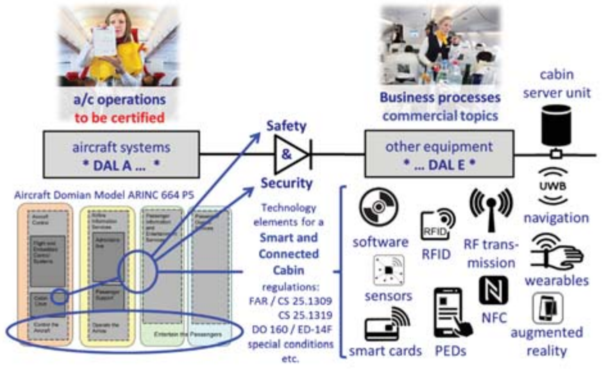

Fig. 2 System approach for safe and secure A/C operations and digitally supported airline business processes

separate such modern digital systems, which are required to support business processes in a smart and connected cabin, from the operating processes of an aircraft. In other words, the systems for a smart and connected cabin serving the airline and passenger comfort should be mapped to the ACD and/or PIESD and measures according to CS-25.1309, and, when communicating and connecting to other systems, measures according to CS-25.1319 have to be taken.

III. Technology Base for Cabin Operations, Airline Business Processes and Passenger Services

In contrast to systems and technologies in use for safe operations of an aircraft and operational cabin management, the technology base for smart airline business processes originates from the consumer market and follows the known trends on the ground in connectivity, microelectronics and embedded systems. Challenging systems to be certified for cabin operations are e.g., the cabin inter-phone for cabin crew communication, the passenger address system for announcements to the passengers as well as the smoke detection system in the cargo hold for detection of fire and smoke. These certified systems and related operating procedures are designed and implemented according to high DAL-levels which require elaborately qualified hardware and sophisticated development processes and tools.

Technology elements for a smart and connected cabin emerge typically from the consumer market. Fig. 2 shows an example of a respective selection with an onboard server unit, software, sensors, RFID tags, smartphones & PEDs, wearables, communication and RF transmission etc. Such elements can typically form a larger system or platform to support airline business processes or to provide new services to passengers. Corresponding technology elements, so-called Commercials of the Shelf (COTS), are usually not specially designed for use in a cabin environment. However, they can usually be well adapted for low DAL levels as ”other equipment”, so that they meet the requirements of CS-25.1309 paragraph (b). And this is exactly where the potential lies in digitally supporting airline business processes and offering passengers more comfort.

IV. Operational Cabin Management, Airline Business Processes and Passenger Expectations

The aircraft domain model in Fig. 2 clearly shows that functions required within the aircraft cabin can be divided into groups. For example, there are a few functions in the cabin that are directly related to the control of the aircraft. Strictly speaking, these are only those functions that are related to the power supply in the aircraft or that are required in the event of emergencies or other abnormal operations, such as fire and smoke on board. In addition, however, a whole host of functions exists in the cabin that is needed for the safe operation of a cabin occupied by passengers. If such functions should fail, this will lead to a reduction in safety margins when transporting the occupants, i.e., the risk that people could come to harm increases. Finally, there is a third group of functions targeting for passenger entertainment and services, which in fact have no influence on the safe take-off and landing of an aircraft. However, these functions are very critical from a commercial point of view, because no passenger would accept to complete a ten-hour flight without any entertainment and service.

The ARINC 664 P5 aircraft domain model was originally introduced and used to classify the criticality of functions and then to establish requirements for the development, reliability and certification of the systems concerned. In the meantime, a massive increase in airline support and passenger service functions has led to an expansion of the two domains for airline operations and passenger amenities in particular. Accordingly, there is an increasing overlap of functions in these two areas. Furthermore, due to this overlap of the adjacent domains, there is a stronger mixing of the criticality of these functions, and this especially from a commercial point of view what is not a part of aircraft certification. For example, passenger data processed electronically by the airline are critical with regard to the General Data Protection Regulation (GDPR). Electronic payment functions implemented via the in-flight entertainment system are critical with regard to Europay International, MasterCard and VISA (EMVCo) regulations. These developments make it very clear that there is an increasing balance act in the implementation of new functions for operational cabin management, airline business processes and passenger services and expectations.

V. Connectivity: An Enabler and a Security Challenge at the Same Time

In digital transformation the underlying mega trend of connectivity is a conditio sine qua non. Connectivity enables communication of data, information and knowledge. The immersion of physical systems of the real world into the cyberspace leads to cyber-physical systems (CPS) and connectivity allows CPS to form networks of cyber-physical systems of systems (CPSoS). Connectivity must be generated and shared between all stakeholders in the cabin and to the ground. Via connectivity and such type of a meshed CPSoS all the business benefits and passenger comfort can be reached. At the same time and with respect to “airworthiness security” of formerly isolated aircraft systems opening up cyberspace is like opening Pandora's box! Connectivity and the cyberspace instantaneously enhance the attack surface of a system and even if a system failure does not lead to loss of critical aircraft functions, a successful attack can cause a loss of trust and lead to commercial damage for the airline.

Because the technology elements and systems that support digitization in the cabin are typically communicating systems the certification specification CS-25.1319 "Equipment, systems and network information protection" for system integration gains equal importance than CS-25.1309 "Equipment, systems and installations". All interfaces and interconnections of a newly forming CPSoS have to be investigated and secured with respect to their vulnerabilities due to wireless or wired communication. It becomes challenging, for example, when a previously wired communicating system in a trustworthy aircraft domain intentionally or unintentionally gets in touch with another system from a less trustworthy domain. The resulting complicated architectures, for which risk management with regard to attack security must be carried out continuously throughout the life cycle, are very difficult to handle, so that future-oriented design methods of model-based systems engineering (MBSE) [6] and systems security engineering are being researched and used today [7].

VI. Communication Architectures in an Aircraft

Relying on Fig. 3, the German Government funded R&T program "LuFo-VI-2 i+s cabin 2.0" describes the activities of OEM and TIER suppliers. Current communication architectures in the aircraft cabin are mostly proprietary and limited to the boundaries of the diverging systems, i.e., existing cabin systems operate mostly isolated from each other. Modern system design, however, requires a shared communication platform in order to enable novel services by means of a contract-based data and information exchange.

Data-driven predictive maintenance applications are one example for which the fundamentals are studied intensively, but its integration into a multi-system environment with respect to communication requirements is often neglected. As the aircraft cabin is a highly dynamic environment with changing air pressure, humidity, temperature, and flight attitude, context information is needed in order to get meaningful predictions for e.g., the Remaining Useful Life (RUL) of a system, component or item.

Also, novel passenger-related services such as meal ordering from the seat with a passenger-, route- and inventory-specific menu require the exchange of information between multiple systems. These examples emphasize that the underlying communication protocols should handle a wide range of data update rates, amounts of exchanged data, and communication patterns such as fault-tolerant one-to-many and reliable one-to-one communication. In this paper, the requirements of contract-based multi-system information exchange are transformed into requirements for the communication protocols under development. These requirements include different paradigms for data exchange, access control, encoding, and addressing schemes. Addressing

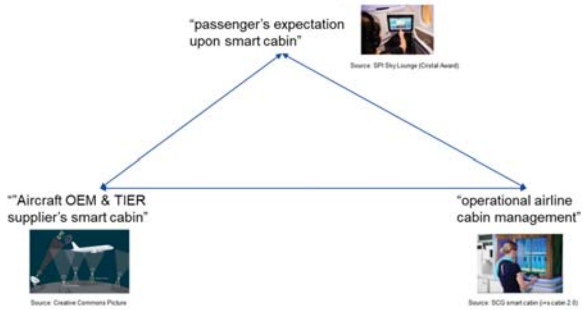

Fig. 3 Connectivity views at Connected Cabin from OEM, TIER, Airlines and Passengers

WP 2 - CABIN & CARGO SYSTEMS PARTICIPANTS

	CABIN DEMONSTRATOR: Enabling Technology	Leader	Core partner (when applicable)	Partners
ET1	New system architecture for data communication	DIEHL		SAFRAN SPI SCG
ET2	Cabin power conversion & power management	SAFRAN SCG		SAFRAN SCG SPI
ET3	Connected cabin equipment (seats, galley & trolley)	SAFRAN SCG		
	- Connected Seat		SAFRAN SSFR	SAFRAN SPI SCC
	- Connected Trolley & Galley		SAFRAN SCG	SAFRAN SPI SCG
	- PED Interfaces		DIEHL	

	CARGO DEMONSTRATOR: Enabling Technology	Leader	Core partner (when applicable)	Partners
ET4	Water & Waste system with re-use of water	DIEHL Aviation		
ET5	*Halon-free Cargo fire suppression linking to On-Board Inert Gas Generation System (cancelled)*	DIEHL Aviation		SAFRAN SAET

Fig. 4 Responsibilities for Enabler Technologies (ET) in ACCENT

schemes (IPv4 or IPv6) need to be designed carefully as software is deployed on network nodes in different cabin configurations, but may always process the same type of information, e.g., the state of all ovens in all the galleys [7].

VII. Architecture and Realization of the Connected Cabin View

SAFRAN Cabin Germany leads the European funded Program "Clean Sky 2 SYS Aircraft Cabin & Cargo Enabler Novel Technologies (CS2 SYS ACCENT)" handling "Connected Cabin". The ACCENT consortium partners are on SAFRAN side Cabin Germany (SCG), Cabin Controls (SCC), Passenger Innovation (SPI), Seat France (SSFR) and on Diehl Aviation (DAS) and Aerospace (DAG) sides. The main "Enabler Technologies (ET)" are shown in Fig. 4.

In order to reduce the involvement of cabin crews supervising passengers before take-off and landing for safety reasons, the cabin seat and luggage are on main focus. The optimization of the catering during flight is a main crew involvement as well. Therefore, the sensor-based data acquisition at Seats, Galley and Trolley installed in the Connected Cabin is demonstrated in the CS2 SYS ACCENT program. The Connected Cabin Demonstrator at SCG at a glance is shown in Fig. 5.

The cabin monuments are equipped with dedicated sensors within seats, Galleys and Trolleys. The sensor data are transferred via a data bus (e.g., ARINC664 or CAN) to a controller. In order to display seat relevant information to a Personal Electronic Device (PED), a gateway and an adapted Human-Machine Interface (HMI) are used, which is shown in Fig. 6. The figure shows in blue circles the connected seats,

Fig. 5 Connected Cabin Demonstrator at SCG

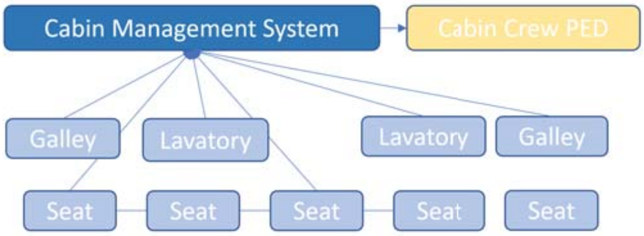

Fig. 6 Schematic Overview of the Connected Cabin

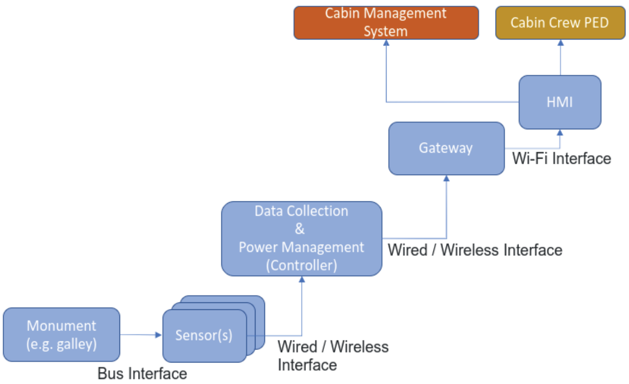

Fig. 7 Connected Cabin demonstrator architecture

with red circles the galley and the grey colored circle stands for the cabin management system. A more detailed architecture is shown in Fig. 7.

The centerpiece of the network is the gateway, which provides the network infrastructure of the connected cabin. All devices connected to the gateway are addressable either via an IP address or by their hostname. To do so, the gateway comprises DHCP and DNS servers as depicted in Fig. 8. The gateway provides three kinds of network interfaces: Ethernet, Wi-Fi and IEEE 802.15.4e and supports both IPv4 and IPv6 (to tackle the increasing number of sensors) addressing schemes.

Each network interface serves a different purpose:

- Ethernet: maintenance and backup solution
- Wi-Fi: PED
- IEEE 802.15.4e: IoT network

In addition, the gateway provides application hosting capabilities, which enables third parties to develop and host

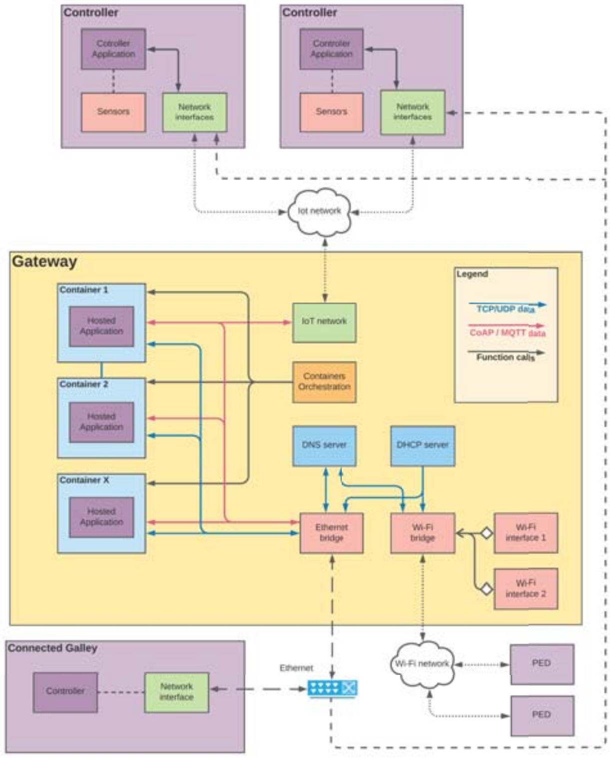

Fig. 8 Detailed architecture of the gateway

their applications on the gateway on secured and segregated containers and/or virtual machines. On the application layer, we use either CoAP (secured with Datagram Transport Layer Security - DTLS) or MQTT (secured with TLS) to transfer most of the monuments' information. For our use cases, all data sent by the controllers are sent to the gateway and gathered by one of the applications:

1) The data concentrator retrieves the data using CoAP.
2) Once collected by the data concentrator, the sensors' information is stored in another piece of software: the database application, which categorizes the data by seat number.
3) Finally, the last application exposes the sensors data to PEDs whereby a web server, which serves clients with an HMI page. The information is taken from the database App and displayed by the HMI. Moreover, whenever there is a sensor update, the HMI will display the new information.

Furthermore, each seat is equipped with a sensor module (SM) aggregating all seat sensors' data such as tray table, arm rest and seat recline positions, passenger detection and so on. The data are then sent to the seat row controller powered by the Seat Power Box (SPB) through a data bus or a wireless connection. Then, the controller forwards the data to the gateway for further processing.

The sensors, the controllers and the gateway require dedicated power management especially for the Galley, the Inserts and the Trolleys (see Fig. 7). Particularly,

Fig. 9 View into the Connected Cabin Demonstrator in SCG Herborn

the controllers include both gateway functions and power management functions.

VIII. Conclusion

On the way to a future smart and connected cabin, this paper describes the requirements that must be considered from a regulatory point of view when integrating systems with regard to safety and security certification. Accordingly, the current developments and results from the research project "Clean Sky 2 SYS Aircraft Cabin & Cargo Enabler Novel Technologies (CS2 SYS ACCENT)" led by SAFRAN are presented. The Institute of Aircraft Cabin Systems at the Hamburg University of Technology has been working on technologies for a smart and connected cabin since 2008. The focus is on the architectural design under integration and certification aspects. Due to the rising complexity and increasing cyber-physical nature of future cabin systems, the institute uses semi-formal languages such as the Systems Modeling Language (SysML) for a model-based Systems Engineering (MBSE) approach for system design. In particular, this considers system security engineering needs, which provides a means of compliance with the new security regulation CS-25.1319 "Equipment, systems and network information protection". Further joint research work and steps towards the model-based design of an overall architecture for a smart and connected cabin, which forms the basis for future simplified implementation and certification, will be part of future publications.

SAFRAN SPI introduced a first stage of the concept of "Connected Cabin" on AIX 2017 which was highly appreciated by Airline operators. The Clean Sky 2 application "Aircraft Cabin & Cargo Enabler Novel Technologies (ACCENT)" in cooperation with Diehl (DAS & DAG) had been contracted by CS2JU in 2018 and started in 2018. The Covid-19 restrictions had braked the R&T activities 2020 and 2021. However, the objectives had been achieved finally by starting up a demonstrator at SCG Herborn in July 2022.

The complete sequences from sensors to PED had been successfully presented. Fig. 9 shows a view into the "Connected Cabin" demonstrator.

There are further cabin monuments and installations which will be equipped by sensors and controller in order to integrate into the "Connected Cabin". The Lavatory, the Passenger Service Units (PSU) and the Overhead Bins are the next applications.

Besides the existing and certified cabin management processes the implementation of novel business processes and services within the aircraft by the airline requires a high availability of the process-related system functions to ensure airline's revenue and customer satisfaction. One approach to reach this target is the digital transformation of the aircraft cabin to improving maintenance, repair and overhaul processes within the aircraft cabin and tom offering an intensified passenger interaction with the cabin systems and the crew. Before certain digital support and service functions are implemented, however, it needs to be assessed where digitalization can achieve significant advantages for an airline and their customers.

To cope with that challenge, this paper describes authorities' prerequisites for a smart and connected aircraft cabin and how digitally supported maintenance processes for any cabin system can be systematically identified, evaluated and rated considering the added value/effort ratio. The evaluation result is recorded within a so-called digitalization scenario card to support transparency of taken discussions and the conservation of key parameters.

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