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Smart Cabin Design Concept for Regional Aircraft: Technologies, Applications & Architecture

Eduardo Leite Simões e Silva[1,*], Alison de Oliveira Moraes[2], Flávia Renata Dantas Alves Silva Ciaccia[3]

1.Departamento de Ciência e Tecnologia Aeroespacial – Instituto Tecnológico de Aeronáutica – Divisão de Aeronáutica – São José dos Campos/SP – Brazil. 2.Departamento de Ciência e Tecnologia Aeroespacial – Instituto de Aeronáutica e Espaço – Divisão de Eletrônica – São José dos Campos/SP – Brazil. 3.Embraer – Eve Air Mobility – São José dos Campos/SP – Brazil.

*Correspondence author: eduardolss.eng@gmail.com

ABSTRACT

The use of smart devices is driving the growth of modern systems markets, resulting in more technological cities, cars, houses, and airplanes. Therefore, it is important to understand which smart technologies can support or even fulfill stakeholder needs and consequently enhance airplane operation and increase product competitiveness for airlines. This paper is the second of two-part series and has as its main objective the study of smart technologies that can be implemented on cabins of regional airplanes, from 60 to 120 seats, to comply with the needs and requirements pre-established on the first part of this series of articles. The integration of those technologies results in a "Smart Cabin" architecture which its purpose is to enhances the passenger experience by granting a new level of cabin comfort, customization, and connectivity that allows the reduction of airplane time on ground because of the real-time monitoring of airplane cabin components that enables the prediction of maintenance procedures; creates new profits and revenues opportunities for services, provides a more sustainable airplane operation and derived services, and creates new business opportunities for all companies that integrate regional aviation ecosystem.

Keywords: Aircraft compartments; Design thinking; Smart devices; Passenger experience; High-level requirements; Stakeholder analysis.

INTRODUCTION

New technologies are increasingly being implemented in people's daily lives and with the growth of smart devices around the globe the users' needs and demands have changed in favor of more technological cities, cars, houses, and airplanes. Thus, it is just a matter of time for its utilization on the interior of the commercial airplanes to become a priority for the Original Equipment Manufacturers (OEMs) as Embraer, Airbus, and Boeing. This trading leads to a new type of concept named "Smart Cabin".

The "Smart Cabin Concepts" are examples of how technology can create a new line of customization for the passenger and the crew. These projects are also developed to be an airliner ally on aspects such as the operational routine of its airplanes, the reduction

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of crew workload, the easiness of the maintenance procedures that reduces the operational total cost and as well be benefited with more passengers satisfied when flying on airplanes with a brand-new technologic cabin that provides a more pleasant journey.

However, most "Smart Cabin" projects and concepts developed by OEMs and other aircraft companies are focused on widebody long-haul airplanes. Although, regional aviation can also be benefited from those types of technology. Thus, this paper is a study that aims the creation of a path for a new benchmarking on the "Smart Cabin Concept" to be implemented on regional airplanes. The following benefits are expected with the implementation of this concept on regional airplanes.

- Enhance passenger experience by granting a new level of cabin comfort, customization, and connectivity.
- Airplane reduction of time on ground because of the real-time monitoring of airplane cabin components that enables the prediction of maintenance procedures.
- Creation of opportunities for profit and revenue on services.
- A more sustainable airplane operation and derived services.
- Creation of new business opportunities for all companies that integrate the regional aviation ecosystem.

A better description about cabin comfort, flight experience and ambient immersion is presented by Vink (2014) "Part of experienced comfort is dependent on what the senses feel prior to the comfort experience. Additionally, the first visual interaction influences comfort as well." Therefore, it is important to consider that in addition to the technologies and its functionalities that are part of the Smart Cabin concept, to fulfill the objective of elevated cabin comfort, it is suggested to implement a design study of the cabin environment. Therefore, the objective of this article is to utilize the regional Smart Cabin High-Level Requirements presented in the first of this series of two papers to develop a High-Level System Architecture for regional aircraft and define which are the functionalities that are going to be implemented on a Regional Airplane Cabin. The next section will revisit the High-Level Requirements that are defined in Silva *et al.* (2023).

REQUIREMENTS

The first of this series of two papers is focused on obtaining high-level requirements for the Smart Cabin concept. The methodology used in this first article is based on the product development process presented in the NASA Systems Engineering Handbook (NASA 2016), this methodology is validated in several programs in the aerospace area, used worldwide and widely disseminated and known in the community. With the design phases and their respective outputs defined based on this handbook, design thinking tools are defined to assist in the search and definition of stakeholders, needs and, consequently, the high-level requirements, a phase defined as Pre-Phase A (Mission Concept Review) that will allow this second paper to reach Phase A (System Requirements Review).

In the first article, the possible stakeholders and their respective interaction with airplane cabin recognizing the needs of each stakeholder is identified, a perspective of the requirements from the Personas method is presented, the users' characteristics, necessities, activities, and its problems in each determined journey are determined, the captured data of each respective persona is organized by means of the utilization of the necessity map and the first version of the High-Level Requirements is presented and validated. After the validation of the requirements is provided, a method to identify which are the requirements with the higher potential opportunity to finally define the final High-Level Requirements is used. It is important to note that even the NASA Systems Engineering Handbook methodology (NASA 2016), then the Smart Thinking tools, are methods that can be used on various areas of research, applications, and projects. However, in this article, the focus will be on the application to a smart cabin concept aimed at regional aviation from 60 to 120 seats.

Thus, with the requirements defined, the first action is to separate those requirements into ten classes that comprise the main aspects of the Cabin: Cleaning, Communication, Entertainment, Accessibility, Connectivity, Environment, Safety, Boarding Service, Support and Cabin Comfort. Those classes represent which are the main aspects that are covered by the requirement and are presented on Table 1 with its requirements.

Table 1. Smart Cabin for Regional airplanes from 60 to 120 seats High-Level Requirements.

HLR ID	Final High-Level Requirements	Class
1	The cabin shall have tools that assist in the cleaning process.	Cleaning
2	The cabin shall have a system that enables the exchange of information between attendant and passenger.	Cabin Communication
3	The cabin shall have a communication system, attendant-pax and attendant-cockpit, accessible to the attendant on any part of the cabin.	
4	The cabin shall enable the battery charging and internet connection of any type of Personal Electronic Device (PED).	Entertainment
5	The In-flight Entertainment & Connectivity (IFEC) system shall allow the customization of its contents such as apps, language, theme.	
6	The cabin shall provide an immersion between the passenger and the cabin entertainment system.	
7	The aircraft shall have a compartment for the user's hand luggage that is easily accessible and helps on the luggage storage.	Baggage Handling
8	The aircraft shall provide uninterrupted connectivity during all the flight phases. [Excluding certification requirements that must be attended].	Connectivity
9	The cabin shall provide accessibility to users with any kind of disability: Physical, Sensory or Cognitive.	Flexibility
10	The cabin shall have a health environment for its occupants respecting air quality, humidity, pressure, temperature, contamination, illumination and noise.	Cabin Environment
11	The cabin shall have instruments to control the passenger cabin and the cockpit temperature separately.	
12	The cabin inboard systems such galley, lavatory, illumination, entertainment and cabin environment shall communicate with each other using a common language.	Cabin Tasks
13	The cabin shall assist on safety and security checks.	Safety Checks
14	The cabin shall assist the preparation and fulfillment of the on-board service tasks.	Boarding Service
15	The airplane shall have an exchange information system with ground support team to allow the filling of maintenance documents, and pre & post flight documents.	Support
16	The airplane shall transmit the components status data to the ground support team.	
17	The cabin shall provide means to elevate the space perception for its occupants.	Cabin Comfort

Source: Elaborated by the authors.

The next section will present research of technologies that was guided by the requirements of Table 1 and its respective classes.

TECHNOLOGIES

The next step of the work is to identify the main functionalities and trends that can be utilized on each of the ten classes, Table 1, and fulfill the Smart Cabin Concept High-Level Requirements. As in the first article, this paper utilizes the methodology described in the NASA Systems Engineering Handbook (NASA 2016) with the objective to define the concept and a baseline architecture – Phase A deliverables – to allow the validation of this architecture and its suggested technology solutions on the next development phases.

This article aims to generate a preliminary architecture with suggestions of technologies to be applied on it. There were studied more than 80 technologies, concepts, papers, and articles of solutions that could be applied on the final concept of the smart cabin, and the research was made mainly by internet surveys, since this work was developed when the COVID-19 outbreak was at its worst. Therefore, following on this article, there are going to be described only the solutions/technologies that have more accordance with the requirements considering its risk, entry into service, ease integration and implementation, elevated TRL and alignment of functionalities with high-level requirements. However, a few technologies that had a lower TRL are also suggested when the technology functionality justify its higher risk. Such TRL methods are presented by Fahimian (2017). In Silva (2021) is presented a detailed analysis of all the 80 researched technologies.

> Requirement 1 – *"Cabin shall have tools that assist in the cleaning process"*.
> There are four solutions that have functionalities able to satisfy Requirement 1. The Recaro Self-Cleaning Seats (Cahillane 2018), the Smarter Faucet (Cranfield University 2018), and the Zodiac Cleaning Light (Honeywell 2020) and the Honeywell UV Cleaning Light (Future Travel Experience 2020) are similar solutions.

- Recaro Self-Cleaning Seats: This solution is based on the seat impregnation with germ-killing disinfectants, allowing the seat to clean itself from determined germs, and for regional aviation, due to the high frequency of flights and passengers boarding and deboarding, this is a solution that reduces the cabin contamination. However, this solution must comply with the safety aspects such as the fire and smoke reactions.
- A Smarter Faucet: This solution is designed to atomize water, breaking it into a fine mist that comes fast enough to clean hands and allows lavatory users to use 90 percent less water. Another feature of the faucet is the possibility of its activation by a touchless sensor. With less water utilization, the water reservoir can be smaller, allowing an optimization of internal space.
- Cabin Cleaning Light: The concept is defined by the utilization of a cart with lights (e.g., UV) that could kill bacteria, viruses and superbugs on aircrafts seats and other exposed surfaces. However, there are two concerns about the operation, the first one is the needed time to clean the airplane, the other is the need to have an available cart in every airport.
- Future Technologies: Besides all those technologies and functionalities, there is one concept that requires more development to be available to OEMs implementation on airplane cabins. This concept is the Diehl Greywater Reuse Unit (Gavine 2020). This system takes handwash water (grey water) from the sink and uses it for flushing the toilet instead of using potable water.

> Requirement 2 – *"The cabin shall have a system that enables the exchange of information between attendant and passenger"*.
> There are two solutions that have functionalities able to satisfy Requirement 2, the Astronics next generation of passenger service unit (Astronics 2020a) and the SkyTab tablets (Future Travel Experience 2020).

- Astronics next generation of PSU: This solution could assist in the exchange of information between the attendant and passenger by providing means to call the attendant, send a message ordering food, or even request a specific service for crew. Those functionalities could speed up the boarding service, and, with the utilization of LED lighting, can reduce the power consumption.
- SkyTab Tablets: This solution is based on a tablet utilization by the crew that aggregate functionalities to assist in the communication with the passengers and pilots. The main benefits of this solution is an inflight sales software that allows passengers to do shopping and payments inboard, with the product availability being displayed in real time. This software also provides a communication with the supplier process to ensure highly efficient logistics, which assists the regional airlines operation. Another vital function of SkyTab is its utilization as a personal information hub for all cabin staff, as it allows access to all communication channels, providing all the necessary information for cabin crew with the information received from the passengers PEDs, PSU or Seat Displays.

Besides the utilization of tablets, there are also studies of a smart watch for collaboration amongst flight attendants that should attend to most of previous functions (Wong *et al.* 2017).

> Requirement 3 – *"The cabin shall have a communication system, attendant-pax and attendant-cockpit, accessible to the attendant on any part of the cabin"*.
> There are two solutions that have functionalities that are able to satisfy Requirement 3: the Astronics Cabin Management (Astronics 2020a) and the SkyTab tablets (Future Travel Experience 2020), that was previously described.

- Astronics Cabin Management: This is a fully integrated solution that allows the user to have control, on its own portable device, of the entire cabin systems such IFE, illumination, satellite TV, climate control and power management.

Requirement 4 - *"The cabin shall enable the battery charging and internet connection of any type of Personal Electronic Device (PED)"*.

There are three solutions with functionalities able to satisfy Requirement 4: The Astronics EmPower Solutions (Astronics 2020c), the Safran New Generation of A+C (Safran 2019), and the B/E Aerospace Solar Eclipse (Shu 2015).

- Astronics EmPower Solutions: There are different types of technologies that provide power for passengers' electronic devices (PEDs), such as Wireless Charging and High Efficiency USB Type-C PED. The electronic devices are important because many regional airlines utilize these devices to generate ancillary revenue through content delivery and wi-fi purchases.
- Safran New Generation of A+C: This new generation can charge the most types of personal electronic devices, including smartphones, tablets, laptops, etc.
- B/E Aerospace Solar Eclipse: This concept is described by its producer as "A window shade with built-in USB ports, and charges portable devices using sun power. Solar Eclipse is an affordable way for airlines to provide in-seat power to small devices, without installing standard power outlets." And it could be an excellent application for regional airplanes because this concept may be lighter than traditional charging systems.

Requirements 5 – *"The In-flight Entertainment & Connectivity (IFEC) system shall allow the customization of its content such as apps, language, theme"*.

Requirements 6 – *"The cabin shall provide an immersion between the passenger and the cabin entertainment system"*.

Both requirements, 5 and 6, are going to have its implemented technologies described together because the customization of IFEC is directly related with the increase of passengers' immersion and with the entertainment system. Therefore, focusing on requirement 5, two solutions have functionalities that can satisfy it: the first one is the Airtime Porta (Kim 2017) and the second one is based on Southwest Airlines Inflight Entertainment Portal (Future Travel Experience 2020). On the other hand, the following solutions: SmartTray (Astronics s.d.a), GemOne (Baldwin 2019), and Panasonic Concept of Travel as the fourth place (Panasonic Avionics 2019), satisfies both requirements.

- Airtime Portal: This solution provides a wireless in-flight entertainment system which would allow passengers to browse the internet, stream videos and read digital magazines on their own personal electronic devices. Characteristics that comply exactly with requirement 5 necessity and enable the passengers to utilize its own customized devices, Tablet, Notebook, Smartphone, to access aircraft IFE. The airlines can create different ways of monetization by the utilization of Airtime Portal such as sponsors, advertisements, shopping, stream, premier access, and more. The biggest implication of this technology is the necessity of a new system to provide wireless IFE inboard. Another implication is related to an aircraft that does not have seat displays, in this case, passengers without a PED are excluded from airplane IFE.
- Southwest Airlines Inflight Entertainment Portal: This solution follows the same path of the previous one, the improvements made by Southwest allows customers to stream inflight content without having to download an app before they board. Passengers can stream content directly to their smartphone, laptop, or tablet, using the carrier's IFEC portal. The same benefits and implications of Airtime Portal are applied here.
- SmartTray: This solution ease utilization of passenger personal device on flight, preventing damages and providing a better immersion with IFE, that is boosted when combined with solutions described early on for requirement 5. The only implication is the installation time and addition of weight.
- GemOne: The solution is a smart wireless handset that allows the passenger to operate IFE, cabin systems (light, gaspers intensity), order meals, make telephone calls, and more. This device is utilized more for those premium passengers and could be also utilized by passengers with disability (which complies with requirement 9 that will be described following in the project). The technology implications are the system's increased complexity and the integration of IFE and GemOne.
- Panasonic Concept of Travel as the fourth place: The concept of Travel as the fourth place incorporates both requirements, 5 and 6. This concept wants to converge affordable travel, exciting new destinations, and modern technology — all calibrated

towards giving passengers the most personalized approach to travel and connecting them from the pre-flight to post-flight. The biggest challenge of this concept is the integration of IFE with Passenger Personal Devices, making both systems work properly and fulfil their respective roles.

- Future Technologies: Besides all those technologies and functionalities, there is one concept that complies with both requirements, and if able to be implemented in the future, could help with the customization and passenger immersion of the airplane cabin. This concept is named as Enable[13] and utilizes the surface of the tray table as an interactive display that provides customized info and functions as an in-flight entertainment display. This concept can revolutionize the IFE systems and the cabin immersion; however, the concept has a technology readiness level too low to be implemented in the next few years because its maturation and availability will take some years of upgrading. Besides the entertainment part of the trip, there is a study to implement sensors on cabin seats that could measure physiological signals such as electrocardiogram, electrodermal activity, skin temperature, and respiration. This information can elevate passengers' immersion and allows an even safer trip for everyone on-board (Schumm *et al.* 2010).

Requirement 7 – "*The aircraft shall have a compartment for the user's hand luggage that is easily accessible and helps with the luggage storage*".
There are two solutions able to satisfy the requirement 7: The Zodiac Overhead bin (Kim 2017) and Astronics Smart Bin (Astronics s.d.b).

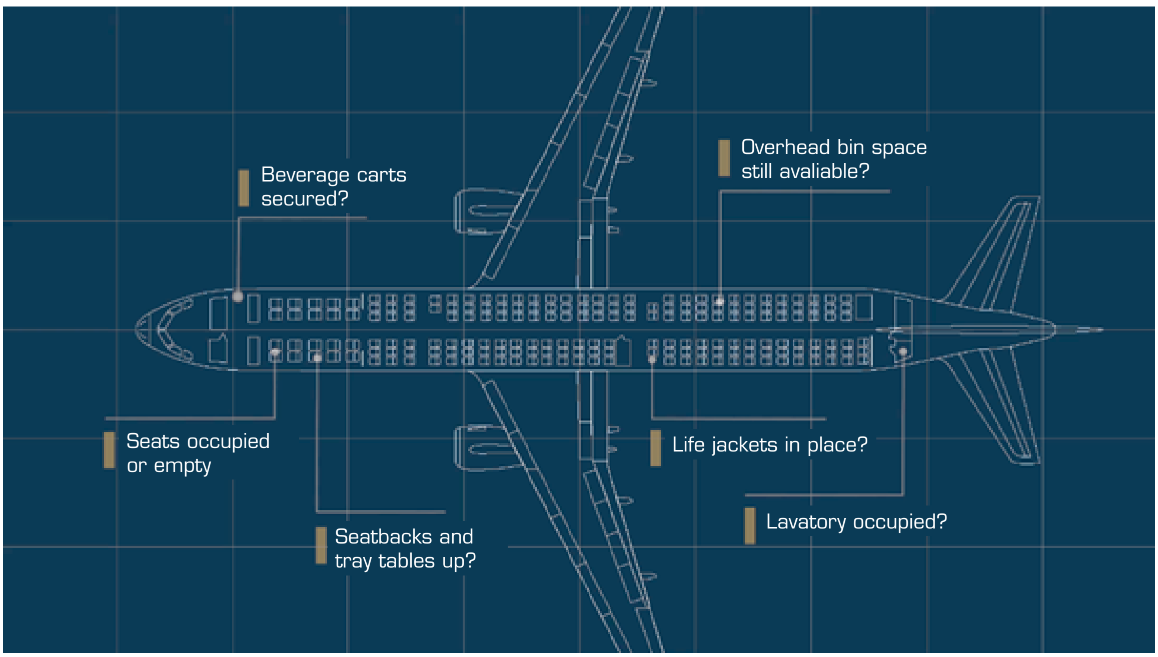
- Zodiac Overhead bin & Astronics Smart bin: The Zodiac solution is based on the utilization of a light sensor placed above the overhead lockers that will indicate the availability of free cabin baggage space. This solution will ease the cabin crew tasks during the turnaround time and could also assist with the identification of baggage forgotten by some passengers. On the other hand, Astronics system has the same objective of indicating bins availability but also has a feature that early detects outgassing from lithium-ion batteries, which increases the cabin safety.

Requirement 8 – "*The aircraft shall provide uninterrupted connectivity during all the flight phases*".
It is necessary to establish the premise that aircraft is able to communicate with the external environment (e.g. Internet access, ground support data exchange, etc.) utilizing systems as GEE (Gavine 2019) and Astronics E-Series (Astronics 2020b) utilizing its air-to-ground antenna or a satellite antenna, which complies with the High-Level Requirement 8. Another important systems trend that could be utilized is the Gogo 5G network (Lavotrel 2021). This technology will be available for business and commercial aviation and will be an air-to-ground network that utilizes Gogo's existing tower infrastructure. As explained by the company "Gogo 5G is the next step in our technology evolution and is expected to deliver an unparalleled user experience, pairing high performance with low latency and network-wide redundancy." The premise that "aircraft is able to communicate with the external environment" is necessary because the main goal of the project is not to study the technologies of data transmission, but how the data/information received or sent by the aircraft is utilized. With this premise properly explained, the features and technologies chosen to integrate the connectivity cluster of the smart cabin concept are going to be presented below.

Requirement 9 – "*The cabin shall provide accessibility to users with any kind of disability: Physical, Sensory or Cognitive*".
This requirement will always require improvement, however, when analyzing the actual airplane cabin, there are three solutions and concepts that will elevate the cabin accessibility: The Bluebox aIFE Platform (Bluebox s.d.), the Smart Sensing on the Aircraft (Astronics s.d.b), and the final one was already described on requirements 5 & 6, the GemOne (Baldwin 2019).

- Bluebox aIFE Platform: This platform is designed to enable users with visual impairments to appreciate aircraft IFE, making the airplane more accessible and with a more enjoyable trip. The only impediment for this technology implementation is that it requires a seat display. However, if it is possible to implement or install a feature with the same characteristics on users' personal devices, on an airplane PEDs friendly, the level of accessibility will also increase. Therefore, the implementation of requirements 5 & 6 are very important.

- Astronics Smart Aircraft System: The features of Astronics smart systems, Fig. 1, that draw more praise on the fulfilment of requirement 9 are: the seat occupancy, which assists on boarding and deboarding of passengers with reduced mobility, or visual impairments; the lavatory occupancy, that allows passengers on not spend time waiting to lavatory to vacancy, but also informs the crew if there is someone inside the lavatory and if this occupant need any sort of assistance; and bin status (if it is full or has space for more baggage), with this information, passengers could ask for help or even allocate luggage on other space. Other features of Astronics Smart Aircraft System are going to be described along the requirements.



Source: Astronics s.d.b

Figure 1. Astronics Smart Aircraft System.

- Future Technologies: Besides all those technologies and functionalities, there is one concept that complies with the elevation on the cabin accessibility, but it requires a major study on the airplane development because it affects the cabin design and the certification safety aspects. This concept is the Row 1 airport wheelchair system by Crawford (2019). This solution eases the accessibility of passengers with reduced mobility, and as described by its developer, "The Row 1 airport wheelchair system allows the passenger to use one seat for the whole journey, taking them all the way from the check-in desk to their destination airport and cutting down the number of seat transfers required. The seat is parked onto and strapped into the existing aircraft seat to allow quick and easy boarding and disembarking. The process is quick and simple, eliminating the concerns that many disabled passengers have of being watched while boarding and being lifted by crew members into their seats. The chair has been designed to be as simple as possible, with adjustable handles, armrests, and wheels for easy maneuvering. The design also features an automatic steering system that is controlled by the user, enabling PRMs to make their own way through the airport" (Techno Designers 2020). This concept, beyond the user benefits, can reduce the crew workload, simplifies the boarding/deboarding of passengers with reduced mobility and reduces the time spent on this action. Benefits that are very positive to regional airlines and its passengers.

Requirement 10 – "*The cabin shall have a healthy environment for its occupants respecting air quality, humidity, pressure, temperature, contamination, illumination and noise*".

There are three solutions with functionalities able to satisfy Requirement 10: the 3M Aerospace White Noise (Moskvitch 2014), VT Miltope Cyber Security (Gavine 2018), and the final one is composed by two solutions that have the same idea, the Astronics Illumination (Astronics 2020a) and Diehl Cabin Light (Diehl Aviation 2019).

- 3M Aerospace White Noise: The description of this concept is traduced by the comprehension that: "Jets that 'sound' better in the future that may not necessarily be quieter." Therefore, the concept focuses on the sound quality instead of just noise reduction, which differs in noise level than noise spectrum. This technology can improve the cabin environment and assists in passengers' relaxation during the flight.
- VT Miltope Cyber Security: With the increase of wireless communication inside airplane cabins and airlines encouraging passengers to bring their own device, it is necessary to implement solutions for a safe communication of cabin systems and passengers' personal devices. Therefore, the VT Miltope Cyber Security is a security software for wireless cabin networks that allows a safe communication for everyone inside an airplane cabin, including the aircraft systems.
- Astronics Illumination and Diehl Cabin Light: Astronics and Diehl are presenting different types of illumination with lower weight and high efficiency to be applied along all airplane, however, the solution that could assure the requirement 10 accomplishment for the illumination aspect from all those types of illumination is the Cabin Mood Lighting. This feature is a color changing light that could change in different scenarios, from simulating a daylight to a sunset to a sunrise, dinner atmosphere, or even a cloudy or starry sky. Besides these simulations, the mood illumination could also help on passengers' thermal comfort as presented on "The influence of colored light in the aircraft cabin on passenger thermal comfort" (Winzen *et al.* 2013). Thus, this technology, once implemented on airplane cabins, will provide a more comfortable environment for its occupants.

Requirement 11 – "*The cabin shall have instruments to control the passenger cabin and the cockpit temperature separately*".
For this requirement, there are some solutions that utilize manual gaspers on PSU and cockpit to increase or reduce the air flow and they consequently reduce or elevate the temperature. However, based on the studies done before and the technologies research, one solution that will comply with requirement 11 is the utilization of temperature sensors placed on selected positions all along the cabin that will have the function of transmitting its status to a central Aircraft Database. Therefore, another computer will analyze the data – Decision Making algorithm – and if it is necessary, actuate on the air flow to control the cabin and cockpit temperature according to information set by the crew on the CMS. The implementation of this solution could affect the internal system complexity such the AMS, IFE, PSU, but on the other side, this solution brings benefits to a regional airplane cabin such as the elevation on cabin comfort by better temperature control (especially in airports with extreme temperatures – low or high) and can also elevate the efficiency of the air conditioning system, allowing the system to spare power on some occasions.

Requirement 12 – "*The cabin inboard systems such as galley, lavatory, illumination, entertainment and cabin environment shall communicate with each other using a common language*".
There are three technologies with functionalities that can satisfy Requirement 12: the Diehl Aerospace Power Line Communication (Kim 2017), the Ultra-wideband (Schmidt *et al.* 2021), and the final one is the 5G application on the Aviation Industry, the Gogo 5G Network (Lavotrel 2021) that was already presented on Requirement 8.

- Diehl Aerospace Power Line Communication: The Diehl concept utilizes aircraft's power distribution cables to also distribute network; thus, one cable will be providing both power and data. This solution offers a significant reduction in aircraft wiring, weight, and volume, allowing less consumption of fuel and cable material with a more sustainable operation.
- Wireless and Intra-Aircraft Network: The Ultra-wideband utilizes electromagnetic pulses to establish a communication between two or more components. Therefore, "Wireless Connectivity in Airplanes: Challenges and the Case for UWB" shows that the increase on wireless solutions for on-board communication and the challenges of aircraft industry such as safety, reduction on aircraft costs, lower environmental impact, passenger entertainment services availability and the application of

UWB on smart components installed all along the cabin, allows a unique tradeoff between power consumption and data rate for intra-aircraft communication.

- 5G on Aviation: In addition to the Gogo solution, the 5G brings to aviation industry many more innovations, some of those are presented in the article "What Will 5G Bring to the Aviation Industry?". For example, Lufthansa is utilizing the 5G to enable collaborative virtual engine inspections between engineers at its shop in Hamburg and customers in other locations. There are concepts that Unmanned Traffic Management (UTM) increasingly defined by civil aviation regulators on a region-by-region basis, 5G could serve as a mean for data and information sharing between drones or electric air taxis, air traffic and wireless network service providers in the future. Also, 5G could assist in the internal communication of components disposed all along the airplane cabin (Garrett-Glaser and Bellamy 2020).

> Requirement 13 – "*The cabin shall assist on safety and security checks*".
> This requirement is satisfied with the implementation of two solutions: the Airbus's WAIC (Kim 2017) and Safran AISEE (Verpraet 2019). Also, the Astronics Smart Aircraft, presented on Requirement 9, will assist on Requirement 13 fulfillment by allowing cabin crew to know if all seats, trays, windows, and seat belts are in position to takeoff or landing.

- Airbus's WAIC: The Wireless Avionics Intra-Communication (WAIC) offers the possibility of utilizing smoke detectors, lighting and temperature regulation controlled by radio frequency, without the necessity of cables. Also, there is a study of airborne wireless sensor network for an airplane monitoring system that can be composed by temperature and humidity sensors, vibration sensors, strain sensors, piezoelectric sensors, and RFID sensors (Gao *et al.* 2018). Therefore, without the necessity of cable utilization, many concepts that utilize sensors will benefit from this solution with a lighter system that could fulfill different functions. The biggest obstacle of this solution is to ensure that this communication will be safe and secure.
- Safran AISEE: This solution utilizes information from inside the cabin to identify and recognize situations that need attention: spotting suspicious behaviors such as aggressiveness, passengers that are lying down the aisles, or if an obstacle is blocking an important access or emergency door. Thus, this technology elevates the security for airplane occupants. However, the biggest implication is the system's robustness to identify the cited situations.

> Requirement 14 – "*The cabin shall assist the preparation and fulfillment of the on-board service tasks*".
> This requirement can be satisfied with the implementation of three solutions: the Airborne Cooking Robot[27], the ReTrolley (Kim 2017), and SAFRAN Modernized Galley (Verpraet 2019).

- Weigele Aerospace Airborne Cooking Robot: The Airborne Cooking Robot is an energy-saving oven that allows cold and warm food to be prepared on one plate at the same time. This solution can speed up the work of the ground crews that prepare the food, but also assists the flight crew on meals preparation and on the boarding service. Furthermore, it is possible to utilize less material for different food preparations (only one plate for warm and cold food), which is more ecologically sustainable.
- SAFRAN Modernized Galley: Safran modernized galley is composed by several smart components and functionalities. The first interesting functionality is its connection with other cabin systems, for example, the galley works on a connected "IoT" version that can communicate with passengers IFE allowing the galley to start to heat up food autonomously. Another feature of the modernized galley is a cooled compartment that does not require a separate chiller, and especially for short-haul flights (Regional Airlines), the noise and weight of the chiller is not desirable. This compartment is approximately half the weight of a regular chiller, it is also completely silent, and the temperature can be controlled through the integrated tablet. The last feature is an electroluminescent paint that can be used in all compartments that need some illumination but don't require bright lights. This paint lights up by itself without using any power, allowing a reduction on power, less cabling, and a simplified galley system, all those benefits turn the airplane operation more sustainable.
- ReTrolley: The solution design features a trolley that could recycle and compress the airplane occupants' rubbish as it passes through the aisle. This solution can replace the standard bin trolleys, reduce the aircraft's total waste volume by 30 per cent, reduce up to 30kg in equipment weight without the use of electronic compressors and free up space in the galley. For regional

airlines, this reduction in volume and weight could benefit the operation. Also, the ease of carrying the trolley through the aisle and the compress done along the way will help on the crew tasks.

> Requirement 15 – *"The airplane shall have an exchange information system with ground support team to allow the filling of maintenance documents, and pre & post flight documents"*.
> The solution able to satisfy the requirement 15 is the Electronic Flight Bag (EFB) (ANAC 2020). This technology has a high level of maturity and is utilized on commercial airplanes like Embraer E2 with many advantages such as: the possibility of the display of a variety of aviation data, the performance of basic calculations, the functionality of host databases and applications including the functionality of the requirement. Also, there are technologies that allow an expansion of EFB to enable a large interaction with ground support (Allen 2008). It is good to empathize that all those functionalities are done without the utilization of paper, which makes this technology greener and easier to organize. The only implication on the technology implementation is the necessity of electronic connections, which can increase system complexity.

> Requirement 16 – *"The airplane shall transmit the components status data to the ground support team"*.
> There are two solutions with functionalities that are able to satisfy Requirement 16: the Software as a Service – SaaS (Panasonic Avionics 2019), and the Aircraft Health Analysis and Diagnosis – AHEAD (Fly Embraer 2010).

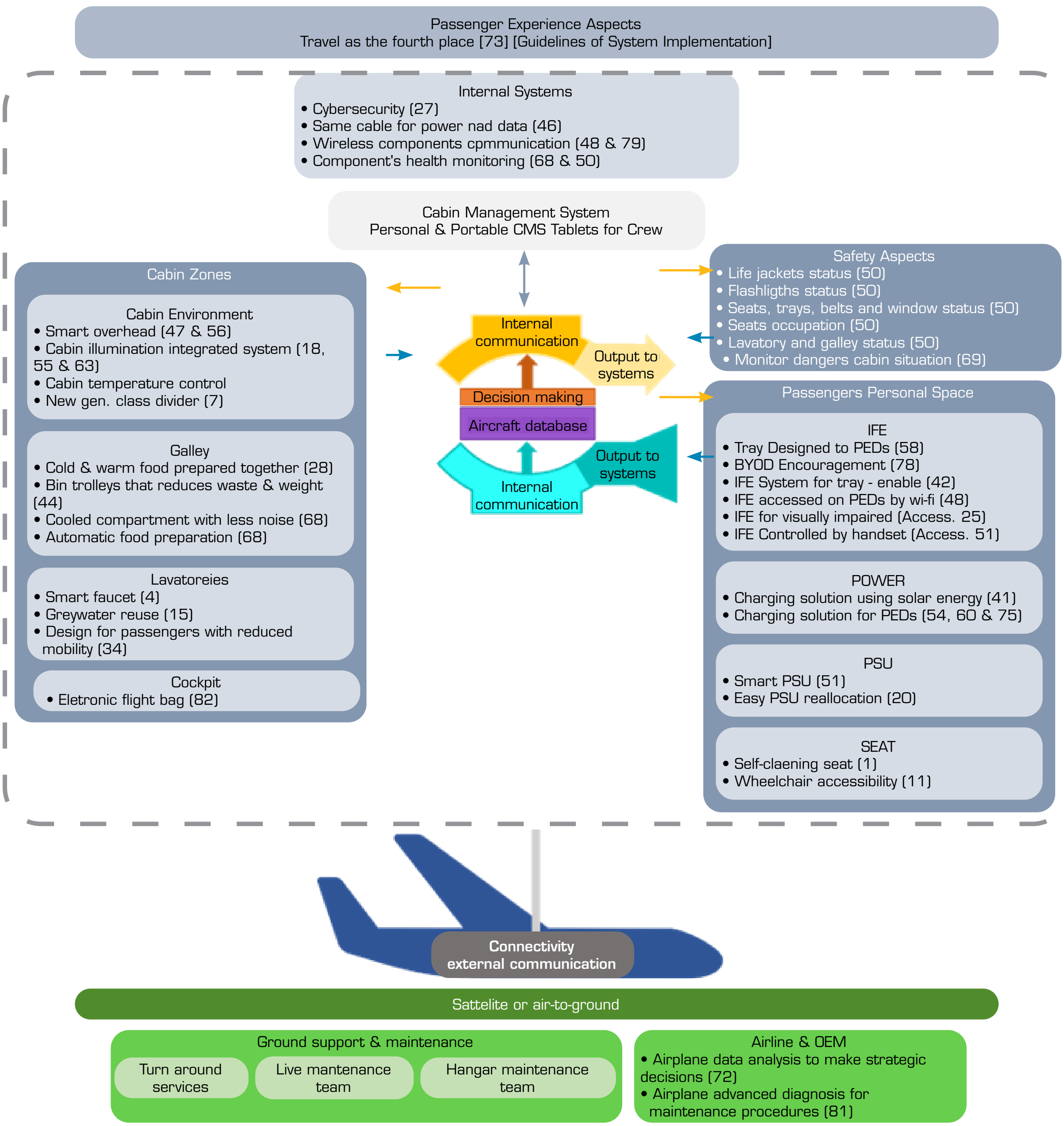
- Software as a Service – SaaS: This technology, as described by its producer, analyses data in real-time from many of the aircraft systems such as IFE, Connectivity, Location, Weather Monitors, etc, to provide airlines actionable insights. With this information, airlines could make smarter business decisions, improve passenger experience, make operational savings, pre-empt maintenance needs and ultimately drive additional revenue.
- Aircraft Health Analysis and Diagnosis – AHEAD: The AHEAD solution offers an advanced diagnosis of the airplane health and provides an effective troubleshooting to operators on daily occurrences. Based on data extracted from the airplane, the responses are ruled by an integrated technical publication and specialists' decisions. The data extraction could be made by an SD card or even by an automatic transmission via wi-fi or satellite network.

> Requirement 17 – *"The cabin shall provide means to elevate the space perception for its occupants"*.
> There are two solutions that support the requirement 17 and does not require many physical changes in the cabin, the AerQ' class divider concept (Pallini 2020) and the Experience Line Bridge (Gavine 2020).

- AerQ' class divider concept: The main idea of this class divider is to give the aircraft a more open feeling but it also gives airlines more room for additional seats. Besides these benefits, the concept introduces the possibility of showing selected media on those dividers, allowing airliners to create auxiliary revenues. Both benefits are applied on regional airlines that have smaller airplanes with reduced internal space. The implications of this solution are the safety requirements, the increase in systems complexity, and for airplanes with a narrow cabin width and a longer length, the absence of a barrier can cause discomfort in passengers due to a tube sensation.
- Experience Line Bridge: The solution is an integrated system cabin that combines cabin surfaces, image projection and cabin lighting to space up the cabin and create a new flight experience for occupants. This system could expand the situational ambient for smaller airplanes such as the regional ones utilizing more efficient systems that those utilized before. For example, on "Financial Analysis of an Illumination Retrofit for Regional Aircraft" (Guimarães *et al.* 2021), it is possible to understand the benefits of LED illumination, which offers high durability, energy efficiency and luminosity. Despite its high initial price, it has many advantages, and the operational cost is lower than other types of illumination, such as fluorescent lamps. Therefore, in some cases, airlines should consider the possibility to make an illumination retrofit to LED lamps, because weight is directly correlated to the fuel consumption and operational costs and the energy economy can bring new improvements to the aircraft. Benefits that are fully correlated to the Experience Line Bridge, however, one of the implications of this solution implementation is the elevation in system complexity and the initial investment cost.

ARCHITECTURE

Guided by the market study that considered all the needs and desires of the stakeholders, it was possible to identify and select the technologies that enable the passenger's cabin to comply with the elaborated requirements. Thus, with the technologies, concepts, and functionalities chosen, it is possible to develop a diagram of the concept of High-Level Architecture, Fig. 2. This diagram presents all systems clusters with their respective technologies, concepts, solutions, functionalities and summarizes the smart cabin operation through all airplane ecosystems.



Source: Elaborated by the authors.

Figure 2. Smart Cabin for Regional Airplanes: Final Architecture Detailed Architecture.

Internal Communication

In the center of the diagram, it is located the Internal Communication cluster that is composed by data Input, data Output, Aircraft Database and Decision Making. This cluster is responsible for organizing the system data sharing by providing a common platform for all smart devices to send their data. The platform integrates this data, process it, analyzes it and, finally, returns it to devices commands or status that are valuable for system operation. This operation can be compared with an IoT system that works from inside the airplane.

Cabin Management System

The Cabin Management System, or CMS, is the main component of Smart Cabin architecture backbone. This component aggregates the cabin smart systems monitoring and controlling functionalities that are available because of the possibility to send and receive data from all cabin components though the internal communication system. Therefore, cabin crew will be able to understand the aspects that surround the airplane operation to make possible the optimization of cabin tasks, reduction of crew workload, reduction of airplane's time on ground, and elevation of passenger experience.

Systems Functionalities

The systems functionalities and characteristics that are connected to CMS and compose the smart cabin concept are presented on the right side of the diagram.

Passenger Experience Aspects

The first one is the Passenger Experience Aspects. This cluster includes concepts focused on Passenger Experience toward a seamless journey for travelers, these concepts influence how smart cabin components are going to be integrated into passenger journey.

Internal Systems

The second aspect is Internal Systems. This cluster is composed by all the technologies that are utilized i n the system as a path to reach the final objective. For example, one of the chosen functionalities is a cybersecurity system, this feature is utilized to elevate the security of PEDs utilization, but it also ensures the security of airplanes systems that utilizes wireless communication. Another important functionality is the possibility of monitoring the health of cabin components/systems. This feature will optimize airplane operation and maintenance procedures because it will be possible to predict when a certain component will have to be replaced, or even if a component fails during the flight. Therefore, the maintenance team will always be prepared to act.

Safety Aspects

The third cluster is the Safety Aspects. This cluster involves all the features that are going to be utilized in the increase of safety and ease the tasks that must be performed by the crew. For example, the monitoring of safety equipment status and health (life jackets, flashlights, boats), the right position of seats, trays, belts and windows for takeoff and landing, cabin seats occupation to allow the right weight distribution. Therefore, with cabin crew understanding the whole cabin status, they are capable to optimize cabin tasks and focus on zones that require attention.

Passengers' Personal Space

The fourth cluster approaches the Passengers' Personal Space. This cluster unites all functionalities that include the passenger personal space; thus, this personal space was divided into four categories: In-flight Entertainment and Connectivity (IFEC), Power, Passenger Service Unit (PSU) and Seat.

For In-Flight Entertainment and Connectivity, the main functionalities are correlated to passenger Personal Electronic Device (PED), since there are several regional airlines that encourage passengers to "Bring Your Own Device" (BYOD). The main functionalities are a tray designed to assist passengers on utilization of PEDs, the cabin internal IFE system that allow passengers to have wireless access to IFE utilizing its personal electronic device and a concept called Enable, that utilizes airplane trays to create an entertainment environment for passengers. There are two other functionalities that enhance the passenger experience for visually impaired passengers and passengers with accessibility limitations. Lastly, the IFE customization allows airlines to generate revenue in advertisements and publicity by capturing passengers' preferences on personal devices. However, with the growth of passengers' personal electronic devices and the aircraft IFE based on its utilization, it is important to keep these devices charged. Thus, the functionalities utilized on cabin aircraft to power up the devices are the utilization of solar energy to charge small electronic devices by the USB outlet, a new generation of lighter energy outlets and the utilization of wireless chargers that ease passengers to keep their devices charged and working. On the other hand, the passenger service unit functionalities go from the possibility of passengers to order food and call an attendant, to the capacity of controlling aspects of the personal space environment such as temperature and illumination. Finally, the passenger Seat is where each passenger will pass the most time of trip, therefore, it is important to feature the self-cleaning material that could eliminate germs and assist with cabin cleaning. Another important feature that enhances the experience for passengers with limited locomotion is a row on cabin that allows a wheelchair to be easily attached and detached.

Cabin Zones

The fifth cluster is Cabin Zones. This cluster links the functionalities of all four categories of cabin zones, Galley, Lavatories, Cockpit and Cabin Environment, that includes cabin illumination, cabin air management system, temperature, overhead bin, cabin floor, and other spaces that are not covered by the other three zones.

For Galley, the main functionalities are related to crew tasks such as easiness on food preparation to optimize cabin crew time, lighter trolleys that reduces crew physical effort, reduction on cabin waste that makes the aircraft's operation more sustainable, and reduction on noise to provide a more comfortable ambient for occupants. On the other hand, Lavatories utilizes functionalities that reduce water waste and weight of water tanks by Smart Faucet and Greywater reuse solutions. Thus, the re-design of lavatories can enhance the experience for passengers with reduced mobility. For Cockpit, the application of an electronic flight bag reduces paper waste, optimizes cabin documents fulfillment and cockpit operation by reducing pilot workload. The Cabin Environment utilizes distributed sensors all along the cabin to monitor and control many aspects such as overhead bin capacity, cabin illumination and cabin temperature.

External Communication

Another aspect of the diagram is the External Communication box. This communication is utilized as a mean of access for external networks such as ethernet for passengers. This communication is also necessary to allow information exchange between Airline/OEM ground stations and airplanes. This channel of communication will allow airlines to anticipate and program maintenance procedures. Also, airlines will make strategic decisions that are going to optimize the whole aircraft fleet operation reducing unnecessary expenses. Therefore, the processes of data analytics, data processing, maintenance planning, spare parts, etc, could result in earns to OEM, creating gains in services and opening a new niche of product.

CONCLUSION

The utilization of Smart Things on airplane cabins has been growing over the last years with the development of new technologies that improve airplane operations by reducing time of cabin tasks, turnaround time tasks and assisting on maintenance planning. Besides those benefits, the implementation of smart components in the cabin brings a higher implementation cost, increases the complexity of systems, and requires constant monitoring of their functions, but it also enhances passenger experience and contributes to a more sustainable operation. Therefore, to achieve and validate these conclusions it was necessary to understand the Concept High-Level Requirements developed on Silva *et al.* (2023), which were defined based on the needs of the stakeholders involved with the cabin of a regional aircraft, and organize each requirement into ten classes: Cleaning, Communication, Entertainment, Accessibility, Connectivity, Environment, Safety, Boarding Service, Support and Cabin Comfort. Those classes are going to be the concept focus.

Following, a research of all existing technologies, functionalities and concepts that could be utilized to satisfy the High-Level Requirements was done. Then, the system architecture was developed along with the definition of which are the functionalities that are going to be implemented on Smart Cabin Concept. The definition of these technologies considers the benefits and implications that each functionality brings for the concept. After all studies, it is possible to elaborate a diagram that represents the architecture and operation of the "Smart Cabin Concept for Regional Airplanes", Fig. 2. Lastly, making the connection between High-Level

Requirements classes and the final architecture, it is possible to demonstrate the requirements fulfillment and its benefits for stakeholders when utilizing the Smart Cabin Concept on Regional Airplanes summarized as follows:

- Cleaning: The implementation of new technologies on lavatory, self-cleaning seats, lighter trolleys that reduces cabin waste and cabin cleaning lights will provide to a regional airplane the capacity to reduce crew workload, the weight of the water and the number of germs inside the cabin. Therefore, the time needed on cleaning tasks will be lower, with a less utilization of water, the airplane uses less fuel or can transport more cargo, thus, the cabin will be cleaner for passengers.
- Communication: With the utilization of personal and portable CMS tablets by cabin attendants and the installation of smart PSU on passengers' personal space will ease the exchange of information between passengers and attendants. Also, attendants will be able to know cabin components statuses on the palm of their hands, allowing cabin crew to be more effective on the accomplishment of cabin tasks. On the other hand, the implementation of cables that can be utilized for transporting data and power, and the possibility of wireless data exchange between cabin components allows a reduction on weight related to cabling and ease cabin assembly and retrofit.
- Entertainment: With the encouragement for passengers to bring their own device, the cabin system utilizes wireless communication to allow passengers to have access to In-Flight Entertainment on their PEDs. Therefore, the smart cabin enables PEDs utilization by providing trays designed to accommodate those devices and powering up personal devices with the implementation of a new generation of charging solutions that includes wireless chargers and solar energy USB outlets. These technologies implementation elevates IFE customization, enhances passengers experience and reduces weight, which allows a more sustainable operation with the reduction of fuel burn and without the necessity of spreading cables all along the cabin. Also, a more customized IFE creates new opportunities for revenues and services.
- Accessibility: The implementation of technologies such as an IFE controlled by handset and an IFE developed for visually impaired passengers makes airplane cabins more integrated and accessible for every occupant. Also, the research developed during the project highlighted the importance of having a cabin more accessible to wheelchairs, which enhances passenger experience by assisting the boarding and deboarding, but it also reduces airplane time on ground.
- Connectivity: Enabling the connectivity with external networks is essential for the operation of the smart cabin concept. Therefore, technologies like the GEE, Astronics E-Series and Gogo 5G Network allows airplanes to receive and send data on all flight journeys.
- Environment: By implementing a system to control cabin temperature, the internal comfort is improved. Also, monitoring the overhead bin with a smart system allows cabin crew to organize baggage allocation and brings agility on boarding and deboarding.
- Safety: The monitoring status of safety components such as life jackets availability and flashlights charging, makes the airplane operation even more secure in case of an emergency. Thus, cabin crew will be able to know if seat belts are fastened, if galley components are locked, if there is someone needing help in the lavatory or even if airplane's seats occupation could disturb airplane weight distribution. Also, safety functionalities allow cabin crew to make sure if seats, trays, and windows are in the correct position for takeoff and landing, functions that reduce attendant's workload, optimize cabin operation and elevates client's confidence on the final product. On the other hand, smart cabin concept also includes a cybersecurity system that will protect passengers' personal devices, but also cabin internal components from threats.
- Boarding Service: The implementation of solutions that integrate galley components to aircraft systems ease cabin crew tasks and reduce its workload. Another solution that fits perfectly with regional airplanes is a utilization of a cooled compartment that reduces internal noise, reduces energy spent and reduces weight. These aspects improve acoustic comfort and help on a more sustainable operation with a lower energy expenditure.
- Support: The utilization of sensors to monitor essential cabin components of galley, illumination, lavatory, IFEC, and other systems, allows airline and OEM to make strategic decisions and an advanced diagnosis of an overall cabin health. Thus, it will be possible to improve maintenance planning, shorten time of problems identification, reduce time on ground due to the increased support agility and create new business opportunities for services, making the airplane operation more profitable for airlines.

- Cabin Comfort: With the implementation of functionalities that allows a seamless journey to passengers, e.g., the IFEC systems cited before, an integrated illumination system, eased communications between passengers and attendant, application of travel as the fourth-place ideas, etc. turns the flight journey something usual, and free of headaches. These aspects make flight trips a more pleasurable event for those who are using it for work, traveling on vacation, or are part of airplane operation. Therefore, the previous characteristics enhance cabin comfort for all occupants, allows a seamless journey, help on gaining new customers and keeps regular clients satisfied.

The concept of Regional Smart Cabin enhances passenger experience with the elevation of comfort, connectivity, accessibility and entertainment. Still, the architecture reduces airplane time on ground with operation optimization, turning the airplane operation more sustainable. Also, the "Smart Cabin" creates revenue opportunities for airlines together with new business opportunities for all stakeholders involved in the regional aviation ecosystem. Thus, because of all the previous benefits, the concept elevates product value for its stakeholders allowing OEM to increase client's confidence and satisfaction.

Finally, it can be highlighted that the utilized methodology not only presents solutions aimed at establishing high-level requirements based on the concept of a "Smart Cabin" for regional airplanes from 60 to 120 seats, but also provides a method for developing and validating market requirements for application in the most different systems and functionalities.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Silva ELS, Moraes AO and Ciaccia FRDAS; **Research:** Silva ELS; **Methodology:** Silva ELS, Moraes AO and Ciaccia FRDAS; **Project administration:** Silva ELS and Moraes AO; **Validation:** Silva ELS; **Writing - Preparation of original draft:** Silva ELS; **Writing - Proofreading and editing:** Moraes AO and Ciaccia FRDAS

DATA AVAILABILITY STATEMENT

This study did not involve the use of any specific dataset.

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