Investigating the Flexible Hydrogen Aircraft System Interface Design using the XR Co-Design Approach

F. Reimer[1], M. Fuchs[1], J. Herzig[1], S. Cornelje[1], J. Biedermann[1] & B. Nagel[1]

[1]Institute of System Architectures in Aeronautics, German Aerospace Center e.V. (DLR), Hein-Saß-Weg 22, 21129 Hamburg, Germany

Abstract

On the road to climate-neutral aviation and the achievement of global climate targets, research into hydrogen-powered propulsion systems is increasingly playing a key role for the industry. Despite a number of advantages over conventional propulsion systems, the development and integration of this technology is extremely complex and poses a particular challenge for the cabin. Novel propulsion systems must fulfil a variety of regulatory, industrial and economic stakeholder requirements in order to ensure the safe and efficient operation of new aircraft concepts. In addition, new system components and their interfaces to the subsystems in existing and future aircraft concepts must be understood in order to significantly reduce time-consuming and expensive development cycles. As part of its research focus, the German Aerospace Center is therefore developing methods for the digital development and evaluation of future cabin concepts.

Within this context, technologies such as XR (eXtended Reality) are playing an increasingly important role and offer numerous opportunities to experience new concepts immersively, map information and translate requirements together with user groups directly in virtual models. This allows a virtual, collaborative, and immersive real-time integration of novel system interfaces in conjunction with key stakeholder groups (co-design).

Therefore, the following paper addresses how collaborative and immersive virtual reality modeling can be used to design flexible and requirement-specific interfaces for innovative system architectures in sustainable and future aircraft cabins. For this purpose, a XR co-design study is conducted and evaluated based on two different integration scenarios. With the help of two expert groups, the definition of fictitious system interfaces is carried out on different scenarios using a physical mockup and a virtual scenario with the help of the VR design tool Gravity Sketch. In addition to recording objective measurement data (time, ideas), subjective measurement data is recorded and evaluated with regard to system usability and co-creation experience. The results of the study indicate that both physical and virtual mockups enable an enhanced user experience and time-efficient creation of different ideas. It was shown that both scenarios, individually and in combination are suitable for defining complex and flexible system interfaces in a time-efficient and requirements-centered manner as part of the XR co-design process. In addition, the findings of the paper provide a basis for linking user-centered XR co-design design methodologies to cabin system design methods, considering essential requirements in real-time and in the early system interface definition process. Besides saving time and personnel resources, it can prevent the production of costly physical mockups and elaborate validation steps. Consequently, decisions in the development process of complex, sustainable, and novel aircraft systems can be made more targeted and simplified.

Keywords: Co-Design, Cabin System Design, Extended Reality, Hydrogen, Aircraft Cabin

1. Introduction

In an era of ongoing global climate change, there is a trend towards a more sustainable and climate-neutral aviation, which necessitates a multitude of new key technologies. Particularly, the exploration of alternative propulsion systems such as hydrogen propulsion exhibits significant potential to substantially reduce the CO2 emissions of future aircraft. However, the integration of novel propulsion systems notably impacts the aircraft cabin and its system architecture. As a safety-critical subsystem of the overall aircraft, system interfaces and the interactions of individual subsystems must be understood and considered. Novel architectures necessitate a modular and flexible integration of the propulsion system, along with the redefinition of altered system and subsystem interfaces, considering additional or absent spatial constraints. Furthermore, such integration requires the direct consideration of multiple and pivotal stakeholder requirements to avoid resource-intensive revisions at later stages of development.

The DLR Institute of System Architectures in Aeronautics is therefore researching new methods and ways to increasingly digitalize the aviation industry and map future concepts and development processes completely virtually. Technologies such as Extended Reality (XR) provide an important puzzle piece in DLR's research for the development and evaluation of future and digital cabin concepts. In one hand, a process has already been developed to visualize complex systems, subsystems and information using a XR platform. This platform provides the visualization of complex systems, subsystems and gives the basis for evaluation by different interest groups [1]. On the other hand, various processes have already been investigated to involve key user groups in the early and digital cabin design process using XR as part of the co-design approach [2]. So far, both processes have essentially followed the approach of making cabin concepts or systems and system components immersive assessable. In the development of holistic cabin concepts, however, it is necessary to combine both approaches in order to realize the connected development and evaluability of virtual aircraft cabin and system concepts.

This paper aims to bridge the gap between both processes and demonstrates the integration of various user groups and their respective requirements into the digital development process of adaptable and prospective aircraft cabin system interfaces. On the one hand, the focus is set making new cabin environments and system interfaces tangible in order to ensure a better understanding of new cabins and system architectures. On the other hand, an interactive real-time development and evaluation of new interface concepts by different interest groups is to be carried out. The findings will serve as a basis for the time- and cost-efficient development of novel and complex system architectures and provide an approach for digital real-time optimization and development of future aircraft cabins.

2. Fundamentals

The following section describes the methodological starting point for the present work. The first part describes the basic terminology and scientific background to the key topics of co-design and Extended reality. The second part describes the basic methods and procedures used by DLR in the design of cabin systems and user-centered cabin design concepts.

2.1 XR Co-Design

Co-Design

With advancing technological developments and increasing societal and economic demands, the aviation research and industry are increasingly challenged to meet a dynamic and broad spectrum of user group requirements. In the context of product design, there has been a notable shift in the role of the user, as indicated by Sanders & Stappers, towards "designing for the future experiences of people, communities, and cultures who are now connected and informed in ways that were unimaginable even ten years ago" [3]. In connection with this, F.S.Visser et al. describe a transformation in the user's role, evolving towards "an expert in their own experience" [4].

Emerging methods to actively involve users in the design process are known as co-creation or co-design. Co-design can be considered an approach that brings together creative designers with experience in implementing creative ideas and individuals with little design experience in a collaborative creative process [5]. Co-design is increasingly establishing itself as an important approach in the development of user-centered products, with companies like Ikea [6] or BMW [7] already successfully employing this approach. According to C.Prahalad and V.Ramaswamy et al., co-creation describes the interaction between companies and customers for the collaborative design of a unique and valuable experience [8] . However, Zhang et al. see involving users in the traditional design process as necessary but also challenging, as general product users lack knowledge of product design [9]. Classic design methods have been developed only for product designers, which is why it is necessary to "explore new ways for users' involvement in product design" [9]. Building on this, Lee et al. see the challenge in co-design as effectively involving users in the collaborative process and creating an environment that enhances users' creativity [10].

In this context, so-called "generative tools" provide a possibility to involve users more effectively in the design process [11]. Sanders understands these tools as a visual and verbal language, particularly characterized by a visual immersion in individual experiences and thoughts. Users are free to choose the appropriate tools to creatively represent their own thoughts and ideas.

Extended Reality

In addition to the provision of suitable tools the user-centred and collaborative design process is dependent on a suitable platform. V. Ramasawamy et al. see a central role in the multidisciplinary use of "interactive system environments among persons and material entities, supported by technological platforms [12]. The interplay of digital and physical elements, artefacts, processes, interfaces and people play a particularly important role in the relevance of platforms. Applications in the context of extended reality are increasingly playing an important role in the provision of digital and interactive platforms. With the advancement of technology, XR has become a permanent fixture that is not only used in a commercial context, but also increasingly in an industrial context. XR technologies and interactive applications offer the opportunity to visualize concepts virtually and immerse oneself in different scenarios. It is also possible to work independently, simultaneously and collaboratively with a large number of user groups in real time. In general, XR is an umbrella term for all technologies that change reality by adding digital elements to the physical or real environment [13]. This particularly includes for example technologies such as mixed reality (MR), virtual reality (VR) and augmented reality (AR) (Figure 1).

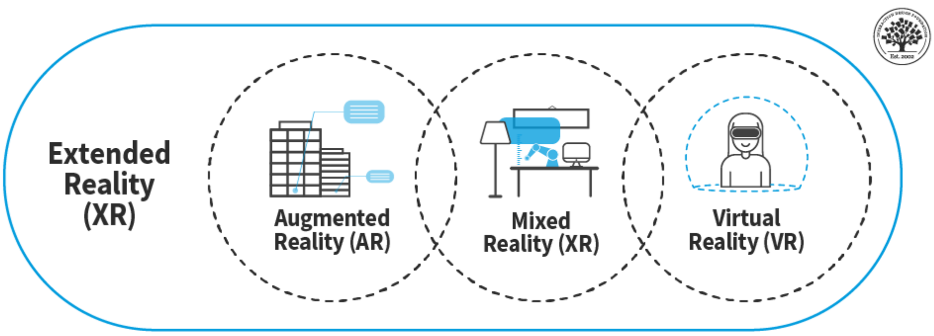

Figure 1 – Definition of the term Extended Reality (XR) [14].

2.2 Cabin System Design Method

The use of XR tools offers numerous possibilities to create and to connect, particularly in the development and representation of aircraft cabin systems. The design of the cabin and its systems is characterized by safety-critical requirements, a high demand for individuality and a large number of components and subsystems. In addition, the system components are highly cross-linked, which in turn increases the overall complexity of the system. A model-based digital end-to-end approach is used to address these challenges to map and to design the overall system holistically.

Figure 2 shows the method and the models for conceptually designing, analyzing and subsequently evaluating cabin system concepts at the DLR [15]. The methodological approach combines heterogeneous and domain-specific models and their data [15]. Depending on the discipline and research question, the models have different degrees of fidelity. First, initial parameters such as the number of transported passengers and range are defined in the preliminary design. Following, the cabin fuselage structure is designed using FUGA (Fuselage Geometry Assembler), a knowledge-based method developed at DLR. The generated data is exported afterwards to a CPACS file [16] [17]. CPACS is the Common Parametric Aircraft Configuration Schema (CPACS) is a data definition for the air transportation system that enables information exchange among engineering tools, supports multi-disciplinary and multi-fidelity design, describes various aircraft and mission characteristics, includes process information for workflow setup, and minimizes interfaces through a central model approach [18]. Using CPACS, the data will be imported for the cabin system design and used as boundary conditions for the available installation space of the cabin in the aircraft, among other things. In the next step of the cabin system design, modeling languages such as SysML or descriptive models are used to model requirements or set up system architectures. Subsequently, analyses are performed for the generated system architectures and the cabin system components are designed in more detail. Numerical models are run in Matlab for comfort calculations or geometric placement checks. The geometric, high-resolution 3D modeling is done using the open-source 3D computer graphics software Blender. Finally, the results (3D models and data) of the design are transferred to a virtual development environment like Unity where users can interact with the developed cabin configurations using virtual reality (VR). The immersive environment enables the user to explore the physical characteristics of the cabin (e.g. spatial perception, accessibility) on a 1:1 scale. Furthermore, changes to the cabin design can be sent back to the design process and the cabin configuration can be iterated.

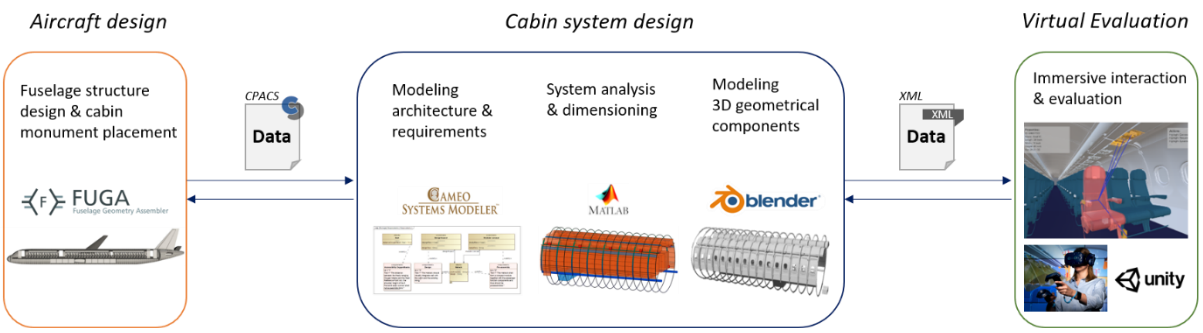

Figure 2 - Graphical representation of the models, domains and their data links between them.

This approach enables the evaluation of product variants, the investigation of new cabin variations (retrofit) in the context of customizing or the integration of new technologies into existing architectures (e.g. hydrogen powered systems). The use of virtual 3D mockups in the early stages of development offers the potential to reduce changes that arise later in the development process by involving all stakeholders at an early stage [19]. In this context, technical and rule-based aspects are increasingly being pursued. However, to develop virtual aircraft cabin concepts and the interaction between different components and systems virtually experienceable and assessable, digital cabin concepts are necessary and build the baseline in DLR´s digital inside out cabin development approach. Therefore, the development of creative and user-centered cabin designs using XR provides an important basis for realizing the full representation of virtual cabins and cabin systems.

2.3 Cabin Concept Design Method

At the German Aerospace Center (DLR), the design and development of future cabin concepts plays an important role to the digital end-to-end development and evaluation process. Employing an inside-out approach for the overall aircraft system definition, cabin design yields important insights into the future layouts and architectures of retrofit solutions and novel concepts. Within DLR´s strong focus on user requirements for future cabin concepts, user-centered design and the implementation of interactive and digital methods such as XR are a key aspect. I. Moerland-Masic et al. combined the Design Thinking approach with virtual and interactive VR design platform Reality Works, enabling multidisciplinary real-time design of early concept ideas [20]. Additionally, research highlights the potential of combining co-design and XR through collaborative platforms to "improve communication cues and create value within a collaborative environment" [21].

In his work, S.Cornelje defined the methodological approach XR+ using the example of collaborative development of future galleys for the Flying-V concept [21]. Physical and digital "make-tools" were utilized and coupled with a VR environment. Throughout the process, central user groups were gradually enabled to define their own requirements and creatively and collaboratively implement them. Due to the high level of immersion and quality of results achieved by integrating virtual and physical elements, this approach forms the basis of the collaborative design methodology for user-centered cabin concepts at DLR. A central element of this method is immersion in the context. Before the workshop begins, participants should be given the opportunity to reflect on their own everyday experiences and define central problems and requirements for a collaborative workshop. During the workshop, creative exchange and physical and virtual "make-tools" are used to immerse participants in the design environment and implement their own ideas through a creative concept. It is crucial to convey to user groups their role as experts in this method, while the designer merely guides the creative implementation of solutions. The main steps are as follows:

- Pre-Workshop
- Introduction
- Context Immersion
- Workshop Creating the new context
- Immersing the new context
- Evaluate
- Reflect

Based on the XR+ approach, the application of the method for designing the cabin of a future emergency ambulance helicopter concept has already been investigated. It was shown that the method can also be applied to interdisciplinary problems in the area of cabin design [22].

In view of the principles outlined above, it appears that the XR co-design process offers many opportunities to generate an increased understanding of flexible system interfaces, which is very challenging and time-consuming in the previous design process for digital system interfaces. The additional and direct involvement of key stakeholders in the process could also increase the maturity of the concept at an early concept development stage and minimize time-consuming development periods.

As the use of "make tools" plays a special role in this process, the extent to if and how realistic and physical make tools can be used in this process in comparison to virtual XR tools will be investigated. It will also be discussed comparatively which tools can be used most optimally in order to realize a collaborative system interface definition process in the course of the XR co-design process. Finally, the question must be answered as to what extent the XR co-design process for cabin concepts can be coupled with the Cabin System Design Method in this context and how can it be utilized for future scenarios.

3. Experimental Setup and Methodology

The following chapter describes the experimental setup for the study and outlines the methodological approach chosen to conduct and evaluate the study. The basis for this is the use case of a physical mock-up, which was converted into a virtual environment using 3D software, 3D scanning and the XR tool Gravity Sketch.

3.1 Methodology

Looking at the current state of development of future hydrogen-powered aircraft concepts, research has so far come up with various approaches for positioning the hydrogen tanks. In this context, different concepts for the storage of liquid hydrogen (LH2) containers have been investigated. Besides the potential storage in the wing [23], or in the tail area and front "cheek area" [14], scientific literature sees the storage of tanks in the tail area is also as possible options [24]. The various options for tank integration can potentially impact the system architecture differently, requiring methods and processes to be flexible in order to quickly and effectively adapt stakeholder requirements on the integration of future cabin systems and their interfaces. As the development of new system interfaces using XR co-design is the primary focus of this paper, the study uses highly simplified scenarios with the aid of a physical and virtual mock-up.

The study consists of three phases:

- The first phase is the immersive and user context-oriented part of the process. Here, the test subjects were sent a fictitious scenario in which two different cabin concepts are shown as a 2D layout. The scenario was explained and they were given the task of using their own expert knowledge to connect two system components in the different scenarios. Questions were also asked about the key requirements and initial thoughts on the task and scenario. Based on the findings of F.S. Visser et al. [4], this part was intended to promote immersive familiarization with the creative task before the start of the workshop and was distributed to the participants four days before the start of the workshop.
- In the second phase, the defined requirements were first iterated together in order to familiarize the participants with the scenario and their own requirements. Additionally, the test subjects interacted with the physical and virtual environment in randomized groups and orders. While the groups in the physical scenario were allowed to solve the task using self-selectable tools, the task in the virtual scenario was carried out using XR tools and the XR environment. After completing the task, both groups switched the work environment, so that both groups performed the task in the virtual and physical environment each.
- The third phase included the process steps after completion of the tasks in the respective scenarios. After completing the task, all participants were asked to complete a questionnaire and evaluate the usability and the experience within the concept development.

It is important to always take the described sample characteristics into account when interpreting the results of the present study, because the study did not aim at generating results representative for the German population and it cannot fulfil this criterion. Nevertheless, it can provide helpful insights into the usability of XR co-design and the different platforms and make-tools to define flexible and future hydrogen aviation cabin system interfaces.

3.2 Use Case

In collaborative design, it is usually open and individual which physical "make-tools" are best suited for different test subjects.

In the previous use of the XR co-design method, however, models, 3D prints or layouts in reduced scales were usually used, as the creation of physical prototypes in original size is very costly. In the course of this study, a mockup with a 1:1 scale will be used as an example in order to establish comparability with the virtual mockup. A physical cabin mockup of an A320 cabin at DLR in Hamburg Finkenwerder was used for the study. The mockup is a small cabin section with original sidewall panels, rows of seats and baggage compartments with parts of the passenger service functions. The mockup was used to create a cabin environment that is as realistic as possible, with a fictitious and highly simplified cabin system as the starting point. The following figure (Figure 3) shows the conceptual layout for the physical prototype as a sketch and as a real mockup.

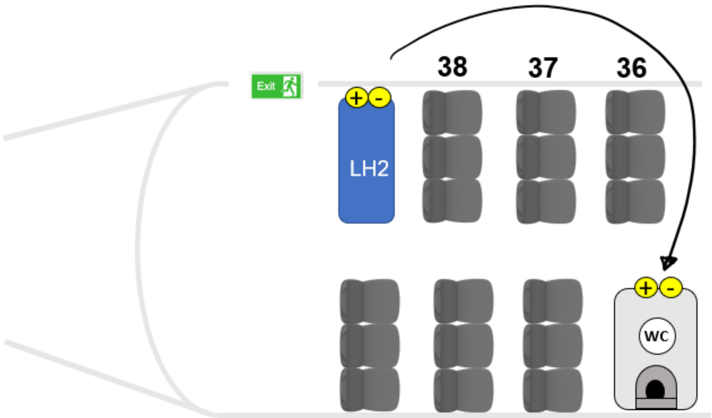

Figure 3 – Conceptual layout plan physical test scenario.

For the experimental study, a scenario was outlined in which the mockup was located in the rear section of a standard fuselage aircraft on the left-hand side. A simplified power source mockup was located behind the last row of seats, which is powered by liquid hydrogen. An exemplary placeholder for a lavatory has been placed next to the front row of seats as an exemplary electronic consumer. The additional rows of seats only served to complete and integrate the concept into the aircraft architecture. The scenario outlined was also created in the physical mockup. The mockup included three rows of seats, each with three economy class seats, seat rails, floor, sidewall panels and fixed bin hatracks. Unlike in the sketched version, the additional rows of seats were omitted due to the limited free space. The test subjects were provided with various aids to complete the task. A yellow wire (20 meters) could be used as a simplified "cable connection" for the physical interface definition. In addition to post-its and adhesive tape, the test subjects were given the choice of directly drawing the concept.

The same components were to be connected to each other for the virtual mock-up. The same cabin components were used, but this scenario differs from the physical mockup in terms of the positioning of the components. Figure 4 shows the physical mockup (left) and the prototyped lavatory including the power connection point (right).

Figure 4 – Physical Mockup with seating area (left) and Lavatory (right).

The same components were to be connected to each other for the virtual mock-up (Figure 5). The same cabin components were used, but this scenario differs from the physical mockup in terms of the positioning of the components.

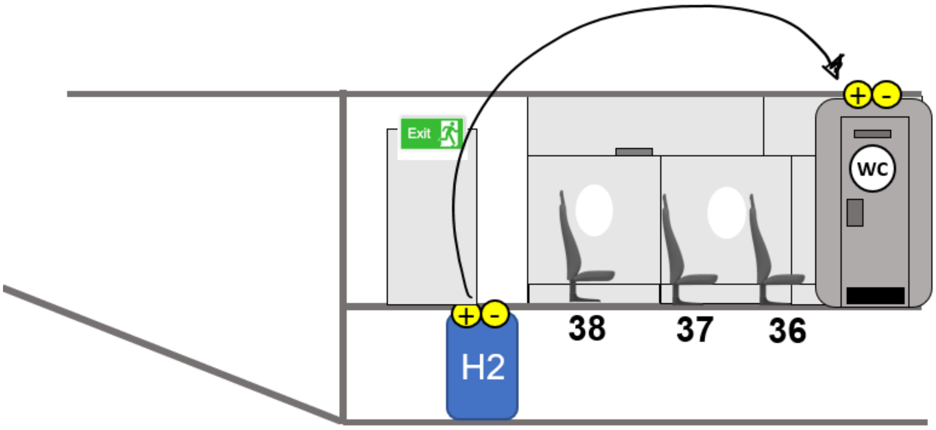

Figure 5 – Conceptual layout plan virtual test scenario.

Unlike in the first scenario, the power source was positioned in the rear cargo area. Compared to the first scenario, the lavatory was rotated by 180° and positioned in front of the first row of seats on the right-hand side of the cabin. The other rows of seats were reinserted into the scenario.

To use realistic data of the seats, 3D scans of the physical mockup and the laboratory environment and re-modelled 3D cabin data have been used. The same applies to the power source, for which the 3D scan of a fuel cell was used for the greatly simplified scenario [24]. Individual modules such as the side wall paneling, luggage compartments and the lavatory were created using the Rhino3D design software. Figure 6 shows the virtual mockup in a transparent view (left) and in the original and non-transparent view (right).

.

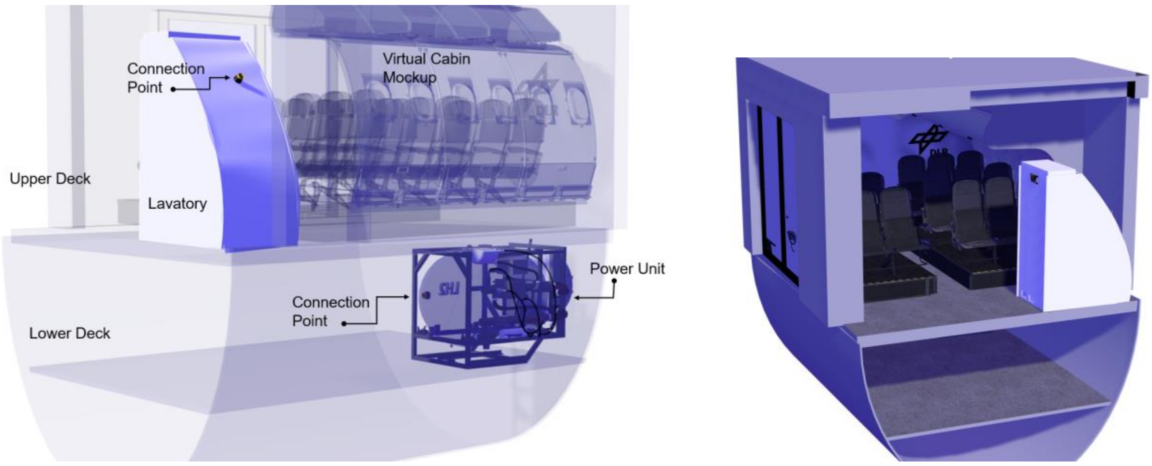

Figure 6 – Virtual mockup in Gravity Sketch.

The 3D data was edited using the software Blender and imported into the collaborative XR software Gravity Sketch. The test subjects in the virtual environment were enabled to move virtually through the cabin using this software. Additionally, it was possible to switch between AR and VR at will. VR glasses of the type Meta Quest 2 and Meta Quest 3 were provided for two people. A desktop VR view was provided as a third option. The image from this application was also transferred to a large screen. Using the desktop VR application, it was possible to track the work and positions of people wearing VR glasses in real time and to place their own ideas using virtual post-its. Additionally, it was also possible to use a virtual laser pointer to point at objects that the participants could see in the virtual space. All participants were given sufficient time to familiarize themselves with the environment and the function of the tools beforehand.

3.3 Participants & Experimental Protocol

When selecting the test subjects, care was taken to ensure that key interest groups in the field of research into hydrogen drive systems and the integration of cabin systems took part in the study. Six test subjects have been selected for the study. The test subjects consist of five male and one female test subject. All test subjects are scientific employees of the German Aerospace Center and had no additional information about the planning and research objectives of the study. Four of the test subjects stated that they had a scientific background in the field of research into the industrialization of future aircraft cabins. Two subjects stated that they worked in a scientific context in the field of hydrogen system technology in aviation. The latter two subjects were each categorized into different groups. The other subjects were randomized to these two groups. All subjects were informed about the risks and safety instructions for the study and gave their consent in the form of a signed informed consent form. All sessions were filmed and photographed. All sensitive data was anonymized. Each subject also represents a code for the physical scenario and virtual XR co-design scenario for the respective group (A,B), for the scenario (virtual, physical) and personalized subject number (1,2,3...x). The test subjects stated that they had little or no experience in using XR tools. The following table (Table 1) lists the different tasks and the duration for the physical and virtual part:

Environment	Process Step	Time
Physical Mockup	Welcome, Task description	10 Min.
	Mockup Introduction	10 Min.
	Task	25 Min. (max.)
	Discussion & Presentation of results	10 Min.
	Questionnaire	10 Min.
Virtual Mockup	Welcome, Task description	10 Min.
	VR Introduction and training	15 Min.
	Task	25 Min. (max.)
	Discussion & Presentation of results	10 Min.
	Questionnaire	10 Min.

Table 1 – List of tasks.

Group A started by carrying out the co-design task in XR (virtual scenario) and then worked on solving a new task in the physical demonstrator (physical scenario) in a subsequent session. Group B started solving the tasks at the same time, but in reverse order, first in the physical and then in the virtual scenario.

3.4 Measurement Methods

Two different types of data have been generated for the collection of quantitative data within the co-design sessions.

The first type is objective data for the respective sessions. It was determined by the number of clearly identifiable ideas mentioned. In particular, virtual and physically stored notes were categorized as ideas. Ideas that were clearly recognizable to the session leader, which caused a change or adaptation of the concept at the time of execution, were also counted as ideas. In addition, the time from the start to the end of the task was recorded and taken into account as an objective factor for the evaluation.

Additionally, subjective data has been collected by means of the SUS (System Usability Scale) according to J. Brooke [25]. The SUS has been used for years to assess the perceived usability of systems in various areas such as automotive, e-commerce, healthcare, UX and education [26]. To record the co-creation experience, on the other hand, an evaluation was carried out according to the factors Expectations, Hedonic Experience, Cognitive Experience, Social Experience, Personal Experience and Pragmatic Experience. The factors and the method are based on the study by K.

Verleye [27] and have been adapted to the present study design. Using six questions, the test subjects were also able to carry out an evaluation here using a five-point Likert scale.
All questions were adapted for the evaluation using the SUS for the scenario of this study. The same applies to the questions for determining the co-creation experience. After the end of the study and the final questionnaire, the test subjects were also asked to compare the virtual and physical scenarios and to state their preferences for a particular working environment.

4. Results

The following chapter describes the key results of the collection of subjective and objective data. In addition to the key results on the SUS and the evaluation according to the co-creation experience scheme, the results and the time aspects in the implementation of the concepts in the respective scenarios are presented.

4.1 Subjective Data

System Usability Score (SUS)

According to Brooke, a general distinction can be made between different areas within the SUS scores. The SUS scores can be divided into individual subcategories A (90-100), B (80-90), C (70-80), D (60-70) and E (<60). According to Brooke, SUS scores in the 70-100 range are typically considered "acceptable", scores between 50-70 as "marginal" and scores <60 as "no acceptable".

The following Figure (Figure 7) shows the calculated SUS score in comparison between the virtual and physical application in the form of a boxplot diagram. A difference can be seen in the median between the results of the virtual (72.5) and physical scenario (80). The physical variant also shows a greater distance in the dispersion of the values.

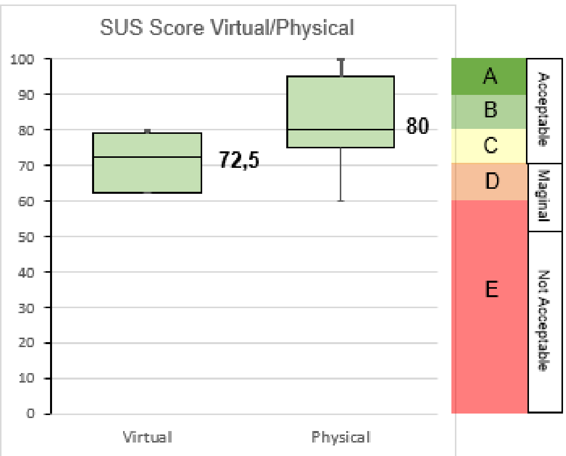

Figure 7 – Results SUS score comparing virtual and physical scenario.

In this case it can be shown, that the test subjects perceived a slightly higher usability when working in the physical scenario. Despite some differences, the median of both results is within the acceptable range (C). The dispersion of the values is within the acceptable and marginal range.

In the following SUS score calculation (Figure 8), the focus was on the usability of the environments calculated by rounds. These alternately include the results of one task solution each in the physical and virtual scenario.

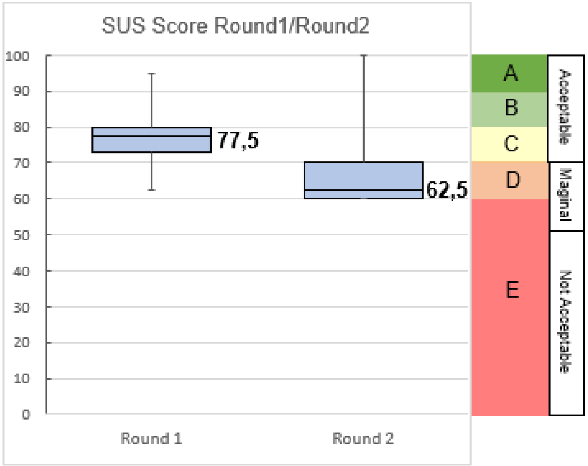

Figure 8 – Results SUS score comparing round 1 and round 2.

As in the previous results, both scores and the dispersion of the values are within the acceptable and marginal range. As the scores in the first round show a higher median (77.5) than in the result for the second round (62.5), a lower usability can be assumed in the second round. Although the value is still in the marginal range, values <68 are typically considered below average. Compared to the first round, however, a wider distribution of values and a maximum value of 100 can be observed.

A further distinction was made in the evaluation of the SUS scores based on the order in which the respective scenarios were solved. The SUS scores for group A (virtual/physical) and group B (physical/virtual) were determined (Figure 9).

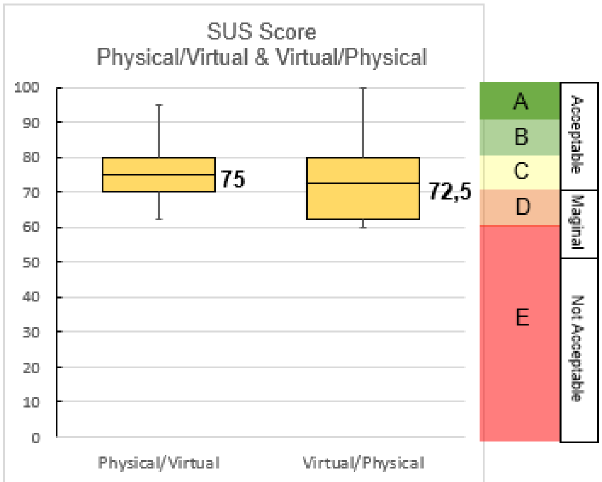

Figure 9 – Results SUS score comparing the different sequences and working environments.

For Group A in the physical and subsequent virtual scenario, the median SUS score is 75. This value and the distribution of the individual scores are within the acceptable and marginal range. Compared to this, the SUS scores for the comparison case are distributed within a larger range between 62.5 (1st quartile) and 80 (3rd quartile). Compared to the other scenario, the median SUS score here is slightly lower at 72.5. The low variance within the values and the slightly higher SUS score could indicate that the physical/virtual sequence is rated positively in terms of usability.

Co-Creation Experience

Comparable to the evaluation of the SUS scores, different factors were analyzed for the evaluation of the co-creation experience. The examples for three comparison scenarios are listed below. The average evaluation results for the respective question areas are listed for comparison.

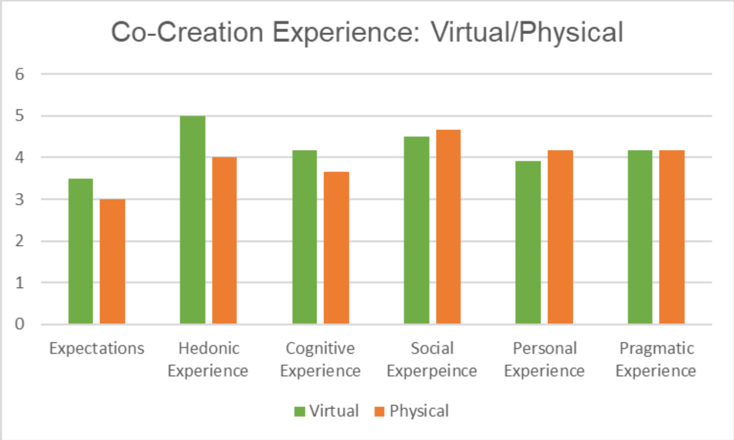

Figure 10 – Results Co-Creation Experience, comparing the virtual and physical scenario.

Figure 10 shows the comparison of the average results of the co-creation experience between the virtual and physical scenarios. While the average values for the Expectations, Cognitive, Social, Personal and pragmatic Experience areas differ little or not at all, the results for the hedonic Experience area show a slight tendency towards the virtual (5) scenario compared to the physical scenario (4). The test subjects seemed to rate the experience of collaborative work in XR as particularly positive compared to the physical scenario.

The following figure (Figure 11) shows the comparison of the average results for the co-creation experience between group A (virtual/physical) and group B (physical/virtual).

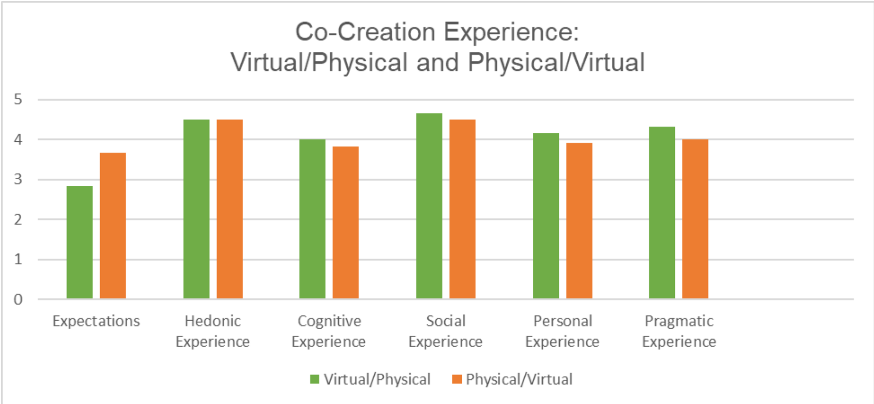

Figure 11 – Results Co-Creation Experience, comparing the different sequences and working environments.

With the exception of the results for “Expectations”, it is noticeable that the perceived experience differs minimally to hardly at all for both groups and the respective sequences and only slightly higher values can be observed for the virtual/physical sequence. The results for the “Expectations” show a greater difference, where the average value for the co-creation experience for the order Physical/Virtual (3.6) differs more strongly from the comparison factor (2.8).

This could mean that Group B perceived the task processing in the physical and then in the virtual scenario as more positive for the fulfilment of previously defined requirements than in the comparison scenario.

The following figure shows the average results for the co-creation experience in comparison between Round 1 and Round 2.

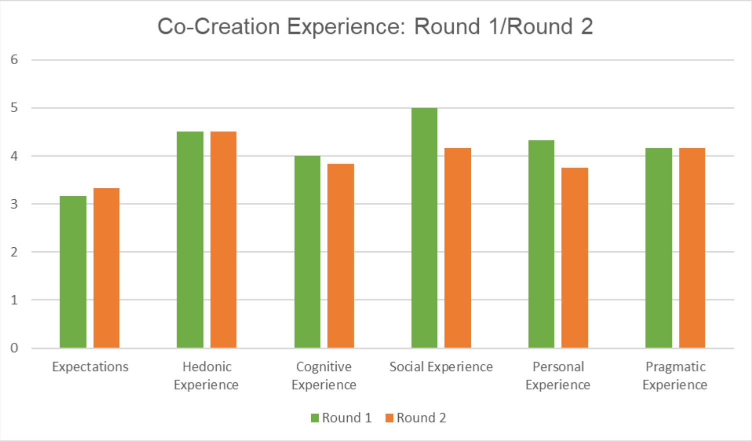

Figure 12 – Results Co-Creation Experience, comparing round 1 and round 2.

While there are no or hardly any recognizable differences in most areas, there are individual deviations in the results of the social experience and the personal experience. Possible reasons for this could be a lack of motivation to complete the task again. Difficulties in dealing with the virtual tool or an increased need for discussion could also have an influence on the social experience.

4.2 Objective Data & Co-Design Concepts

The concepts of the groups in the different scenarios are briefly described below. Based on this, the time factors and the number of quantifiable ideas is listed. Moreover, the concept results and the main observations made during the implementation of the work in the group are described. At the beginning, the results of Group A (virtual; physical) are described. followed by a summary of the results of Group B (physical; virtual).

Group A (Virtual, Round 1)

The following figure (Figure 13) shows the final results of group A in the virtual platform.

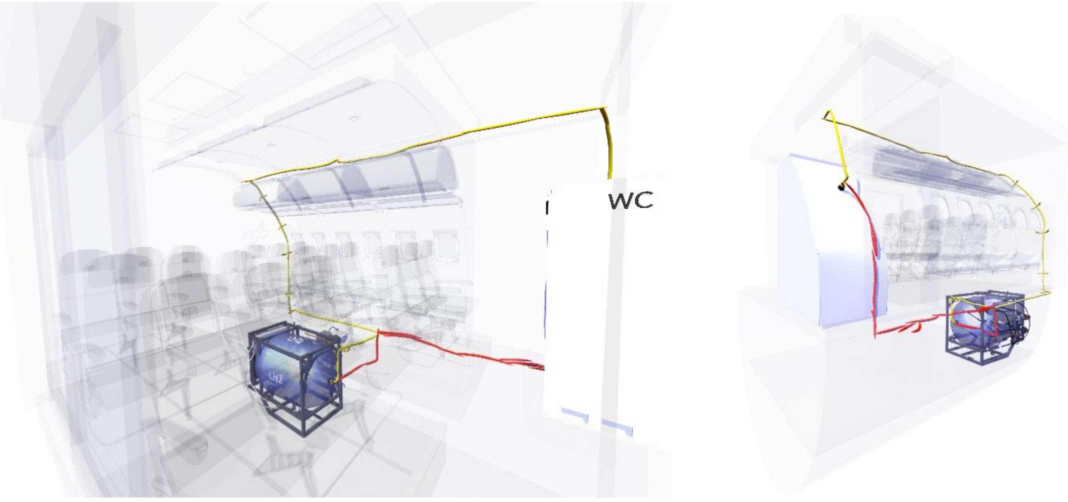

Figure 13 – Results of Group A in virtual scenario, round 1.

In the first approach to the concept (yellow), Group A decided to route the first cable from the power unit directly upwards to the rear area of the transition between the bulkheads and the side wall. Brackets were also drawn in to indicate a fastening and guide for the cable along the wall. The connection was then laid at the height of the air ducts behind the hatracks along the cabin in the direction of the consumer and connected to it. In a second option, the aim for Group A was to minimize the distance of the connection. Optimized accessibility for maintenance personnel was also an important factor.

The following ideas were identified as quantifiable and listed in the concept:

- Routing concept 1
- Alternative routing concept
- Fixing the rear wall
- Rotating the LH2 tank and the power output
- Retrofitability of current power distribution system

After a short introductory period of twelve minutes, the test subjects quickly got to grips with the virtual scenario and mastered the basic functions and orientation in the room. Two people decided to carry out the task in VR, one person gave instructions and ideas using desktop VR.

An exemplary footage of the virtual design process of Group A is shown in the figure below (Figure 14).

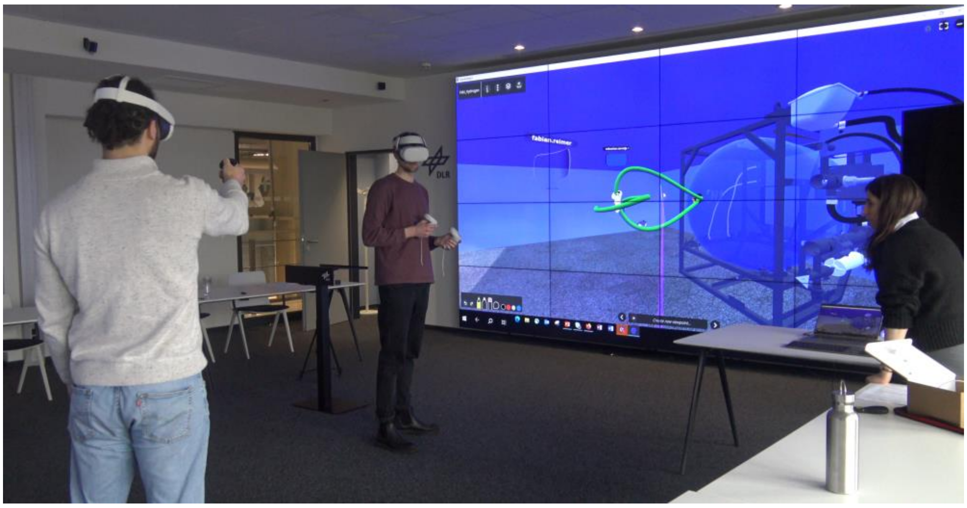

Figure 14 – Group A (Round 1) during virtual co-creation process.

It was also observed that communication increased as time went on, with orientation in the room playing a major role. Many ideas were quickly implemented and different approaches were exemplified and adapted in the course of discussions. Group A needed a total of 21 minutes to complete the task.

Group A (Physical, Round 2)

The following figure (Figure 15) shows a section of Group A's work in the physical demonstrator in the second round. To provide an increased understanding of the, a schematic sketch has been created, showing the rough concept.

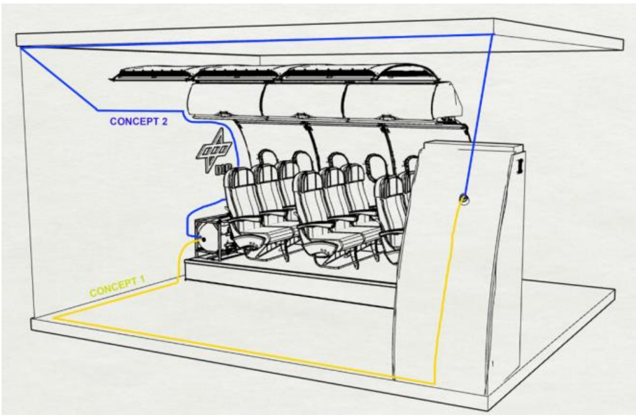

Figure 15 – Schematic image of Group A´s (Round 2) result for physical co-design concept.

The work on the task in the physical demonstrator was carried out immediately after completing the task in the virtual scenario. Firstly, the power supply unit was turned around in order to position the power output towards the side wall. A direct connection was then conceptually made to the central bus system in the central area of the fuselage with the power supply unit. The system connection was routed along the outer wall at the height of the crown module to the opposite side of the cabin. From this position, a connection was then made along the side wall to the consumer. In a second option, a more ergonomic approach was chosen in which the system connection runs in the same direction as in the first approach. The following illustration shows the integration of both variants, starting from the power supply unit (Figure 16).

Figure 16 – Group A (Round 2) during physical co-design process.

The following ideas can be identified as quantifiable approaches:

- Solution approach 1 (routing in the upper area)
- Approach 2 (routing in the floor)
- Connection to BUS Network PSU (retrofitability)
- Place cables as far away as possible from the passenger area (safety)
- General retrofitability and re-use of existing system architecture and interfaces
- Routing behind the wall and to the bus network

In contrast to the virtual scenario, the Group did not require an instructive tutorial for the physical tools. However, the procedure for concept creation was discussed for about three minutes before the active start of concept creation. While the use of the physical make-tools was easy to understand, the accessibility of the ceiling and the system connection to the end user posed a challenge. As a result, the concept had to be provisionally attached with instructions. The first concept was finalized after 15 minutes, and the test subjects needed a further six minutes to expand the concept. Overall, this round revealed a high level of communication and queries with the test supervisor. It was also noticeable in this round that many ideas were quickly doubted or discarded.

Group B (Virtual, Round 2)

Figure 17 shows the results of group B in the virtual scenario.

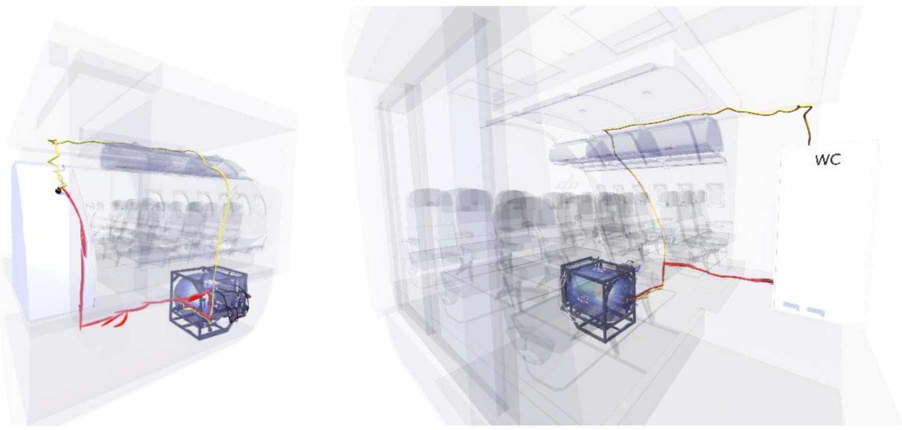

Figure 17 – Results of Group B in virtual scenario, round 2.

Equally to Group A, Group B chose two variants in their approach within the virtual scenario. In the first concept variant (yellow), a system connection was routed from the power supply unit directly upwards through the floor, along the side wall and up to the height of the air systems above the Hatracks. From this position, the cable was routed along the side wall in the direction of flight up to the consumer and connected to the power input of the consumer from above. In the second approach (red), the system connection was routed to the ceiling of the cargo area and routed through the cabin floor to the position of the consumer and connected to it. Figure 18 shows the exemplary and virtual design process by Group B. The following quantifiable solutions are listed:

- Solution approach 1
- Solution approach 2
- Transfer of the solution approach from the task in the physical demonstrator

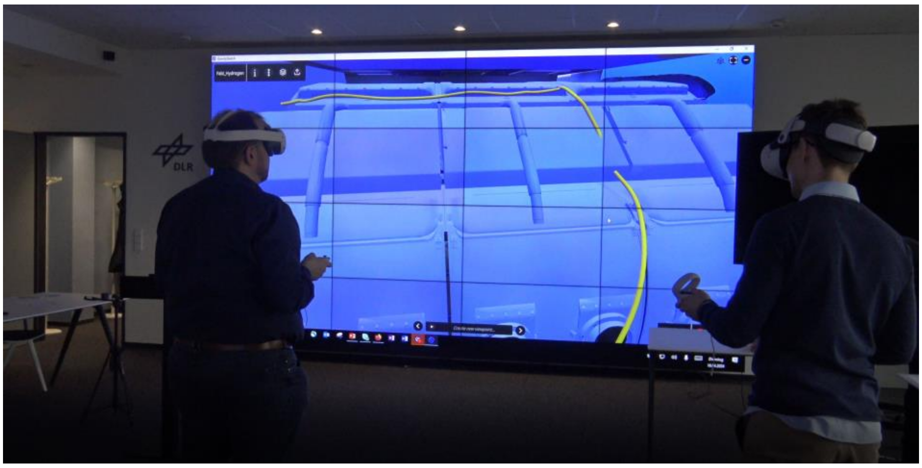

Figure 18 – Group B (Round 2) during virtual co-design process.

Summarized, all test subjects in this round were able to use the tools and moved around the environment very quickly. It should be mentioned that one person had to leave the study due to time constraints. The test subjects in this round therefore immediately decided to use the VR glasses and also chose to use AR for improved orientation in the room. The particularly short introduction time (eight minutes) and the short duration of the task solution (seven minutes) can be highlighted here. Compared to group A, less discussion was noted, which could be explained with the smaller group size and the approach to re-use the concept from the physical session.

Group B (Physical, Round 1)

Unlike Group A, Group B started by carrying out the task in the physical scenario. The following figure shows an excerpt from the concept in the demonstrator as well as a schematic sketch to support the concept description (Figure 20).

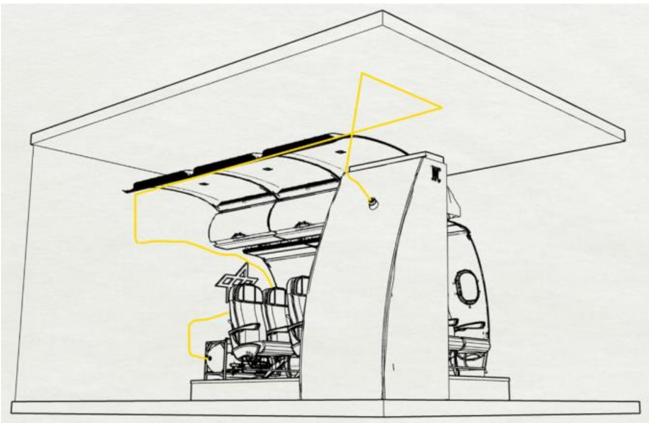

Figure 20 – Schematic image of Group B´s (Round 1) result for physical co-design concept.

Group B chose a variant with one solution in the concept realization. Here, the system connection was routed directly from the power supply unit via the side wall to the central crown module area in order to utilize the existing bus system. From here, a further connection was made to the other side of the cabin and routed to the end user. The test subjects used post-its to indicate that the systems run behind the paneling. The aim was to create a symmetrical network that would enable the connection to the respective systems to be distributed from central interfaces. Figure 19 shows Group B in the concept development process in the physical mockup. The following ideas were highlighted:

- Symmetrical bus system
- Re-use of existing system architecture
- Solution approach and connection via the central crown module area

Figure 19 – Group B (Round 1) during physical co-design process.

Observing the processing by Group B, it was noticeable, that ideas were initially exchanged in the course of a discussion. After three minutes, some test subjects began to use physical tools to realize their initial ideas.
After some time, there was more discussion about the concept. After a brief reminder from the test administration, the ideas were then finalized again using the physical tools. In total, the participants needed 20 minutes to complete the physical scenario, including discussions. In sum, there was an increased need for discussion in this round, meaning that the physical tools were used slightly less to communicate ideas. All participants seemed to be equally involved in the realization of ideas. It was occasionally observed that the subjects found it difficult to visualize the scenario in reality due to the presence of the cabin parts.

Round	Process Step	Time: Group A (Virtual)	Time: Group A (Physical)
1	Introduction	10 Minutes	
	Orientation & Training in environment	12 Minutes	-
	Discussion and Ideas	-	3 Minutes
	Finalization of concept	21 Minutes	15 Minutes
	Additional concept implementations	-	6 Minutes
	Concept Description	10 Minutes	10 Minutes
	Total Time	**53 Minutes**	**44 Minutes**
Round	**Process Step**	**Time: Group B (Virtual)**	**Time: Group B (Physical)**
2	Introduction	10 Minutes	
	Orientation & Training in environment	8 Minutes	-
	Discussion and Ideas	-	3 Minutes
	Finalization of concept	7 Minutes	4 Minutes
	Additional concept implementations	-	13 Minutes
	Concept Description	10 Minutes	10 Minutes
	Total Time	**35 Minutes**	**40 Minutes**

Table 2 – Process steps and time

The following table (Table 2) summarizes the final times required to finalize the tasks of the different groups in the respective scenarios and rounds. It is noticeable here that the utilization of individual process steps in the different scenarios differed from one another. While the group work in the physical environment did not require any orientation in the environment, this was particularly important and time-consuming in the virtual scenario. At the same time, it was noticeable that time-consuming discussions were often held in the physical mockup without actively working on the concept. In the virtual space, on the other hand, the discussions merged with the active and conceptual elaboration of the ideas and were implemented directly. With regard to the overall duration of the task processing, it can be stated, that all environments guaranteed task processing in the shortest possible time of less than one hour. In addition, it could be observed, that the duration of the task solution was significantly reduced in the second round for both groups.

This indicates that both physical and virtual methods for concept creation represent an opportunity to realize innovative and conceptual system interfaces while taking stakeholder requirements into account. The results also indicate that a combination of physical and virtual processing can have a positive influence on the duration of task processing.

5. Conclusion & Outlook

This study demonstrates the utility of the XR co-design process in defining system interfaces for flexible and future aircraft cabin concepts and their system architectures. Emphasizing the integration between physical and virtual tools like XR, a study was conducted to exemplify and analyze the XR co-design process for defining adaptable system interfaces. Through alternating engagement of two expert groups in two distinct tasks and environments, four solution approaches were developed by the groups.

Objective and subjective data were collected during the participant study to evaluate the overall process and compare scenarios. While both physical and virtual scenarios yielded several outcomes within a task completion time range of seven to 21 minutes, no significant qualitative or quantitative differences were observed. However, nuances in participants' tool handling suggested differences in task approach. In the virtual scenario, a longer period was required for tool and environment comprehension, yet subsequent discussions and idea exchange were promptly implemented using sketched or modeled concepts. Motivation in utilizing the virtual tool was reflected in the co-creation experience, highlighting collaborative work and social engagement compared to the physical scenario. Challenges in orientation and positioning necessitated frequent consultations among participants in the virtual setting.

Conversely, in the physical scenario, ideas were extensively discussed before task initiation, with active idea implementation often paused for content-related consultations. Nevertheless, participants demonstrated immediate proficiency in using physical tools, resulting in slightly higher SUS scores and broader answer distributions compared to the virtual scenario. Challenges were encountered in accessing elevated positions in the 1:1 mockup, limiting concept implementation. Clear conclusions regarding scenario sequence and task processing differences were elusive, although trends suggested higher perceived usability and experience in initial rounds.

There are minor differences in the way the two variants are approached, as well as advantages and disadvantages in terms of capturing the environment of the tool and the environment. Due to the minor differences, it can be assumed that a virtual and physical approach is equally suitable for conceptually developing immersive solutions for connecting new types of system interfaces. This could lead to higher flexibility in the conceptual approach to future and similar problems. The results also supported the findings from the literature, according to which a combination of physical and virtual tools can lead to increased immersion and effectiveness in solving complex problems. In summary, the XR co-design process offers an effective approach for stakeholders to collaboratively define flexible and innovative system interfaces.

Therefore, this approach enables users to empathize with problems and implement requirements in real-time, leveraging digital implementations of individual needs and real 3D data.

This paper validates previous findings in XR and co-design, indicating its potential for expediting the development of complex cabin system architectures. Within DLR's digital development and evaluation process, this approach presents an immersive, stakeholder-centric option supporting existing cabin system design methodologies.

Leveraging insights from the XR co-design process, user requirements can be directly adapted to new system interfaces, facilitating targeted information and 3D data transfer for system-wide integration.

Contact Information:
Fabian.reimer@dlr.de

6. Copyright Statement

References

[1] M. Fuchs, F.Beckert, J. Biedermann and B. Nagel, "Experience of Conceptual Designs and System Interactions for the Aircraft Cabin in Virtual Reality," AIAA Aviation 2020 Forum. American Institute of Aeronautics and Astronaut, doi: 10.2514/6.2021-2773 , 2021.

[2] F.Reimer, J.Herzig, M.Lindlar, P.Weiand, S.Cornelje, L.Winkler, J.Biedermann and B.Magel, "Create Your Own Cabin - Connecting Multidisciplinary User Perspectives and a Future Rescue Helicopter Concept Within the Applied Xr Co-design Process," Preprint.doi:10.21203/rs.3.rs-4174792/v1 , 2024.

[3] E.B.N.Sanders, "Exploring co-creation on a large scale: Designing for new healthcare environments," ID StudioLab Pres, Designing for, with, and from user experience (pp.10-26), , 2009.

[4] F.S.Visser and V.Visser, "Re-useing users: co-create and co-evaluate," Springer-Verlag London, DOI: 10.1007/s00779-005-0023-x, 2006.

[5] E.Sanders and J. Stappers, "Co-creation and the new landscapes of design," International Journal of CoCreation in Design and the Arts, DOI: 10.1080/15710880701875068, 2008.

[6] L.Klink, "Das IKEA von Morgen: Was wir unter Innovation & Co-Creation verstehen," IKEA, 27 June 2022. [Online]. Available: https://www.ikea.com/de/de/this-is-ikea/corporate-blog/entwicklung-mitmachen-innovation-pub588b8ce0. [Accessed 4 March 2024].

[7] M.Bartl, "The Making-of Innovation," 11 September 2010. [Online]. Available: https://michaelbartl.com/2010/09/11/launch-of-the-bmw-group-co-creation-lab-2/. [Accessed 4 March 2024].

[8] C.K.Prahalad and V.Ramasawamy, "Co-creation experiences: the next practice in value creation," Journal of Interactive Marketing; Volume 18, Issue 3, 2004, Pages 5-14, https://doi.org/10.1002/dir.20015, 2004.

[9] Z.Zhang, Q.Peng and P.Gu, "Improvement of User Involvement in Product Design," Procedia CIRP, Volume 36, 2015, Pages 267-272, doi: 10.1016/j.procir.2015.01.019, 2015.

[10] J. Lee, M. Jaatinen, A.Salmi, T.Mattelmäki, R.Smeds and M.Holopainen, "Design Choices Framework for Co-creation Projects," International Journal of Design, 2017.

[11] E.Sanders and J.Stapper, Convivial Toolbox: Generative Research for the Front End of Design, BIS Publishers; 3rd edition, 2012.

[12] V.Ramasawamy and K.Ozkan, "What is co-creation? An interactional creation framework and its implications for value creation," Journal of Business Research, Volume 84, Pages 196-205, doi:10.1016/j.jbusres.2017.11.027, 2018.

[13] L. Tremosa, 2024. [Online]. Available: https://www.interaction-design.org/literature/article/beyond-ar-vs-vr-what-is-the-difference-between-ar-vs-mr-vs-vr-vs-xr.

[14] R. News, "Future Transport-News," December 6 2021. [Online]. Available: https://futuretransport-news.com/aerospace-technology-institute-liquid-hydrogen-concept-aircraft-unveiled/.

[15] M.Fuchs, Y.Ghanjaoui, J.Biedermann and B.Nagel, "An Approach for Linking Heterogenous and Domain-Specific Models to Investigate Cabin System Variants," 33rd Annual INCOSE International Symposium, Honolulu, Hawaii. doi: 10.1002/iis2.13090, 2023.

[16] J.N.Walther, C.Hesse, J.Biedermann and B.Nagel, "Extensible Aircraft Fuselage Model Generation for a Multidisciplinary, Multy-Fidelity Context," 33rd Congress of the INTernational Concil of the Aeronautical Sciences (ICAS), Stockholm,Sweden, 2022.

[17] J.N.Walther, C.Hesse, M.Alder, J.Biedermann and B.Nagel, "Expansion of the cabin description within the CPACS air vehicle data schema to support detailed analyses," CEAS Aeronautical Journal.Springer, doi: 10.1007/s13272-022-00610-5. ISSN 1869-5590, 2022.

[18] M.Alder, E.Moerland, J.Jepsen and B.Nagel, "Recent Advances in Establishing a Common Language for Aircraft Design with CPACS," Aerospace Europe Conference 2020, Bordeaux, France; , 2020.

[19] M.Fuchs, F.Beckert, F.Rauscher, C.Goetz and B. J.Biedermann, "Virtual reconfiguration and assessment of aircraft cabins using model-based systems engineering," 33rd Congress of the INternational Conuncil of the Aeronautical Sciences, ICAS, Stockholm, Sweden. ISSN 2958-4647, 2022.

[20] I.M.Masic, F.Reimer, T.M.Bock, F.Meller and B.Nagel, "Application of VR Technology in the Aircraft Cabin Design Process," CEAS Aeronautical Journal, 1-10, doi: 10.1007/s13272-021-00559-x, 2021.

[21] S.Cornelje, "Mixing Realities: Combining Extended and Physical Reality in Co-Creative Design for the Flying-V," Delft University of Technology, Netherlands, 2023.

[22] F.Reimer, J.Herzig, M.Lindlar, P.Weiand, S.Cornelje, L.Winkler, J.Biedermann and B.Nagel, "Create Your Own Cabin - Connecting Multidisciplinary User Perspectives and a Future Rescue Helicopter Concept Within the Applied Xr Co-design Proces," CEAS Aeronautical Journal (Research Square); Preprint, doi: 10.21203/rs.3.rs-4174792/v1 , 2024.

[23] M.Fuchs, J.Abulawi, C.Fuchs, D.Meier, B.Merkel and T.Timur, "Modellierungsstrategie zur Analyse des Einflusses von alternativen Antriebskonzepten auf Kabinensysteme.," Deutscher Luft-und Raumfahrt Kongress 2023, Stuttgart, Deutschland; dou: 10.259667/610104, 2023.

[24] F.Rauscher, M.Fuchs, Y.Ghanjaoui, N.Markusheska, J.Biedermann and B. F.Meller, "Permanently updated 3D-model of actual gemetries of research environments," CEAS Aeronautical Journal.Springer, doi: 10.1007/s13272-023-00661-2 , 2023.

[25] J.Brooke, "SUS: a “quick and dirty” usability scale," P. W. Jordan, B. Thomas, B. A. Weerdmeester, & A. L. McClelland (eds.). Usability Evaluation in Industry. London , Taylor and Francis, 1986.

[26] M.Soegaard, "Interaction-Design," 2024. [Online]. Available: https://www.interaction-design.org/literature/article/system-usability-scale.

[27] K.Verleye, "The Co-Creation Experiences from the Customer Perspective: Its Measurement and Determinants," Journal of Service Management 26, 321-342, doi: 10.1108/JOSM-09-2014-0254 , 2015.