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Advancing Sustainable Prototyping of Future Aircraft Cabin Designs Through Extended Reality Technologies †

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Abstract: This paper explores the virtual development of cabin concepts for hydrogen-powered aircraft, emphasizing sustainable, safe, and comfortable transport solutions. It examines how digital technologies can accelerate product development by involving engineers and other experts early in the design process. Specifically, the study focuses on a Virtual Reality (VR) application that allows stakeholders to design, iterate, and evaluate 3D cabin concepts in real time, offering a flexible and scalable alternative to physical prototypes. The findings highlight the effectiveness of user-centered design approaches, such as immersive co-design in Extended Reality (XR), in enhancing collaboration and improving the efficiency and sustainability of integrating innovative design concepts within a virtual environment.

Keywords: sustainable prototyping; co-design; cabin design; extended reality; user experience

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1. Introduction

In order to ensure the sustainability of commercial aviation in the future, the exploration of new energy sources and the impact on aircraft system architecture is crucial. One promising alternative propulsion system is hydrogen combustion, which has shown great potential as a means of propelling aircraft on short- and medium-haul flights [1].

Beyond propulsion, the integration of the cabin and its systems plays a critical role in achieving not only sustainable but also safe and comfortable air transport. Each new aircraft concept presents unique challenges that require adjustments to the cabin architecture to accommodate innovative systems. These redesigns must balance evolving technological demands and stringent regulatory requirements, while meeting passenger needs and optimizing space utilization to ensure economic efficiency [2,3].

Traditional design methods that rely on physical cabin models are highly resource-intensive, making them both costly and time-consuming. Moreover, they offer limited flexibility and adaptability due to inherent physical constraints [3].

To seamlessly link aircraft design with cabin development while minimizing the use of resources, the German Aerospace Center (DLR) employs the concept of the digital thread. This approach aims to achieve comprehensive digital integration and connectivity at every stage of aircraft development. The goal is to achieve a smooth and continuous flow of data throughout the entire lifecycle of an aircraft—from initial design through production to maintenance. This process involves a fully virtual representation of digital development processes and concepts, enabling digital prototyping and iterative adjustments [1–3].

To address both technical and environmental challenges while meeting future user needs, a user-centered design approach using advanced technologies such as Extended Reality (XR) will be explored. This approach aims to engage stakeholders early in the digital development process, providing them with the opportunity to actively contribute to the design phase [3].

2. Fundamentals

The involvement of users in the development process of new products is becoming increasingly important to keep pace with technological progress and to ensure the acceptance of new products. This user-centered design approach places users at the forefront, treating them as "experts of their experiences" [4]. This approach is known as co-creation or co-design. According to Sanders and Stappers, co-creation includes "any act of collective creativity, i.e., creativity that is shared by two or more people" while co-design refers to "the creativity of designers and people not trained in design working together in the design development process" [5].

In addition to involving end users, it is equally important to include other stakeholders in the design process. According to Sanders, this "changes the nature of design activity from one of individual creativity to one of collective generativity" [6].

The sense of community that can develop within this collective contributes to a better experience of the co-creation process, which, in turn, has a significant impact on the quality of the resulting design [7]. Lee et al. therefore argue that it is crucial not only to identify relevant stakeholders but also to develop a thorough understanding of the key functions and design choices of co-creation in order to create a sense of community within the collaborative process. This includes defining project requirements and carefully designing co-design activities to improve the quality of stakeholder engagement and thus project outcomes [8].

2.1. XR Co-Design

To involve stakeholders more deeply in the co-creation process and leverage the knowledge of the "experts of their experience" [4], the designer provides "generative tools" for idea generation and expression [9]. Both the tools and the platform play a crucial role in facilitating active and creative user participation, so careful selection is essential [10]. The use of immersive technologies such as Virtual, Augmented, and Mixed Reality—collectively known as Extended Reality (XR)—has proven effective in creating a platform where designers, (end) users, and other participants can collaborate simultaneously and regardless of their location [11].

The so-called XR co-design uses the potential of three-dimensional immersive environments to facilitate collaboration within the design process. Previous studies have demonstrated that virtual collaboration not only facilitates the development of collaborative design concepts among various stakeholders but also enhances the creativity and motivation of the participants [12,13].

The strength of the XR co-design methodology lies in the combination of XR tools, which enable the virtual development and evaluation of design concepts in real time, with the co-design approach. This allows designers to learn directly from the experts and empower them to participate in the design process. Furthermore, it ensures that future cabin designs align with technical requirements while prioritizing user needs.

To enable early user involvement in the design process, immersive technologies and digital models also allow for the reduction or elimination of physical models [3], thereby shifting the prototyping process from the physical to the digital realm. But does this make virtual prototyping sustainable?

2.2. Sustainable Prototyping

Sustainability can be categorized into social, environmental and economic sustainability [14]. Social sustainability, as defined by Corsini and Moultrie, is critical to fostering positive change that addresses pressing societal challenges, particularly in the humanitarian development sector [15]. Thus, Roedl and Bardwell et al. position "makers" as pivotal actors with specialized skills driving positive social change. The term "maker" refers to individuals or communities involved in creating, modifying, or adapting physical or digital artifacts, often leveraging accessible tools and materials. Makers are distinguished by their hands-on approach, creativity, and focus on personal empowerment or collective innovation. Acting as central agents of social and technological transformation, they apply their skills to address challenges and foster positive change [16]—an ethos closely aligned with the principles of co-design, which emphasizes collaboration and inclusivity in the creation process.

However, the development of aircraft cabins must pay particular attention to environmental and economic sustainability.

In digital product development, two key factors must be considered to ensure environmental sustainability: "the material and the process used in making the prototypes" [14]. Renewable resources and the efficient use of tools can contribute to more sustainable production and can be evaluated using the Life Cycle Assessment (LCA) approach [16]. While environmental impact focuses primarily on waste reduction, energy efficiency, recycling, and reuse, economic sustainability also considers factors such as repair, refurbishment and local production [14].

Lazaro et al. extend the concept of sustainability beyond the manufacturing process to include the entire prototyping cycle. Their research emphasizes the importance of adopting techniques that enhance the sustainability of design and prototyping processes, from conception to the end-of-life phase [17].

The rationale behind developing prototypes is manifold. According to Soomro et al., prototyping offers "an opportunity to transform a design idea into a tangible form", which is particularly useful in the early stages of the design process for "concept testing and evaluation purposes" [14]. In the user-centered design thinking method developed at Stanford, rudimentary prototypes are used in the fourth of five phases to obtain early user feedback and iteratively improve the solution [18]. As these prototypes may be low in detail and only needed for a short period of time in the design process, or alternatively, they may require ongoing changes, physical implementation is not always necessary [3].

As posited by Yadav et al., virtual prototyping can significantly contribute to sustainable development by reducing material waste and decreasing energy consumption through minimizing the need for physical prototypes and testing phases. Another significant advantage of virtual prototypes is that they facilitate effective collaboration between global teams based in disparate locations, thereby encouraging interdisciplinary teamwork and integration into the product development process [19].

3. Study

As part of the ongoing research into the XR co-design methodology, the potential of these technologies was explored to not only enhance the co-design process for aircraft cabin design but also establish their viability as a sustainable digital prototyping tool. In order to address this question, a virtual cabin configuration application was developed as a use case, and to evaluate its potential, a user experience study was conducted. The application allows users to design, test, and iterate their own cabin concepts in real time and at full scale.

The VR application, which was created using the Unity real-time development platform, is based on a simplified version of the single aisle cabin of the D250-TPLH2 MHEP short-haul hydrogen aircraft configuration from DLR's internal project "EXACT".

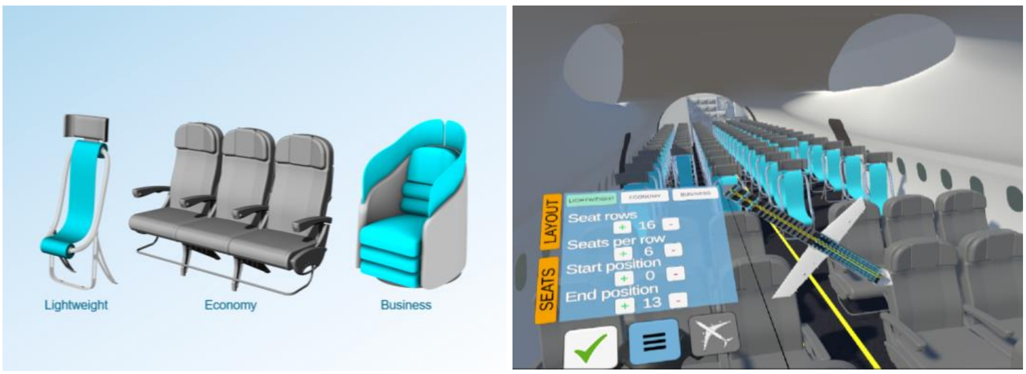
3.1. Experimental Setup

The HTC Vive Pro was used as the VR device, along with the previously introduced VR cabin configuration application. The application ran on an Alienware laptop and was connected to the large display wall to observe the participants in VR and guide them through the task (see Figure 1).

Figure 1. Experimental room setup: facilitator (**left**) and a study participant (**right**) developing a seat layout design.

Participants in the study were asked to design a seating layout for a future hydrogen aircraft cabin for an exemplary short-haul flight between Hamburg, Germany, and Mallorca, Spain, estimated to take around two and a half hours.

To solve this task the participants were offered a choice of three different seat types: the half standing lightweight seat, the economy seat, and the business seat (see Figure 2a). They were given the option of utilising all or only some of the provided options. Based on this selection, they were required to design a 36-metre-long cabin layout in consideration of their individual preferences. To streamline the task, participants were instructed to concentrate solely on the seating arrangement, without worrying about precision or considering seat pitch, galleys, lavatories or other cabin monuments.



(**a**) (**b**)

Figure 2. (**a**) Available seat types (from left to right): half standing lightweight seat, economy seat, and business seat. (**b**) User interface of the VR application from the perspective of a participant.

Figure 2b illustrates the user interface of the application from the perspective of a participant. On the left-hand side of the controller, a pop-up menu enables the user to select the seat type, add rows of seats, and define the start and end points of the seat configuration. To enhance the overview of the cabin, the user has the option to display a top view of the aircraft, which is accessed by selecting the small aircraft icon. Movement within the cabin is initiated by pressing the trackpad of the left controller in the desired direction of movement.

The total time available to each participant was 25 min, with participants completing the task individually and sequentially. The adjustment of the headset required approximately one minute. Subsequently, the participants were provided with a four-minute introduction to the Virtual Reality (VR) application, during which they were instructed on the functions for navigating, creating, and arranging seats. Following this, the participants were allotted 15 min to complete the assigned task. After ten minutes, the facilitator provided a reminder that they still had five minutes remaining to review the current concept. This was followed by verbal feedback and a five-minute time slot to complete the questionnaire.

The group of participants consisted of a total of 15 individuals, with an average age of 33. Of these, 36% were female and 64% were male. The distribution of participants by occupation is illustrated in Table 1.

Table 1. The distribution of participants by occupation.

Profession	Number of Participants	Percentage (%)
Engineer	5	34
Scientific Researcher	3	20
Designer	2	13
Technical Assistant	2	13
Controller	2	13
Architect	1	7

3.2. Methodology and Analysis

In her research, Santhosh identifies three key aspects of XR co-creation or XR co-design that can be used to assess its quality: collaboration, interaction, and user experience [10]. This application and the associated study focused on analysing the individual actions of the participants in combination with the support of the tool provided by the designer. As there was no collaboration between the participants, only the individual interaction quality and the user experience are analysed in the following study.

Accordingly, a two-part questionnaire was employed for the collection of subjective data. The initial section of the questionnaire comprised a user experience questionnaire, which consisted of established psychometric measurement instruments for evaluating the user experience within the virtual environment [20]. The questions were divided into the following sections: interactivity, immersion, telepresence, emotional response, autonomy, action competence, and satisfaction.

The utilization of VR also implies a particular form of human–computer interaction (HCI), which must be considered in the analysis [21]. To this end, the System Usability Scale (SUS) was employed in the second part of the questionnaire to evaluate the usability of the application [22].

Both questionnaires are based on a 5-point Likert scale, ranging from “1—strongly disagree” to “5—strongly agree” [20–22].

A further evaluation of the usability, efficiency and performance of the HCI was carried out by measuring the time taken to complete the task. Participants were given a maximum time window of 15 min to complete the task in order to collect objective data.

In addition to the questionnaires that formed the basis of the data collection, the study was videotaped with the consent of the participants and subsequently analyzed.

3.3. Results

The box plot in Figure 3a shows the average number of seats selected in the different seating concepts. There is a large variation in the seating concepts developed, ranging from a minimum of 126 seats to a maximum of 288 seats in total. The mean number of seats is 182, with the first quartile at 144 seats and the third quartile at 210 seats, highlighting the diversity in design approaches.

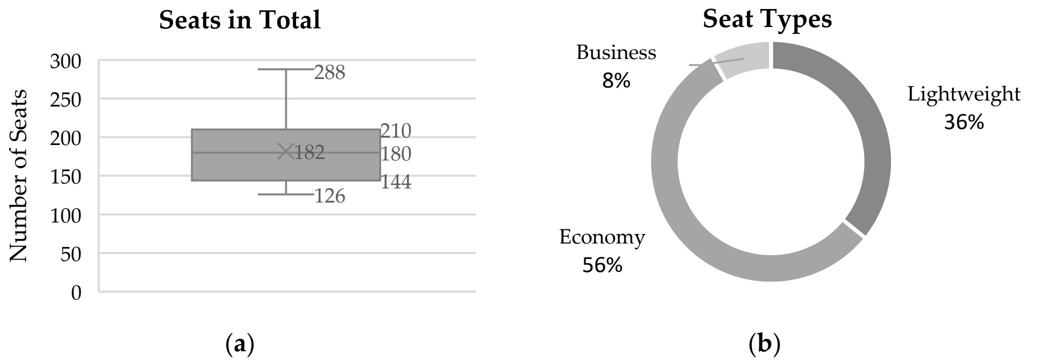


Figure 3. (**a**) Average number of seat selection. (**b**) Distribution of the total number of selected seat types.

Figure 3b shows the distribution of the three different seat types. More than half of the cabin, namely, 56%, is assigned to Economy Class. Surprisingly, 36% of the cabin was equipped with light standing seats. Business seats were generally occupied by no more than two rows, representing 8% of the total capacity.

The results of the System Usability Scale (SUS) from the questionnaire are presented below. As no qualitative differences were observed between the female and male participants (80.333 to 80), no distinction was made in the subsequent analysis.

In terms of the overall usability of the application, the initial evaluation was positive, with six "A" ratings (excellent), eight "B" ratings (good), and one "D" rating (poor).

In the course of this SUS evaluation, an anomaly was identified when the different professions were compared. Four out of six groups rated the application as "A", while two groups only gave it a "B". These were the groups of designers and controllers. It should be noted that the designers had a certain amount of experience with VR, while the other participants had no or only marginal experience with this technology. The subsequent discussion with the participants led to the conclusion that an excess of expertise in relation to the VR tools mentioned can result in a critical attitude, while insufficient expertise might lead to feelings of overwhelm.

The results of the user experience analysis indicate that the various aspects, including "interactivity", "immersion", "emotional response", "autonomy", "action competence" and "satisfaction", all receive high scores of 4 or above (see Figure 4).

The only category that was below average, with a score of 2.7, was "telepresence". This is particularly notable as the closely related aspect of immersion received a much higher average score of 4.3. This discrepancy may be a potential explanation for the observed differences in participants' perceptions. While the results demonstrate that the application effectively immerses users in the virtual cabin, it falls short of creating a convincing sense of physical "presence" within the environment. This indicates that although participants felt immersed in the virtual environment, they did not fully experience the feeling of actually "being there".

Additionally, minimal discrepancies were observed between the genders with regard to the user experience scores. The mean score for women was 4.2, while that for men was 4. A comparison of the user experience scores of the different professional groups shows a deviation of 0.158. Due to its relatively small magnitude, this difference was not analyzed further.

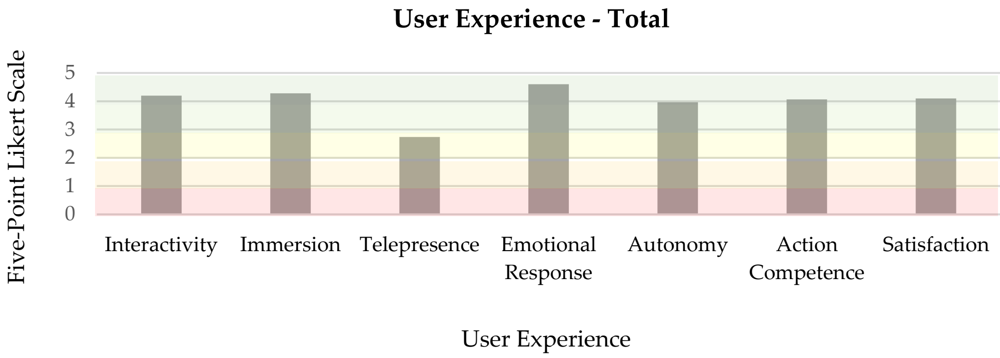


Figure 4. Evaluation of the user experience questionnaire divided into different sections.

Based on the objective data collected, i.e., the time measured, all participants successfully created a seating concept within the allotted 15 min. A total of 33% of participants used the maximum time available, while the remaining 66% finished earlier. On average, participants took 14 min and 31 s to complete the task.

4. Conclusions and Outlook

The VR application in this study enabled the rapid prototyping of a cabin seat concept without relying on physical resources. It facilitated a swift modification and iteration process, promoting innovation while maintaining a resource-efficient approach that aligns with long-term environmental responsibility. After a total duration of 6.5 h, 15 different digital cabin concepts were created by different experts, providing a sufficient knowledge base to identify key focus areas for future aircraft seat layouts. This approach could be particularly beneficial in the early stages of developing new aircraft and cabin concepts as it facilitates efficient digital collaboration between experts from different disciplines and locations.

The application of the XR co-design method led to promising results, particularly with regard to the emotional response and satisfaction of the participants. This resulted above all in a high level of motivation and enthusiasm for the task. The increased commitment was also reflected in the fact that 73% of participants were interested in seeing and discussing the cabin concepts of others.

It is also worth noting the different approaches employed by the participants in this study. While the engineers focused on calculating weights and taking the center of gravity into account when selecting and positioning seats, the designers and architects concentrated more on the spatial design and use of the cabin. The non-experts (controllers), on the other hand, looked at the situation from the passenger's point of view.

The approaches presented exemplify the effectiveness of the co-design method by integrating the knowledge of multiple experts, enabling analysis and development from different perspectives.

However, this study primarily focused on the use of a VR application for sustainable virtual design of cabin concepts. As the participants worked on the task individually, there was no collaborative interaction between them. Thus, the co-design process was limited to the interaction between the designer, the available tools, and the participant in his role as an expert.

It has been shown that the main strength of this method is its ability to involve different experts in the design process. In this study, such collaboration between the participants could have reduced the wide variation in layout designs—some of which proved unfeasible—while leveraging the combined expertise from different disciplines for a more efficient workflow.

In general, the XR co-design method is well suited for the early digital development and iteration of cabin concepts that can be seamlessly integrated into other phases of aircraft development. Its digital nature provides a resource-efficient approach to prototyping, contributing to a more sustainable future in aviation.

The next step in the development of the application is the integration of a multi-user mode, which will enable the joint validation of cabin concepts by different stakeholders.

The application should also be able to provide more detailed feedback. For example, additional information about the cabin, emergency exits, and details about the number of seats already in use and their dimensions. It would also be beneficial to offer a wider range of objects, systems, and other monuments to enable a more detailed realization of a cabin concept.

In order to optimize telepresence, it would be beneficial to utilize a high-fidelity model and to integrate a seating option within the designated space. In this regard, the findings of this study are relevant as 60% of the participants expressed a desire for a physical chair to better understand the seating row spacing. The integration of simple physical elements, such as a chair, could enhance the user experience in terms of immersion and telepresence, thereby improving the ability to perform tasks virtually as they would in reality.

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Institutional Review Board Statement: Ethical review and approval were waived for this study due to the research being an internal study that only involved employees of the organization. The study utilized de-identified, aggregate data collected as part of routine organizational processes, with no direct manipulation or intervention. Participation was voluntary, and no sensitive personal information was disclosed or accessed beyond what is typically available within the organization's operational data. Given that the study did not involve vulnerable populations, posed minimal risk to participants, and adhered to the organization's internal privacy and confidentiality guidelines, the waiver of full ethical review was deemed appropriate.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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