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SI.: PROTOTYPING AND DEVELOPING REAL-WORLD APPLICATIONS FOR EXTENDED REALITY

Facilitating and enhancing co-creation through multi-sensory mixed reality experiences: a paradigm shift in stakeholder engagement

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Abstract

Co-creation has become increasingly important as companies strive to develop more customer-centric products and services by involving stakeholders throughout the design process. This paper introduces XR-CO, a multi-sensory, multi-user mixed reality co-creation platform. XR-CO utilizes an optical see-through head mounted display to create a 1:1 immersive mixed reality environment over essential physical prototypes, allowing stakeholders to physically interact with functional prototypes inside the digital environment. By incorporating visual, auditory, somatosensory and vestibular senses, XR-CO maximizes collaboration and triggers meaningful interactions among stakeholders, leading to improved co-creation quality. To validate XR-CO's effectiveness, a study was conducted involving 32 participants in co-creation sessions for the development of cabin interiors of a new concept aircraft, the Flying-V. Half of the participants used XR-CO platform, while another half used the conventional desktop co-creation setups. The participants appreciated the XR-CO platforms, as indicated by their high scores in CSI, SUS, co-creation experience, and quantity of ideas in terms of quantitative data analysis. Additionally, 4D scanning of participants movements demonstrated that XR-CO provided a true-to-life perception of the digital space. XR-CO facilitated the discovery of more design issues compared to conventional setups, a finding affirmed by an expert panel using qualitative Delphi techniques. The positive user experience and meaningful outcomes observed in these co-creation sessions serve as strong evidence of the efficacy of the XR-CO platform, particularly the newly introduced somatosense. In summary, our study highlights the significance of XR-CO in co-creation processes. The platform's immersive nature, combined with the integration of multiple sensory inputs, fosters collaboration, enriches interactions, and ultimately leads to improved outcomes.

Keywords Co-creation · Extended reality · Collaboration · Co-creation platform

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1 Introduction

The need for human-centric processes in the world of business and innovation has opened up new avenues for engaging stakeholders, including customers, employees, partners, and suppliers, in the design of new products and services. Co-creation has emerged as one such approach, which involves collaborating with stakeholders to design and develop new products to create solutions that better meet their needs and expectations (Ind and Coates 2013). While co-creation is commonly recognised as beneficial in the fuzzy front end of the design process, studies have demonstrated its benefits throughout various phases of product development (Payne et al. 2008). However, the role of stakeholders varies across different activities and their expertise related to the goals (Bartl et al. 2010). Similar concepts like participatory

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design, co-design, and user-centered design have also emphasised involving end users in the product development process (Sanders and Stappers 2008). Regardless of the terminology used, the underlying essence remains the same: collaborative development of new value in terms of products, solutions, concepts and services (Payne et al. 2008), Amin et al. (2024) . Bal et al. (2023) conducted a systematic literature review to provide a comprehensive overview of the conceptualisation of VCC (Value Co Creation), as well as the stakeholders' expected and realised value through collaboration. Thus, the success of co-creation depends on how effectively the users are mobilised and how well they collaborate and interact (Prahalad et al. 2000). Zhang and Xu (2024)explores the impact of the incentive mechanism on live streaming sales.

In this framework, it is particularly challenging to create an environment in which diverse participants with different roles can exist and interact. Co-creation sessions compel stakeholders to work towards a common goal. The experiences which the user bears imply quality of interactions and lead to positive relationships and achievements of the goals of the session (Prahalad and Ramaswamy 2004). Therefore, the platforms, tools or environments that are adopted for a co-creation session have a significant impact on the level of involvement, creativity, interaction, and experience and thus co-creation (Ramaswamy and Ozcan 2018).

Technical advancements in recent decades have revolutionised collaboration and communication methods. While communication tools like sketches, 3D models, and cardboard prototypes are commonly used to aid understanding and engagement during iterative design phases, there is still a gap in cognition due to a lack of sufficient stimuli for situation awareness and sensemaking (El-Jarn and Southern 2020).

The concept of virtual worlds for co-creation has been studied for countless reasons ranging from telepresence, real-time feedback collection, media rich information, real-time sharing and active engagement (Kohler et al. 2011). Virtual worlds offer a range of tools and features that foster creativity, inspire new ideas, and enable users to experiment and explore new possibilities, reducing the reliance on physical mock-ups and meetings, leading to lower costs and reduced environmental impact. Most recently, Richter and Richter (2023) conceptualised the Metaverse as an evolution of such Virtual Worlds in interactive and distributed simulations evolved with new technologies, such as virtual and augmented reality, which have enabled even more sophisticated immersive experiences and new applications, such as virtual tourism and art. Furthermore, Nambisan and Nambisan (2008) have highlighted a framework on virtual customer environments and five possible customer roles, which influence the customer environment and experience during product development. It has been featured that dominant customer experience components and virtual technologies vary according to the nature of customer contributions and their roles. The co-creation experience significantly affects the quality and quantity of ideas generated, emphasising the importance of designing co-creation environments and experiences (Prahalad and Ramaswamy 2004). Meanwhile, studies have highlighted the need to explore technologies and compare different virtual worlds to study the effect of different experience dimensions for different co-creation tasks (Kohler et al. 2011). These promising opportunities have led to the proposal of Extended Reality (XR) technologies as potential co-creative platforms, incorporating the three factors that leverage the platform: collaboration, interaction and user experience (Santhosh 2022). XR technologies have evolved in supporting remote collaboration, intuitive interactions, and immersive experiences, making them an ideal fit for executing co-creation sessions (Vasilchenko et al. 2020). However, there is limited research on the establishment and analysis of XR for enriching co-creation sessions, and suitable validation methods need to be developed to understand its potential contribution (Poretski et al. 2021; Cascini et al. 2020).

In this context, this paper introduces XR-CO, a multi-user, multi-sensory Mixed Reality system developed for Microsoft HoloLens2 as a co-creative platform aimed at enhancing the quality and quantity of generated ideas, promoting creativity and improving user experience. XR-CO is expected to reduce the development time and costs of the prototype, boost user involvement and provide a deeper and wider understanding of the target design and product. Furthermore, the XR-CO system includes functional prototypes integrated into an immersive XR environment, enabling users to physically interact with the product and experience a sense of the product's touch and feel, which stimulates creativity. The real-scale immersive environment allows user to perceive the digital space, which further induces their task assessment skills. The key scientific contributions of this study include:

- A novel XR-CO platform framework that enables intuitive interactions between stakeholders, physical prototypes, and the virtual environment, thereby fostering a more effective co-creation experience.
- The practical application of the XR-CO platform through a co-creation experiment focused on designing new aircraft interiors, demonstrating its potential in real-world scenarios.
- A comprehensive evaluation of XR-CO's effectiveness using subjective and objective measures to assess process efficiency and outcomes.

2 XR-CO: a multi-sensory, multi-user mixed-reality co-creation platform

Traditionally, evaluating new designs requires physical prototypes and full-scale mock-ups, which can be costly and time-consuming. The iterative nature of design calls for alternative tools and environments that support a more efficient and interactive process (Berg and Vance 2017; Moerland-Masic et al. 2021). With the rapid growth of cutting-edge technologies aimed at creating innovative communication channels, immersive technologies have attracted considerable attention for their potential to develop collaborative and interactive environments. These technologies, among the fastest-growing of today, offer real-time collaboration, visualisation, and platforms that support interaction within digital to semi-digital environments.

Extended Reality in particular offers significant potential for enhancing the co-creation process, especially by improving the user experience. The power of XR technologies is well-demonstrated in numerous studies, including those outside the aeronautical sector (El-Jarn and Southern 2020). The main advantages of XR lie in its immersiveness and interactivity within a real-time environment. Over recent years, companies and research centers have developed several XR creation software tools to assist users. One of the greatest advantages of XR is its ability to bridge geographical and scientific distances, allowing different users to be placed in the same virtual room, interacting live within the same workspace, despite current technological limitations.

Quantifying the effectiveness of a design process can be complex and application-dependent. However, in the context of collaborative design in the aeronautical industry, XR can offer significant benefits. The complexity of aircraft systems and the variety of experts and users involved across various scientific and non-scientific fields make collaborative design tools extremely valuable, especially when combined with XR. These tools can help bring experts together and bridge the physical distance between them, making collaboration more efficient. For example, the VR tool developed by Seymourpowell aims to shorten design time and harmonise the requests of designers, engineers, and regulators through a dynamic, iterative process (Seymourpowell 2025). Similarly, Airbus is developing a VR tool in collaboration with leading players in the industry, like Unity, to help with in-house design and implementation. This VR tool allows customers to evaluate and modify aspects of the A350 XWB cabin, such as seats, carpet, and lighting (Airbus 2025).

Several studies have attempted to estimate and quantify the benefits of collaborative design in a virtual environment, usually through case studies with small groups of participants, evaluating their feedback using questionnaires and efficiency indicators, such as time to complete tasks. As an example (Breland and Shiratuddin 2009) conducted experiments with architectural students using a dedicated Collaborative Virtual Environment (CVE). Results showed collaborative CVE use improved productivity, reduced design errors, lowered stress, and enhanced group mindset compared to individual use. Yigitbas et al. (2023) explored the potential of using virtual reality (VR) technology for collaborative UML software design by comparing it with classical collaborative software design using conventional devices (desktop PC/laptop). Rosenman et al. (2007) presents a collaborative virtual environment for multi-disciplinary design. However, to the authors' knowledge, no major studies have been conducted specifically on the potential benefits within the aeronautical field. One notable example is the work of the DLR (The German Aerospace Research Center) research group, which is developing a tool for multi-design optimisation and collaborative design: the Common Parametric Aircraft Configuration Schema (CPACS). This tool standardises the storage of geometrical, physical, and system information for aircraft in an HTML format, providing a common language that enhances collaboration between different fields.

In a study by Fuchs et al. (2021), CPACS files were used to generate a VR model of an aircraft cabin for analysis, particularly regarding comfort and safety. The potential of CPACS lies in its ability to store results from different simulations and research, which could later be uploaded into XR environments for further collaboration. The authors highlight that VR can significantly improve communication among research partners, with all observers able to directly participate in the evaluation and optimisation process. By combining Multidisciplinary Design Optimization (MDO) tools such as CPACS with XR technologies, remote collaboration between different partners can be greatly enhanced, facilitating the collaborative design of complex systems such as aircraft (Cooper et al. 2021).

In this framework, we developed a methodology that integrates an extended reality-based platform (XR-CO) to involve different stakeholders in aircraft cabin design co-creation activities. By leveraging immersive technologies, the XR-CO platform enables stakeholders such as cabin crew and passengers to intuitively interact with and assess designs in an innovative, immersive, and multi-user co-creation environment. This approach is expected to enhance the design and evaluation process, facilitating a more efficient, collaborative, and interactive design experience. The XR-CO platform foresees a scene designed as a 1:1 world-scale environment, integrating physical prototypes and virtual elements to provide an immersive co-creation experience. Key components include:

Real-Scale Digital Environment A virtual model is projected onto the physical space using an active spatial awareness system, ensuring accurate alignment between digital and physical elements.

Multi-Sensory Interactions Users interact with the system using hand-tracking menus displayed via Microsoft HoloLens2. Hand gestures allow users to place feedback markers and manipulate objects using natural movements.

Collaborative Features XR-CO supports remote and co-located interactions, enabling synchronous and asynchronous collaboration. Avatars represent remote participants, ensuring a shared spatial awareness and a cohesive experience for all users.

In order to investigate the effectiveness of the platform for product testing, and particularly evaluating its impact on creativity, collaboration, interaction, and coordination a cabin design use case scenario has been developed. Moreover, to understand how user experience (UX) in an immersive environment influences the co-creation process, the XR-CO sessions was compared with conventional desktop co-creation methods.

2.1 Use case scenario: the Flying-V concept

When designing aircraft interiors, there are various aspects to be considered rather than merely visual designing, often leading to long and tedious decision-making. The safety of passengers and cabin crew onboard is the first and foremost requirement for a successful cabin design (Moerland-Masic et al. 2021). Additionally, the cabin is a complex product that caters to various users and contexts, each with its preferences and requirements. Within this frame of reference, we introduce Flying-V, a new design for an energy-efficient long-distance airplane developed in collaboration between Delft University of Technology (TU Delft), Airbus, and KLM Royal Dutch Airlines as Fig. 1. The Flying-V features a unique wing structure that integrates the passenger cabin, cargo hold and fuel tanks, resulting in a distinctive V-shape. The innovative oval cabin configuration has boosted insights to designers on seat designs and innovations within the Flying-V fuselage (Vink et al. 2020). One such innovation is the Staggered Seats, designed to offer passengers more legroom and individual armrests, thereby creating additional shoulder-to-shoulder space between passengers. The staggered seats are positioned at an angle relative to the direction of flight, resulting in a row of seats that is not aligned in a straight line but rather angled (Vink et al. 2021), as shown in Fig. 2. This new seat design and configuration, developed by TU Delft-IDE, has facilitated a suitable co-creation scenario for gathering constructive feedback from the end users, including cabin crew and passengers, during the design stages focusing on the normal activities to be executed inside the cabin.

2.1.1 XR-CO setup and interaction features in the Flying-V

The XR-CO scene is a setup in a 1:1 world scale environment, featuring two physical prototypes of staggered seats labelled Seat A and Seat B. These seats are clearly labelled to ensure easy identification in the immersive environment. A real-scale digital environment of the Flying-V cabin model is instantiated on the table anchor and projected with an active spatial awareness system to seamlessly merge with the physical seats in the space. Various sitting postures of 3D avatars are placed on the seats within the cabin model to serve as visual representations. A 3D model of meal-tray and sticky notes are added to the project for interactive experiences.

The sticky notes, designed with green and red colours, are modelled in Unity. The HoloLens placed on the calibration point ensures the mesh observer shape is aligned with the physical seats and that the floor of the aircraft model aligns with the physical floor, thus maintaining accurate dimensions and proportions of the seats, as depicted in Fig. 3.

For the experiments, two HMDs (Head-Mounted Displays) are utilised. Users wearing the Microsoft HoloLens2 are fully immersed in the real-scale Flying-V model and can walk inside this environment, simulating the proportions of a physical mock-up, as shown in Fig. 4. The users can even physically touch and sit on the physical seats, providing

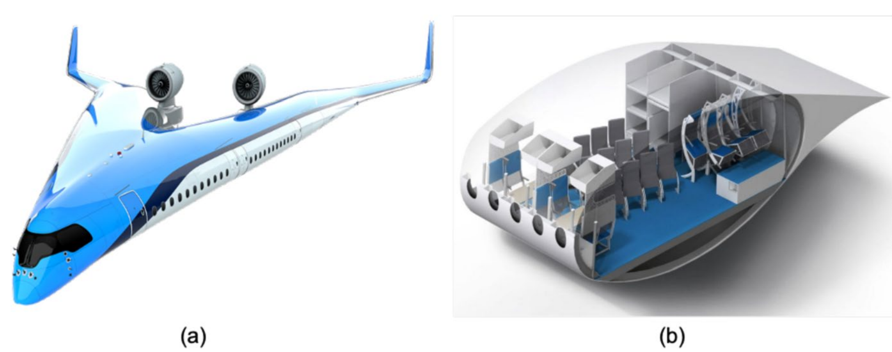


Fig. 1 The Flying-V concept **a** Flying-V aircraft **b** Cabin design of the concept (courtesy of https://www.tudelft.nl/en/ae/flying-v)

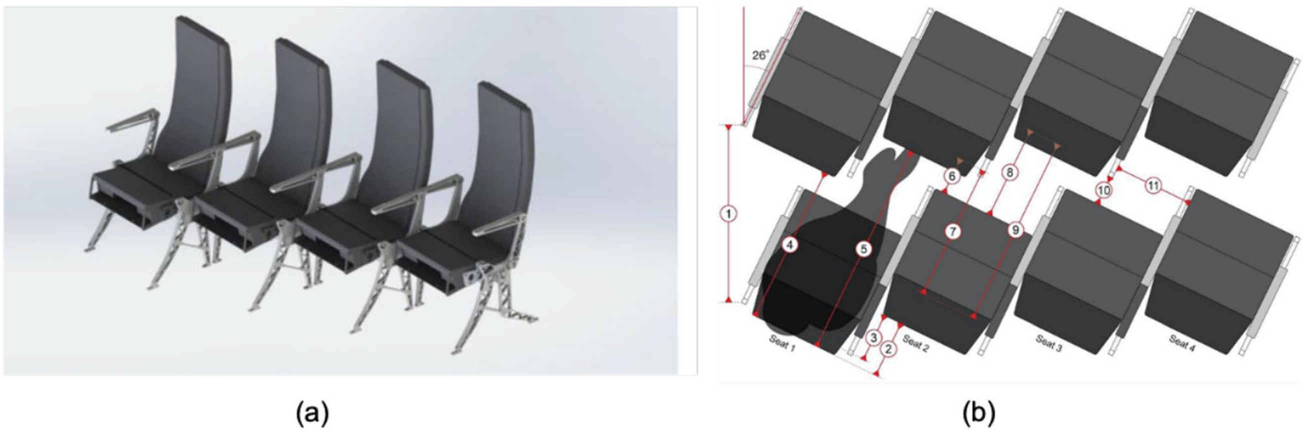


Fig. 2 Staggered Seats design and configuration **a** The Seats **b** Top view of the configuration

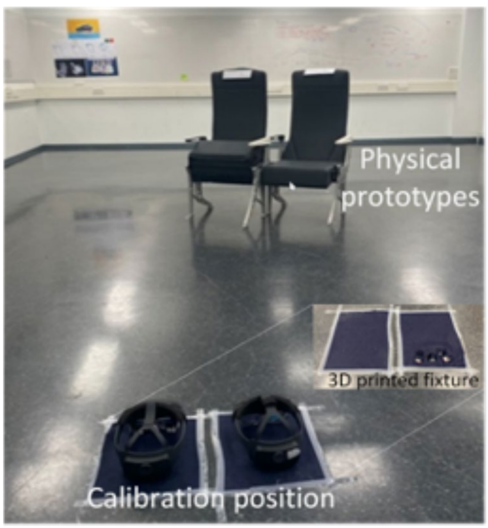


Fig. 3 XR-CO setup and calibration point

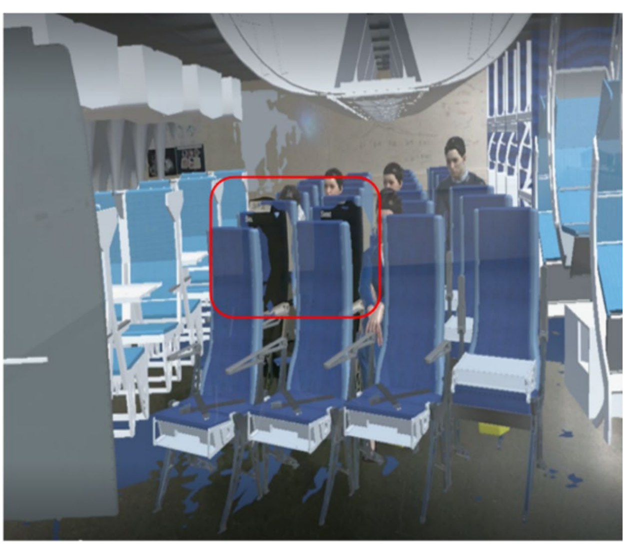


Fig. 4 Extended reality real-scale Flying-V model. Physical seats in the red square

them with a comprehensive experience that encompasses all design aspects. The design of the interaction features is aimed to be intuitive for the users, eliminating the need for extensive training of motion controllers. All interactions were hand-based with hand mesh visualisation in the virtual space. To provide a personalised easily accessible menu to trigger the digital elements, a hand menu with three buttons was created for the users. When the users' palm is faced up and they gaze at their hand, the menu is invoked beside the ulna bone of the hand, as shown in Fig. 5. When pressed by a finger, each of the three buttons triggers the appearance of a different object in the scene: a green sticky note, a red sticky note and a meal tray. The sticky notes, appearing in front of the user, can be moved and placed wherever in the scene with a pinch, hold and move gesture as Fig. 6. The green sticky note indicates positive aspects of the design that the users liked, while the red sticky note represents the doubts, concerns, or aspects that the users did not like. The meal-tray button activates the appearance of a true-to-scale meal-tray, which can be moved with two hands pinch, hold and move gesture, replicating the intuitive interaction found in real-life scenarios, as illustrated in Fig. 7. A tool tip attached to the meal-tray provides instructions on how to move it using both hands. The sticky notes are exclusive and recurrent for each user, allowing them to provide continuous feedback, while the meal tray is triggered only once by the cabin crew and is visible to both users.

3 Methods

The experiment presented in this paper was approved by the Human Research Ethics Committee (HREC) at Delft University of Technology under file number 2599. Informed consent was obtained from each participant prior to the experiment. All sensitive participant data were anonymised following the established protocols.

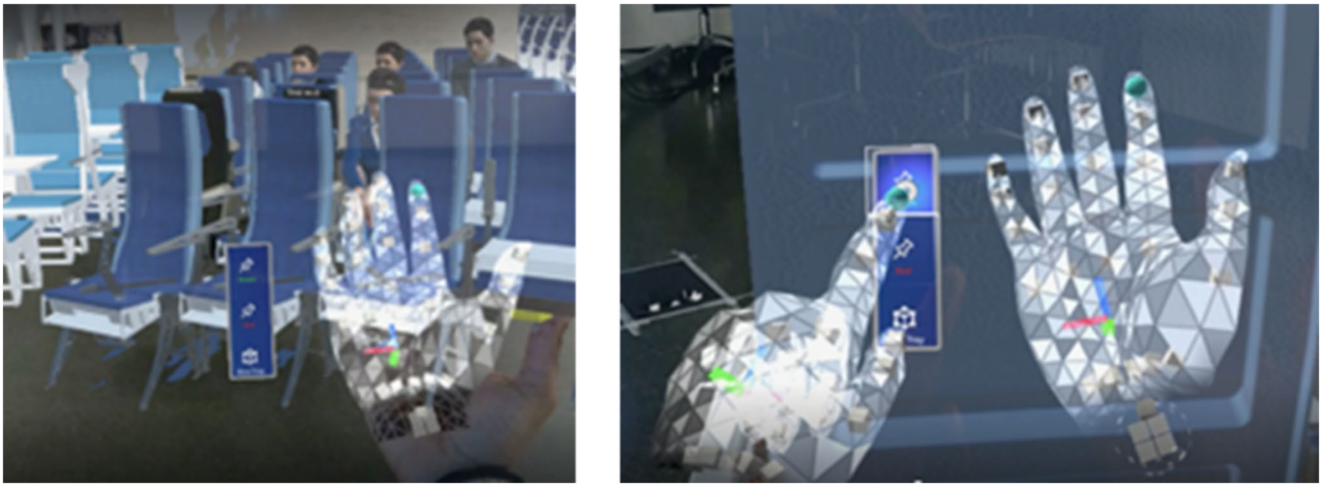


Fig. 5 Interaction in XR-CO through Hand Mesh and MENU

Fig. 6 Hold (a) and move (b) interaction with sticky notes

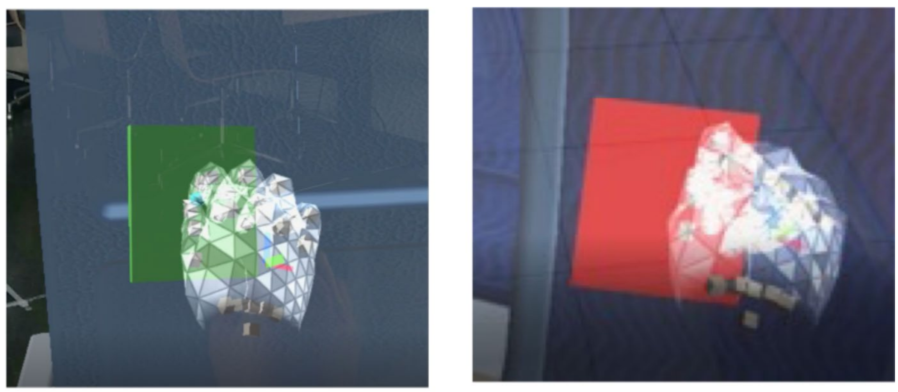


Fig. 7 Interaction with meal tray

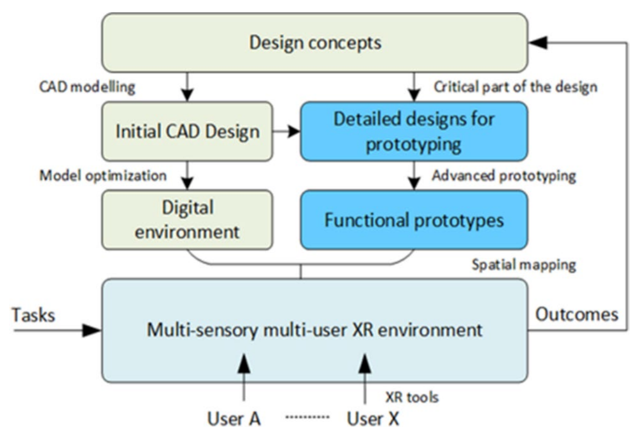


Fig. 8 Illustrated framework of the proposed XR-CO platform

3.1 Apparatus design

The XR-CO platform integrates digital content into the physical world via the Microsoft HoloLens 2 Head-Mounted Display (HMD), as illustrated in Fig. 8. The system employs 3D CAD models as the basis for both the digital environment and physical prototypes.

For the digital environment, 3D models are optimised in Rhinoceros by reducing mesh count and removing unused data while preserving geometry and textures suitable for HMD performance. Materials and textures are assigned in Blender, and the final model is exported in .fbx format to the UNITY 3D game engine. A functional prototype of key product components is also manufactured to provide a tactile representation within the digital space, enhancing users' immersive and realistic experience. Users can explore, communicate, and interact within this shared environment.

To support co-creation among multiple stakeholders the XR-CO platform includes networking and anchor-sharing features that synchronise virtual and user positions. Key elements include:

- Azure Spatial Anchors: Enable shared reference points in the physical space for real-time collaborative experiences.
- Photon Unity Networking (PUN): Facilitates real-time object manipulation and movement tracking across users.
- Calibration System: HoloLens devices are calibrated at a designated ground point using a 3D-printed fixture for precise virtual content alignment.

Holograms of design concepts are placed on table anchors for shared viewing and interaction. Spatial mapping ensures alignment between digital and physical prototypes before deployment.

Interaction features, developed using Microsoft's Mixed Reality Tool Kit (MRTK v2), include hand-tracking, UI controls, and custom tools like highlights and virtual post-it notes, tailored to specific use cases. Users are represented as robotic avatars, enhancing communication and collaboration in both co-located and remote settings (Fig. 9).

3.2 Objective and metrics

For this study, we integrated several research methods to collect and analyse data to assess XR-CO as a co-creative tool. In particular, two types of data were collected through these co-creation sessions to assess XR-CO, as summarised in Table 1:

a. Subjective-qualitative data was collected through questionnaires, which included co-creation experience, system usability and learnability, creativity support score, content analysis and expert panel rankings.
b. Objective-quantitative data was collected through the number of sticky notes, the number of ideas generated during the sessions, walking envelope and expert panel ratings.

Prior to the co-creation sessions, participants filled in a pre-experiment questionnaire to indicate their experience and impression of the technologies. For the post-experiment questionnaire, a comprehensive study was conducted, reviewing eight parameters based on the literature

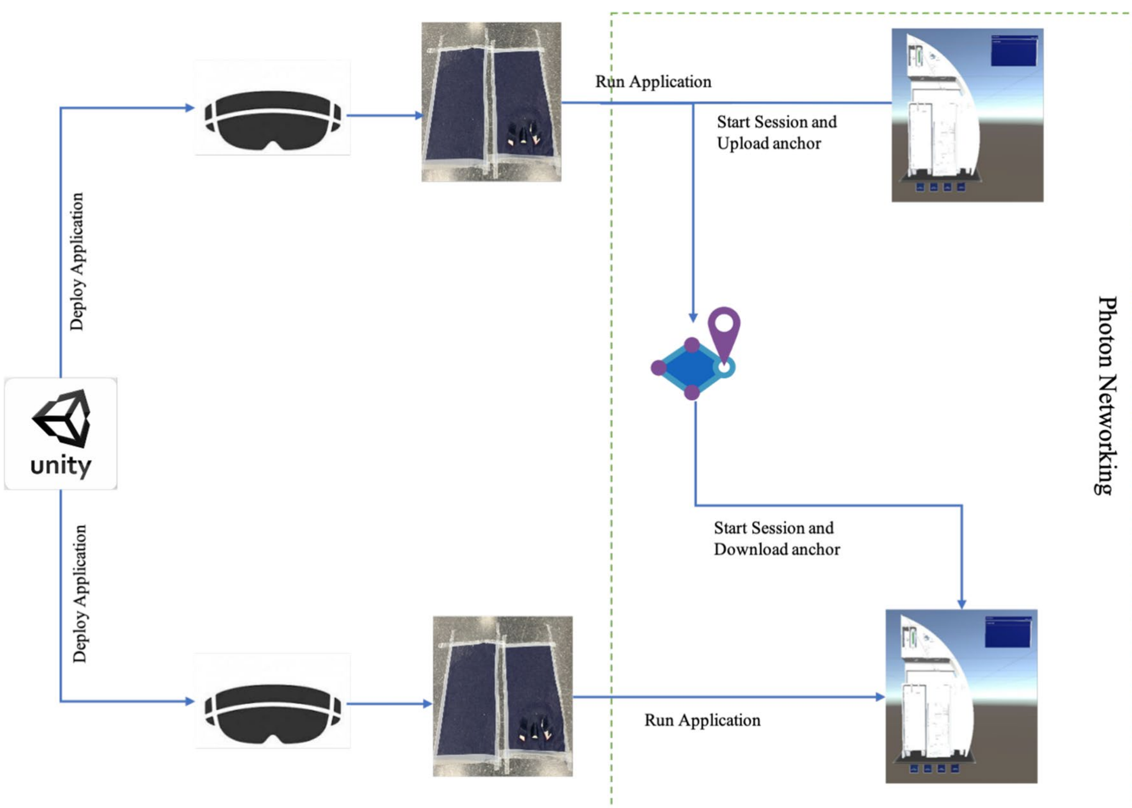


Fig. 9 Collaborative system architecture of XR-CO

Table 1 Definition of co-creative session performance metrics

Method	Metric title	Metric definition	Results
Quantitative	Creativity support index (CSI)	How well the tool supports creativity and the factor of creativity the tool supports the highest	CSI score, individual factor Score
	System usability scale (SUS)	How well the users can use the tool and if they find it useful in such co-creation scenarios along with if they continue to use it in different scenarios to aid co-creation	SUS score
	Co-creation experience	User's experience while using the tool for co-creation activity and co-creation environments	Scores
	Quantity of ideas	Number of ideas generated during the two sessions as listed from the recordings and facilitator. Number of sticky notes used/generated by participants during the session and verified in the post session	
Qualitative	Quality of ideas	Rating the ideas and comments of participants by the expert panel (through Delphi technique)	
	Content analysis	To determine the presence of certain words and phrases during the co-creation session in order to determine participants' cognition behaviour	
Others	Walking envelope	Mapping the perceived space by participants through body tracking	

to measure collaboration, creativity, interaction and co-creation experience (Remy et al. 2020; Schnurr 2017). The existing standard scale questionnaire was used to measure the following constructs after each experimental session:

1. CREATIVITY SUPPORT INDEX (CSI) (Carroll 2013; Dewit et al. 2020), a psychometric survey inspired by NASA Task Load Index (TLX) questionnaire. It assesses the tool's ability to support creativity in the specific task or activity the user was engaged in, as well as the creative process of the users. The CSI reflects on tool, task and expertise level of the participant. The CSI includes rating agreement statements on a scale from Highly Disagree (0) to Highly Agree (10), as well as paired-factor comparison through the CSI application. Apart from the total CSI score, it also measures six dimensions of creativity independently: Collaboration, Exploration, Expressiveness, Immersion, Enjoyment and Results worth Effort.
2. USABILITY (Bangor et al. 2009; Brooke et al. 1996) through 10 standard system usability scale (SUS) questionnaires.
3. CO-CREATION EXPERIENCE (Animesh et al. 2011; Verleye 2015), in order to assess participants' expectations and needs ranging from hedonic, cognitive, social, personal, pragmatic and economic experiences through participant rating statements from Strongly Disagree (1) to Strongly Agree (7) on Likert scale. The questionnaire was customized according to the scenario.
4. QUALITATIVE DATA ANALYSIS (Stemler 2000), conducted through content analysis, which is an approach to quantify and analyze the presence of certain words and themes within the qualitative data collected during the sessions. The video recordings were transcribed and imported to qualitative analysis software, such as Atlas.Ti, to identify the frequency of specific words.
5. DELPHI METHOD OF RESEARCH (Nasa et al. 2021), a technique used to systematically assess the ideas and opinions of the participants by panel of experts. Two experienced cabin crew from KLM Royal Dutch Airlines and one designer of Staggered Seats at TU Delft-IDE had been admitted in three rounds of survey, rating the ideas generated and feedback provided by participants closing the criteria defined a priori.
6. A Microsoft Azure Kinect (Microsoft Azure 2023) was set up during XR-CO sessions to record the participant movements. Point clouds representing the shape of the participants were captured at 30 frames per second (fps) during each session. A self-developed Python program was used to merge the point clouds, and the triangulated volume of the merged point clouds was defined as the walking volume of the participants in that session.

3.3 Participants and test execution

Participants were recruited in pairs to take part in Conventional Deskstop and XR-CO co-creation sessions. In total, 32 participants took part in the experiments, with 16 subjects forming 8 pairs in each environment. The participants were primarily recruited through posters and word of mouth, mainly in the Faculty of Industrial Design Engineering at TU Delft. The majority of the participants were Design Engineering students from diverse cultural and demographic backgrounds, with average age of 27. In the conventional desktop co-creation session, there were 10 male and 6 female participants, while the XR-CO sessions had 8 male and 8 female participants, as shown in Table 2.

In conventional sessions, 100 % of the participants reported having prior experience with some type of digital software for viewing a 3D model. In the XR-CO sessions,

Table 2 Participants involved in the sessions

	Conventional	XR-CO
Number of participants	16	16
Average age	26	28
Gender	62.5% male	50% male
Average height	166	173
% of people who used XR before	87.50%	81.25%

81 % of participants had previous experience with one of the XR technologies, with ratings of 5 or higher on a 7-point Likert item indicating a positive impression of XR technologies. The study has been approved by the Human Research Ethics (HREC) committee of TU Delft, and all sensitive participant data were anonymised following the established protocols. Each participant is represented by a code, such as C_FAx, C_Px for conventional session and XR_FAx, XR_Px for XR-CO session, where x= 1,2,...16.

3.3.1 Experimental setup

The Conventional Desktop-based co-creation setup was selected as baseline due to its widespread use in early stage industrial design processes (Vargas González et al. 2023). To evaluate the efficiency and efficacy of XR-CO compared to a Conventional Desktop-based co-Creation setup, an in-between group analysis approach was adopted. The evaluation focused on the number of ideas generated, the accuracy of feedback collected, collaboration, interaction and the co-creation experience. The two distinct environments and tools are as below:

- *Conventional Desktop co-Creation session* The participants in the Conventional Desktop Co-Creation session control group collaborated around a physical table using traditional communication tools, such as sketches and pictures, during the conventional session. As the utilisation of 3D models has been increasingly prevalent due to technological advancements and improved accessibility, we introduced a desktop 3D model of the Flying-V aircraft. This model allowed participants to interact with it using a mouse and take advantage of features like movement and viewing options within the UNITY 3D software. To gather feedback and input from the users, we provided green and red sticky notes, as depicted in Fig. 10.
- *XR-CO co-creation session* the participants collaborated in an XR environment and interacted with essential physical prototypes, as well as digital elements such as meal-tray and sticky notes through intuitive interactions. In this session, participants performed the scene together in the environment and provided their opinions and ideas.

3.3.2 Experimental procedure

The study consisted of three main phases. Firstly, a preliminary interview was conducted with the two experienced cabin crew members from KLM in a Delphi setup. The purpose was to gather information regarding basic activities performed by members and any difficulties they encountered in the current cabin configurations, if any. The insights gained from this initial consultation helped in identifying the important activities that might be affected by the new staggered seat configuration, as listed in Table 3.

A controlled user experiment was conducted, in which participants were asked to collaborate and interact within

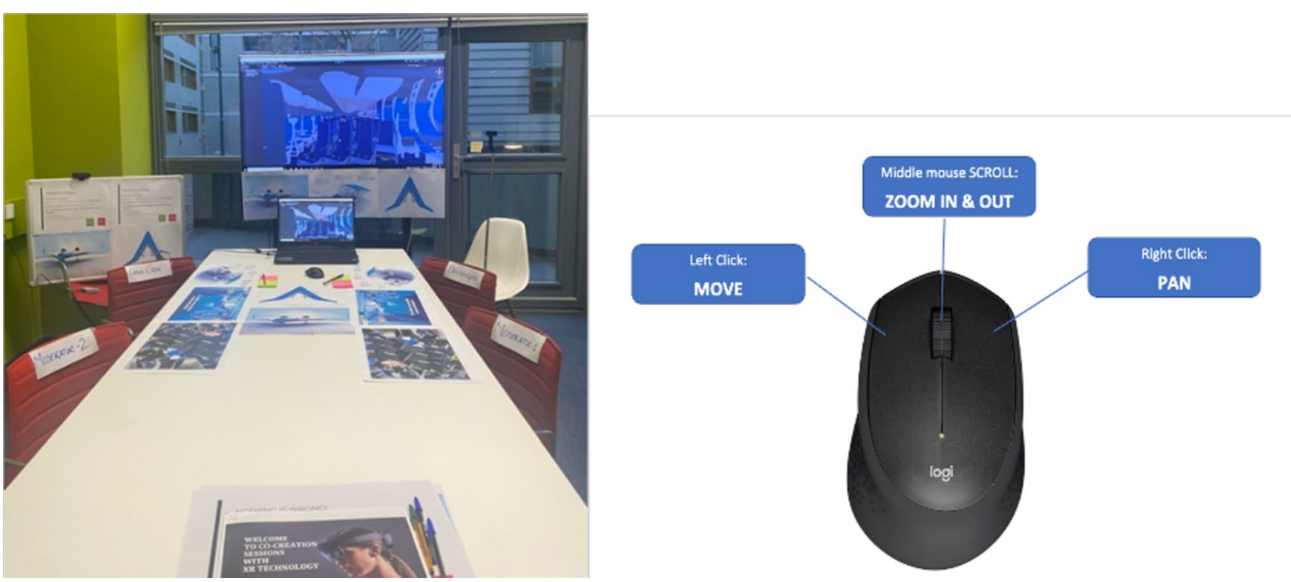


Fig. 10 Conventional desktop co-creation setup and mouse interaction for 3D viewing on desktop

Table 3 List of activities considered for co-creation sessions

#	Segment	Activity	Measurable indicator	Responsible
1	Pre-flight	Life-vest checks under the seat	VISIBILITY	Cabin crew
2	Pre-take off	Seat belt checks (if the seat belts are fastened and secured)	VISIBILITY	Cabin crew
3	During flight	Serving a meal tray to passenger	REACHABILITY	Cabin crew and passenger
4	Comfort	Seat ingress, egress, legroom	COMFORT, SPACE	Passenger

Table 4 Experimental procedure

Activity	Conventional session	XR-CO
Introduction	5’	5’
Sensitizing	10’	10’
Movie on cabin crew activities	2’	2’
Training session with Microsoft HoloLens2		15’
Co-creation session	20’	20’
Filling questionnaire	10’	10’
Post discussion	7-10’	7-10’

the setup while providing feedback using the Think-out-loud protocol (Olson et al. 2018). Two facilitators were present during the study: one facilitator engaged with the participants through pre-determined questions to elicit responses, while the other facilitator observed from the side, taking notes and memos. All the sessions were video-recorded for future reference.

The co-creation session procedure is outlined in Table 4, which takes approximately 1–1.5 h to complete.

The discussion of tasks in both environments was strictly limited to 20 min. To ensure engaging co-creation sessions, significant consideration was given to sensitising the participants. Sensitising is “a process where participants are triggered, encouraged, and motivated to think, reflect, wonder, and explore aspects of their internal context in their own time and environment” (Stappers et al. 2005). To help participants be involved in unfamiliar topics initially, triggering questions were provided based on their full range of experiences in the domain of the study (Sanders 2001). This moment is linked to both past and future, as the past, present and future are all integral parts of the experience. Therefore, in this study, participants were asked to introduce themselves and share about their recent flight experiences to help them engage within the experiments domain. Additionally, relevant topics related to the main session, such as seat preferences, comfort on long-haul flights, and meal service experiences on planes, were outlined as discussion points.

The conventional desktop co-creation session took place in a meeting room with a large table at the center, as depicted in Fig. 10 The XR-CO session was set up in a studio room with two physical staggered seats, and the calibration point set to the ground of the room as in Fig. 11. Both rooms were equipped with two video cameras to record the sessions. Prior to the experiments, all participants signed the informed consent. After the introduction and sensitizing phase, a 2-minute movie was shown to illustrate the cabin crew and passenger tasks that would be discussed. The XR-CO session included an additional 10-15 min training session with Microsoft HoloLens2, where users familiarized themselves with the interactions. The training session covered the hand menu and sticky notes on the table anchor, allowing participants to become accustomed to the gestures and the device. Following the training, both HoloLens devices were synchronized, and the XR-CO session commenced. Throughout the entire duration of the sessions, the facilitator engaged with the participants by asking a set of predetermined questions related to the list of tasks.

Fig. 11 Experimental setup in XR-CO co-creation session

Table 5 Results of creativity support index

	CSI score
Conventional	60.73
XR-CO	79.27

4 Results

The following sections present and discuss the main results obtained during the validation of the XR-CO platform as a tool to facilitate the co-creation sessions in cabin interior design.

4.1 CSI

The CSI scores were calculated according to Equation.1. However, the application scores the questions and generates single CSI score automatically out of 100 for the tool being used, with higher score indicating better creativity support. The overall CSI Scores of Conventional desktop Co-creation tool and XR-CO were 60.73 and 79.27 respectively, as in Table 5, suggesting that the XR tool provides higher creativity support. A breakdown analysis of individual factors are calculated according to average factor counts (number of times the participant chose a particular factor as important), average factor scores, and average weighted factor score, as shown in Table 6.

$$
\begin{aligned}
\mathrm{CSI} = \ & [(\mathrm{Collaboration1} + \mathrm{Collaboration2}) \\
& \times \mathrm{CollaborationCount} + (\mathrm{Enjoyment1} \\
& + \mathrm{Enjoyment2}) \times \mathrm{EnjoymentCount} \\
& + (\mathrm{Exploration1} + \mathrm{Exploration2}) \\
& \times \mathrm{ExplorationCount} + (\mathrm{Expressiveness1} \\
& + \mathrm{Expressiveness2}) \times \mathrm{ExpressivenessCount} \\
& + (\mathrm{Immersion1} + \mathrm{Immersion2}) \\
& \times \mathrm{ImmersionCount} + (\mathrm{ResultsWorthEffort1} \\
& + \mathrm{ResultsWorthEffort2}) \times \mathrm{ResultsWorthEffortCount}]
\end{aligned} \tag{1}
$$

Average Factor Counts : The XR-CO session was observed to have overall high scores of the average factor counts compared to Conventional. However, significant difference was observed on the factors of Immersion, Collaboration, and Results with effort. The highest possible count for any particular factor is 5, indicating that participants chose it as more important than every other factor. Specifically Exploration, Immersion and Expressiveness factors were more important to the users engaged in both co-creation sessions.

Average Factor Score : Table 6 shows that for the XR-CO session, all factors received relatively high ratings compared to the Conventional Session. The XR-CO platform demonstrated its advantages in nearly all criteria such as Collaboration and Enjoyment. This is especially true for immersion, exploration and expressiveness factors, where the scores of using XR-CO is significantly higher than using the conventional tool.

Collaboration The average count for collaboration is 2.4, suggesting it is of moderate importance to users engaged in both sessions. The Conventional tool score for this factor is 14.9, whereas for XR-CO it is 14.8. As the difference is minor, it can be inferred that both tools provide average collaboration benefits. This can be foreseen to be improved if more collaboration tasks can be developed in the XR-CO environment. As per the XR-CO environment of the Flying-V there was only one collaboration task of Meal tray reachability, which actually compels users to collaborate.

Enjoyment The average factor count for Enjoyment is low, 0.8, indicating that users did not consider enjoyment to be an important factor to be engaged in the co-creation sessions. However, the Conventional score for enjoyment is 14.7, and for XR-CO it is 15.6, indicating that the participants were truly immersed in the task and did not deviate from executing the assigned four provided tasks inside the XR-CO environment.

Exploration The average count for exploration is 3.7, suggesting that users considered the co-creation tools were most important for exploring the digital model. The Conventional sessions core is 13.9, and for XR-CO it is 15.5. This indicates that the XR-CO provided different possibilities to induce new ideas and to evaluate the model compared to the conventional session. The possibility to freely move around the model and work at a real scale to perform the tasks might have influenced this factor in the mixed reality environment.

Expressiveness The average factor count for expressiveness is 2.9, making it the second most important factor considered by users to be engaged in the co-creation session.

Table 6 Results of average CSI scores of independent factors

	Average factor counts		Average factor score		Average weighted factor score	
	Conventional (SD)	XR (SD)	Conventional (SD)	XR (SD)	Conventional	XR
Collaboration	2.3 (1.35)	2.6 (1.36)	14.9 (3.78)	14.8 (3.87)	16.73	19.36
Enjoyment	0.7 (0.85)	0.9 (1.05)	14.7 (2.55)	15.6 (3.79)	5.05	6.81
Exploration	3.6 (1.41)	3.7 (1.16)	13.9 (3.83)	15.5 (3.30)	25.26	28.58
Expressiveness	2.8 (1.01)	3.0 (1.58)	14.0 (2.67)	15.3 (3.08)	19.69	22.88
Immersion	2.6 (1.50)	3.1 (1.36)	9.9 (4.82)	14.7 (3.97)	12.73	22.95
ResultsWorthEffort	1.7 (1.16)	2.1 (1.41)	14.8 (2.86)	16.0 (2.99)	12.50	17.00

Table 7 Results of SUS

Variable	SUS score (mean)	SD	Min	Max	Median	Adjective scale	Grade scale	Acceptability scale	NPS scale	Industry benchmark
Conventional	70.62	19.11	12.5	90	73.75	OK	C	Marginal	Passive	Above average
XR	80.47	9.4	70	97.5	77.5	Good	A	Acceptable	Promoter	Above industry standard

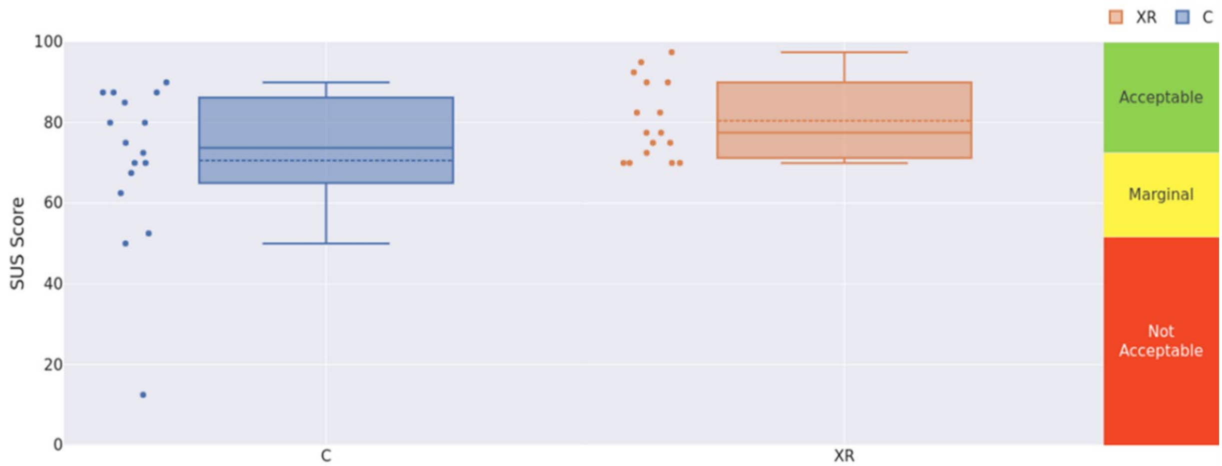


Fig. 12 SUS acceptability scale with data points

The Conventional score for expressiveness is 14.0, whereas for XR-CO is 15.3, meaning that users felt that they could express more with XR-CO than conventional. Perhaps the limitations of the conventional tool offered compared to XR-CO, such as exploring the space made them to express more, and the ability to collaborate in the meal tray task made them to express more of the space, they perceived in XR-CO than to conventional.

Immersion Users engaged in the co-creation sessions considered immersion to be highly important, with an average factor score of 2.8. The conventional score for the immersion is 9.9, whereas for XR-CO it is 14.7, meaning with XR-CO users found it more immersed than the conventional tool. However, it is not statistically significant, indicating high variance across users on this particular scale.

Results worth effort The average count for the results worth effort is 1.9, indicating it as the second most least important factor for the users. The conventional score is 1.7, while XR-CO 2.1, suggesting that users felt they acheived better results with their effort in XR-CO compared to the conventional tool.

4.2 SUS

The System Usability Scores are calculated according to Bangor et al. (2009). Typically, a SUS score below 68 is considered below average. The SUS score of conventional desktop session was 70.62, whereas for XR-CO it is 80.47, as in Table 7. This indicates that participants found XR-CO easier to use compared to the desktop tool. When interpreting the scores in percentiles, the conventional session scored 57.3 % and XR-CO to 88.3 % grading them to C (marginally acceptable) and A (acceptable) respectively. The lower Standard Deviation (SD) of XR-CO Session (9.4) suggests more consistent scores, indicating that a higher number of participants had similar experiences with XR-CO. In contrast, the conventional session had a higher SD of 19.11, indicating more variation in user scores around the mean(M). This could be attributed to users facing difficulties in navigating the 3D scene using a 2D mouse, which affected their perception of the digital system's usability. SUS acceptability graph with data points is as shown in Fig. 12 along with per item chart Fig. 13

4.3 Co-creation experience

In regards to co-creation experience, it was observed that all the items of the experience including interaction, received higher ratings in the XR-CO session, as shown in Fig. 14. On the other hand, in the conventional session, hedonic, cognitive and personal experience were considered more important based on the means. In the XR-CO sessions, participants considered hedonic, cognitive and pragmatic experience to be most important. This indicates that users in both sessions desired pleasurable experiences and acquiring knowledge about the product. However, in the conventional

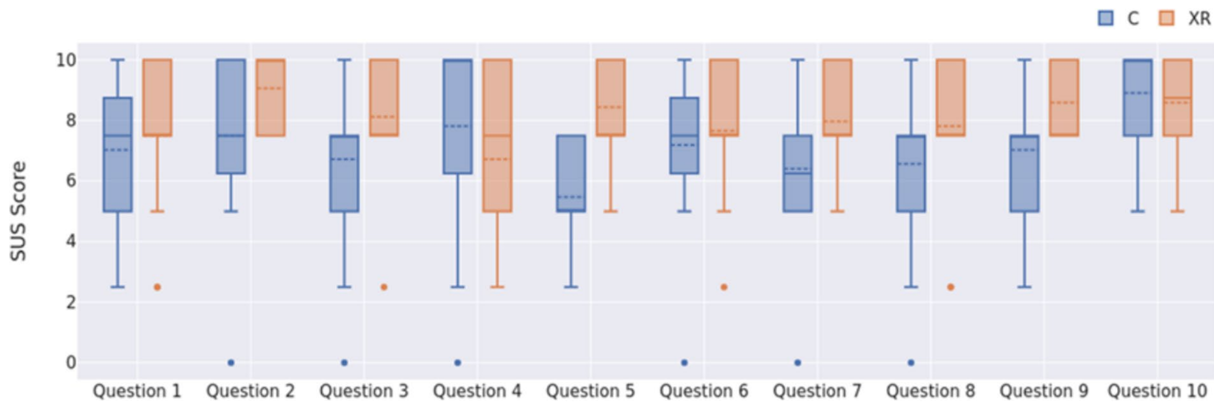


Fig. 13 SUS score per item chart

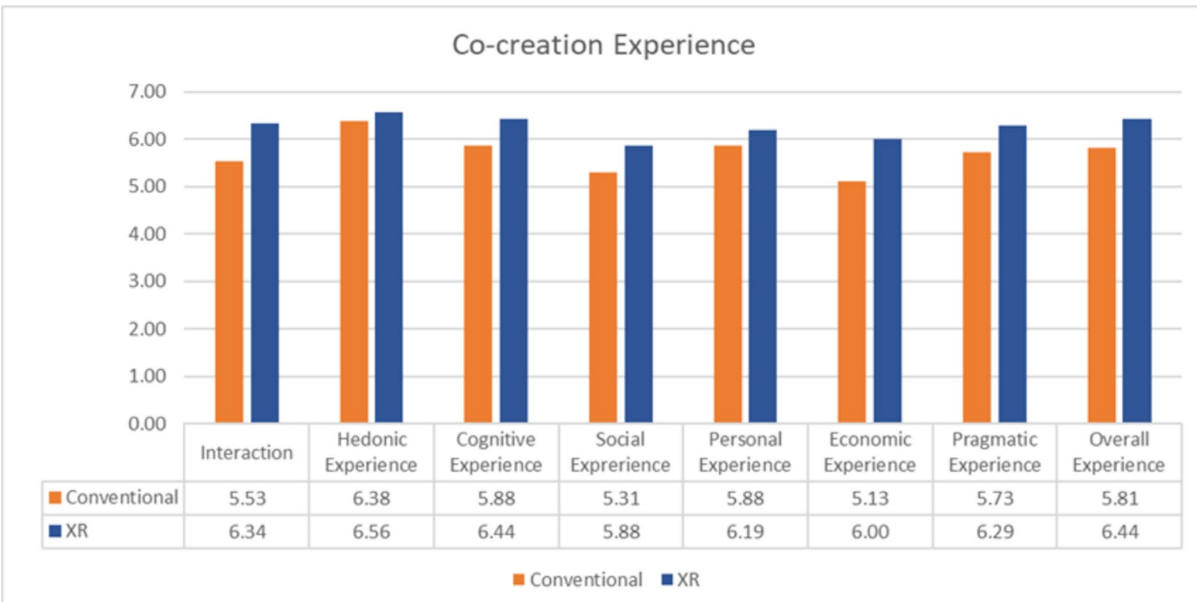


Fig. 14 Results of co-creation experience

session, they placed more emphasis on self-efficacy, whereas in XR-Co sessions, understanding risks was preferred. This highlights the importance for XR developers to focus on specific benefits and aspects when designing XR co-creation sessions. It also suggests that XR developers can concentrate on improving other aspects within XR co-creation sessions. Considering the scenario of product testing, where pragmatic and usability experiences were dominant, the assessment confirms that XR-CO provides a favorable co-creation experience for participants, ultimately fostering collaborative innovation.

4.4 Content analysis

For these experiments, we conducted qualitative content analysis on the primary data obtained from the transcripts of the video recordings in both sessions.Specifically, we employed conceptual qualitative content analysis to examine the explicit data regarding the occurrence and frequency of certain words and phrases. Our aim was to interpret participants skeptical behavior when discussing about the tasks using a particular tool, which reflected their confidence in their answers. In this context, words and phrases such as “I don’t know”, “I’m not sure”, “I can’t imagine/imagining”, “probably”, “I assume/assuming”, “might be” and “maybe” had been considered in the go list of atlas.ti system. The frequency of these words during the sessions is shown in the Table 8.

Table 8 Results of qualitative content analysis

	Conventional	XR-CO
Frequency of skeptical words	709	390
% of data constituted	64.5%	35.4%

The results indicate that during conventional desktop co-creation session, participants exhibited uncertainty in their feedback. In contrast, during XR-CO session, participants appeared more confident in their evaluations.

4.5 Expert panel rating

Two experienced cabin crew members and one designer were selected as panelists for the study due to the resource-intensive nature of recruiting an entire professional team for the experiments. Additionally, design students were chosen for their creativity and potential to provide fresh perspectives and ideas. The panelists were actively involved in the entire process of the experiments, starting with a preliminary interview where they shared insights on their activities inside an aircraft and their motivations towards the new design. They were exposed to both conventional desktop tool and paper-based designs during the study, and an intermediate interview was conducted to gather their feedback on the new design aspects and their opinion. Subsequently, they actively participated in the development of the XR-CO. Finally, the panelists assessed the participants list of ideas, opinions, feedback and comments for all the four tasks, rating them based on accuracy of the comment and suitability of the idea for future improvement of the design. The panelists were unaware of the tool the participants used for co-creation sessions. From the list, most relevant and accurate comments along with the best rated ideas by experts, are presented in Figs. 15 and 16.

It has been noted that the XR-CO session yielded more relevant and accurate comments compared to the conventional desktop session. The immersive nature of the real-scale environment allowed participants to consider and propose solutions for complex issues, such as the discrepancy in the aisle width and navigating from front to back and vice versa. Additionally, regardless of the panel rating, we present the performance metrics of the participants during the session, including the quantity of ideas generated and sticky notes used consumed as in Table 9.

4.6 Walking envelope

The participants were observed to have coordinated their activities and perceived the digital space as true to life by not going over the seats. This is demonstrated by capturing their movement data as walking volume during two sessions through Microsoft Azure Kinect and mapping the walking envelope as in Fig. 17. The walking paths of the two sessions are similar, except in Session A, in which the participants also walk around the virtual seats. The volume of Session A was about 17 cubic meters and for session B, it was 21 cubic meters. A large overlap (more then 80 %) was observed between these two sessions. Figure 18 illustrates some of the postures took by participants during the session in order to perform the tasks.

EXPERT PANEL OF CABIN CREW RESPONSES				
Comment/Feedback/Opinion/Idea	Rating	Number of Times the comment is mentioned		Comments from expert panel
		Conventional	XR	
Life Vests check under the seat – VISIBILITY factor				
Visibility of the life-vests depends on the way of walking in the aisle: not easily visoble when walking from front to back, cabin crew have to bend a lot an it's easy when seats are flipped	Most accurate	3	13	We also realised this during CR-CO session
Seat belt fastened and secured check – VISIBILITY factor				
Sear belt visibility depends on which side of the aisle the check is performed: easy from right (as passengers are facing away) and not easily visible from left side of the aisle	Most accurate	0	7	
Serving the meal tray – REACHABILITY factor				
Meal Tray reachability is good from left side of the aisle as the passengers are facing you and vice versa	Most accurate	1	7	Better to see a passenger, better for communication
The aisle is narrow to take the trolley and meal tray	Most accurate	4	16	Not only to give the meal to the passenger, also walking with your trolley through the cabin
OTHERS				
Having colored seat belts so that they can be easily visible	Good Idea	0	1	Good idea!
Cabin crew can have an interface to flip all the seats at a time before boarding procedure commences	Good idea	0	3	

Fig. 15 Expert panel of cabin crew rating on participant feedback

EXPERT PANEL OF CABIN CREW RESPONSES				
Comment/Feedback/Opinion/Idea	Rating	Number of Times the comment is mentioned		Comments from expert panel
		Conventional	XR	
Entertainment unit design idea: pulled from the front seat and then flipped to place it in front of the passenger with touch inputs	Good idea	0	1	
Transparent seat bottoms can help to see life vests	Good idea	0	1	
Movable Side supports/flaps for the seats to help sleep and be private with music on the support	Good idea	0	2	Great idea
3 staggered seats instead of 4 seats in a row	Good idea	0	1	Would be nice
Meal Tray table coming from the armrest than from the front	Bad idea	5	8	Narrows sear width
Sleeping is better as I won't touch the next unknown passenger	Most accurate	1	3	
Less leg room space and the front seat legs can hit when entering and exiting	Most accurate	3	9	Agree other solutions
Reclining the seats occupies actually two behind seats (half and half)	Least accurate	0	2	Reclining is not possible

Fig. 16 Expert panel of designer rating on ideas generated

Table 9 Results of co-creation performance metrics

		Conventional	XR-CO
Quantity of ideas generated		8	15
Quantity of notes consumed	Green	50	37
	Red	46	42

4.7 Post discussion survey

A follow-up discussion was performed after the co-creation session using a fixed questionnaire on how well the tool supported participants in understanding and evaluating the design, as well as their final acceptance opinion of the new design. Users of conventional desktop tool expressed their satisfaction with the ability to examine the model from various perspectives but expressed a desire for the inclusion of more technology-based tools, such as Virtual Reality (VR) technology. On the other hand, participants who used XR-CO provided overwhelmingly positive feedback, stating that it enhanced their creativity by immersing them in the subject matter and reducing the need for imagination. They also emphasized the importance of physical prototypes in product assessment, considering them an integral part of the design process. Furthermore, participants agreed that XR-CO aligns well with the concept of minimum viable product testing. Although a formal study of cybersickness was not conducted, none of the participants of the XR-CO session reported experiencing severe symptoms during or after the VR sessions.

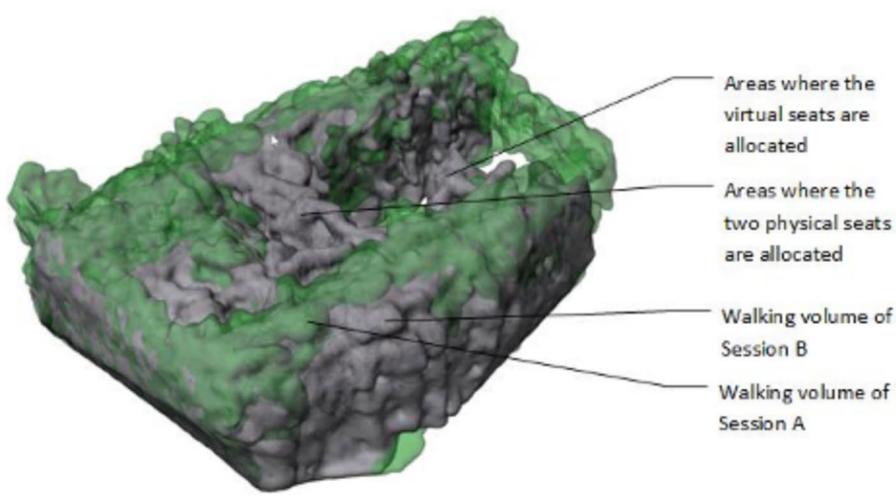
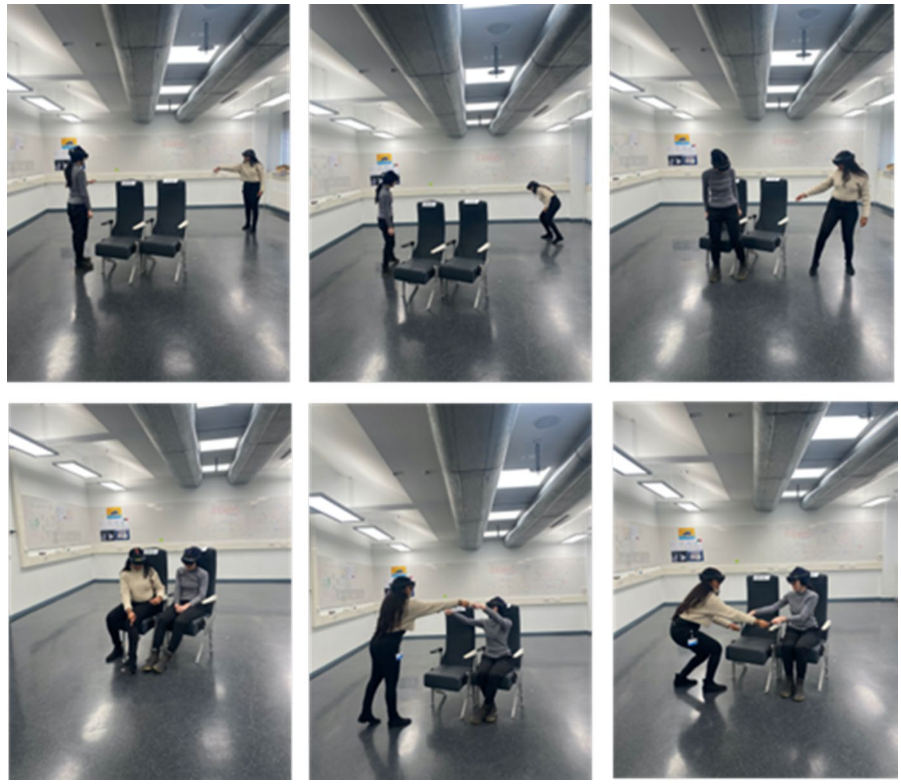


Fig. 17 The walking volume of two sessions

Fig. 18 Postures of participants during XR-CO session



5 Discussion

This study provides both quantitative and qualitative evidence supporting XR-CO as an effective multi-sensory, mixed reality platform for co-creation. Participants using XR-CO not only generated a higher quantity of ideas, but their contributions were also rated as more relevant and actionable by expert evaluators. These outcomes suggest that XR-CO effectively enhances creativity, usability, and stakeholder engagement compared to conventional desktop-based methods. Beyond quantitative metrics, our results include rich qualitative insights derived from participant behavior and verbal feedback. XR-CO users identified specific spatial issues (e.g., aisle width, seat frontal angle for easier egress) and proposed actionable improvements, demonstrating the platform's potential to provide high-quality design feedback. The embodied nature of XR-CO - allowing participants to walk through, sit on, and interact with real-scale physical-digital hybrids - led to a higher degree of perceived realism and task engagement. The design of the XR-CO system was guided by three primary goals: 1) enabling full-scale spatial immersion in the fastest and most cost-effective way, 2) supporting intuitive tangible interaction with physical prototypes, and 3) fostering seamless, real-time multi-user collaboration. These design drivers were informed by literature on XR-supported co-design (Cascini et al. 2020) and domain-specific needs identified through preliminary interviews with cabin crew and designers. The system is developed using Unity and MRTK, with a modular architecture that enables rapid scene adaptation and easy content replacement. Although tailored to a specific case in this study, XR-CO is easily adaptable to a wide range of design domains, such as automotive interiors, workspaces, and healthcare environments, with updated content and minimal configuration adjustments. In fact, even if the XR-CO-creation platform was developed with a specific FlyingV use case in mind, its core framework-integrating extended reality (XR) technologies to facilitate remote, synchronous collaboration-offers significant potential for generalization across diverse co-creation domains. For instance, fields such as urban planning, product design, and cultural heritage preservation often involve stakeholders with different background and objectives and require spatially complex, multimodal engagement. By abstracting the platform's modular components (e.g., immersive visualization, real-time annotation, spatialized communication), the approach can be adapted to accommodate varying logistical constraints, such as limited physical access, asynchronous participation needs, or differing levels of technological infrastructure. This suggests a promising avenue for future research into scalable, domain-flexible XR-enabled co-creation frameworks, thereby extending the platform's theoretical and practical relevance The conventional desktop-based co-creation setup was selected as the baseline due to its widespread use in early-stage industrial design processes (Vargas González et al. 2023).

It offers a familiar, low-cost, and low-immersion environment for rapid 3D visualization and annotation. In contrast, XR-CO offers full-scale immersion, multi-sensory feedback, and embodied interaction. By contrasting it with a non-immersive baseline, we aimed to isolate and evaluate these unique affordances. Meanwhile, comparing XR-CO against experience prototyping (Buchenau and Suri 2000) would provide valuable complementary insights on design outcomes, creative engagement, and practical trade-offs in terms of time and cost. This comparison will be a focus of our future work. Beyond enhancing immediate collaboration, an immersive XR-based co-creation platform has the potential to significantly influence longer-term outcomes such as idea implementation, sustained team alignment, and iterative refinement. The spatial and embodied qualities of XR can foster deeper mutual understanding, shared mental models, and stronger memory retention, which may lead to more cohesive follow-through on ideas generated during sessions. Furthermore, the ability to revisit and manipulate shared virtual artifacts over time supports an iterative design process, enabling teams to refine concepts collaboratively across development cycles. These affordances position XR platforms not only as tools for ideation but as ongoing infrastructures that shape how co-created ideas evolve and materialize in practice. For what concerns the strengths and limitations of XR-CO with other Virtual set-ups, such as immersive VR it is worth to remind the main aspects such as: the Mixed Reality requires a much lower investment in 3D graphics development and hardware facilities needs to run high fidelity simulation compared immersive VR; XR-CO allows to interact with physical components, in our case the aircraft seats and thus do not only rely on visualization as immersive virtual environments; finally, collaboration is natural in XR-CO since the interaction is based on real human to human interaction and not interaction with avatars. The selection of evaluation metrics was grounded in existing literature on creativity support, human-computer interaction, and participatory design. Our framework aligns with previous work in co-creation research (Ramaswamy and Ozcan 2018), Remy et al. (2020). We adopted validated tools such as the Creativity Support Index (CSI) (Cherry and Latulipe 2014) and System Usability Scale (SUS) (Brooke et al. 1996), complemented by objective measures such as the number of ideas generated, expert panel ratings, and walking envelope data. These metrics capture the multi-faceted nature of co-creation performance, encompassing creativity, usability, embodied interaction, and collaboration. Additional metrics, such as assessing XR-CO with the User Experience Questionnaire (UEQ) (Schrepp et al. 2014), evaluating participant engagement behavior (Wu et al. 2024), and measuring the long-term impact of generated ideas (Meister Broekema et al. 2023), - are under consideration for future work exploring diverse tasks and stakeholder groups. While this study demonstrates the value of XR-CO, several limitations be acknowledged. First, the sample consisted primarily of design students from a single university, limiting the generalizability of results to broader stakeholder groups. Second, although XR-CO supports collaboration, the study included only a limited set of collaborative tasks on a single use case (aircraft cabin interior), which may have constrained the evaluation of its full potential. Third, participant familiarity with XR varied despite introductory training, potentially influencing their comfort level and engagement.

6 Conclusions

Extended Reality (XR) technologies are increasingly being utilized in industrial applications, particularly in the realm of new product development. Recognizing their potential, we have explored the use of XR tools as co-creation tools and XR applications as co-creation platforms,supporting key elements of co-creation: collaboration, interaction and user experience. In this paper, we have presented XR-CO, an XR based multi-sensory, multi-user,mixed reality co-creation platform. What sets XR-CO apart from other XR platforms is its incorporation of full tactile sense through the integration of functional prototypes at a full scale. We demonstrate the effectiveness and the efficiency of using the platform by an in-between experiment where 32 subjects joined 16 co-creation sessions for designing cabin interiors of a concept aircraft. The results of the experiment indicate that participants consistently ranked the XR-CO co-creation platform higher in terms of Creativity Support Index (CSI), System Usability Scale (SUS), and overall usability when compared to traditional co-creation approaches. In particular, the participants expressed their appreciation for the inclusion of digital elements such as sticky notes and provided positive feedback in the post-experiment surveys. Moreover, the outcomes of the XR-CO based co-creation process were deemed more fruitful based on the judgment of the expert panel, further validating its effectiveness. Building on the limitations identified in the Discussion section, future research will extend the exploration of XR-based collaborative environments by involving a more diverse range of participants from different disciplines and professional backgrounds, thereby improving the generalisability of the findings. Studies could also explore a broader range of collaborative scenarios and task complexities to better capture the versatility and scalability of XR-CO systems in supporting the various stages of design and decision-making processes. Furthermore, longitudinal studies will examine how sustained exposure to, and increasing familiarity with, XR technologies influences collaborative dynamics, spatial awareness and communication effectiveness. Finally, the integration of adaptive interfaces and personalisation mechanisms could be investigated to accommodate varying levels of XR proficiency and ensure more equitable and effective collaboration among heterogeneous teams. Moving forward, further exploration and implementation of XR-CO in diverse contexts and beyond the immediate collaboration context, hold significant potential for advancing co-creation practices. In conclusion, the XR-CO platform has proven to be a valuable tool for facilitating co-creation sessions, particularly in the scenarios where ergonomics play a critical role. XR-CO serves as a versatile co-creation platform that can be expanded to various domains and design phases, maximizing creativity and expediting innovation.

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Author contributions All authors contributed equally to the study.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval The study has been approved by the Human Research and Ethics (HREC) committee of TUDELFT-IDE.

Consent to participate All participants signed informed consent before beginning the experiments.

Consent for publication All participants and authors provide their consent for publication.

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