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Immersive social and tangible interaction for smes: tools and methods to access the metaverse case studies on fashion and nautical showrooms

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Politecnico
di Bari

Department of Electrical and Information Engineering
Ph.D. Program Industry 4.0
SSD: ING-IND/15–Design method for Industrial
Design

Final Dissertation

Immersive Social and Tangible Interaction for SMEs: Tools and Methods to Access the Metaverse

Case Studies on Fashion and Nautical Showrooms

by
Vangi Fabio


Supervisors:

Prof. Michele Fiorentino



Coordinator of Ph.D. Program:

Prof. Salvatore Digiesi



Course n°38, 01/11/2022-31/10/2025



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**Politecnico
di Bari**



**UNIVERSITÀ
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ALDO MORO**

Fabio Vangi

Immersive Social and Tangible Interaction for SMEs: Tools and Methods to Access the Metaverse Case Studies on Fashion and Nautical Showrooms

Thesis submitted for the degree of Philosophiae Doctor

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Tutors

Prof. Engr. Michele Fiorentino

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Abstract

The thesis stems from the recognition that while immersive tools and the Metaverse are rapidly emerging as key enablers for industrial digital transformation, their adoption remains limited for small and medium enterprises (SME) due to technical barriers, economic constraints, and the lack of specialized skills. This exclusion risks widening the gap between large corporations and small manufacturers, particularly in the Made in Italy ecosystem, where craftsmanship, creativity, and design quality are core values.

The research aims to define methods, tools, and design frameworks to integrate immersive technologies into SME workflows, enhancing product communication, collaborative decision-making, and configurability. Through a research through design approach grounded in Human-Centered Design (HCD) principles, the study explores how social, cognitive, and tangible dimensions of interaction can be leveraged to create more inclusive and meaningful mixed reality experiences.

The thesis is articulated in two main parts. The first part, Social Interaction in XR, focuses on the communicative and collaborative aspects of immersive systems, presenting three progressive (FSM, MAGIC, and MR-CoCo) designed to explore different interaction modalities: from remote collaboration to co-located mixed reality product configuration. Each system was experimentally validated through user testing involving both experts and non-experts, combining quantitative (SUS, UEQ) and qualitative (CCQ, open feedback) metrics. Results highlight the importance of spatial awareness, shared agency, and trust between users in achieving effective collaboration.

The second part, Tangible Interaction, investigates how physical engagement and embodied actions can enhance the sense of presence and well-being in extended virtual exposure. A novel Mixed Tangible Catalog (MTC) was developed as an adaptive tangible interface supporting long-term tasks in immersive environments. The study demonstrates that tangible interaction improves user comfort, reduces cognitive fatigue, and contributes to a more natural integration between human and digital counterparts.

Finally, the discussion and conclusions connect these results to the broader vision of Industry 4.0, emphasizing the central role of human well-being and inclusion in the design of industrial metaverse systems. The proposed frameworks and experimental platforms contribute to

Abstract

bridging the gap between immersive technologies and real industrial practices, promoting sustainable innovation and accessibility for small and medium enterprises.

Preface

This doctoral research has been conducted within the PhD Program in Industry 4.0 at the Politecnico di Bari, in collaboration with Hevolus S.r.l., a leading Italian company specializing in immersive solutions for digital retail and industrial communication. The partnership was established under Ministerial Decree No. 352/2022 (“Doctorates in partnership with enterprises”) and aimed to combine academic research with real industrial challenges in the development of extended reality (XR) systems.

Throughout the three years of research, several collaborations were established to support the experimental phases:

- **Hevolus S.r.l.** (Molfetta, Italy): industrial partner and co-funder of the PhD project, providing access to the *H-Verse* platforms.
- **Emme Evolution S.r.l.** (Martina Franca, Italy): textile company that contributed to the *Metaverse B2B product presentation* and *Mixed tangible catalog* offering data and feedback on product management and digital asset structuring.
- **NeoYacht** (Bitonto, Italy): collaboration established for the *MR-CoCo* and *MAGIC* case study, focusing on collaborative product configuration of sailboat components in mixed reality.

In addition to these industrial partnerships, during the doctoral program, the candidate took part in the MICS (Made in Italy Circular and Sustainable) "Emotional project" in Spoke 2 block. This national research initiative, funded by the Italian PNRR (National Recovery and Resilience Plan), is dedicated to fostering research and collaborations between Italian universities, and this participation led to various talks and presentations.

Such collaborations represented an essential bridge between design research and industrial needs, strengthening the applied nature of this doctoral project. They enabled the research to evolve through iterative prototyping and validation in real industrial contexts, ensuring both scientific rigor and practical impact. The continuous dialogue between academia and industry shaped the development of the presented testbeds and contributed to defining guidelines for the adoption of immersive

Preface

technologies by small and medium-sized enterprises (SMEs) within the Italian manufacturing ecosystem.

This thesis is submitted in partial fulfillment of the requirements for the degree of *Philosophiae Doctor* in Industry 4.0 at the *Politecnico di Bari*. The work was supported by the company *Hevolus S.r.l.* and developed within the *Mixed Experience Laboratory (MELAB)* of the Politecnico di Bari, under the supervision of Professor **Michele Fiorentino**, in collaboration with the *VR³Lab — Virtual Reality and Reality Reconstruction Laboratory*.

To the best of my knowledge, this work is original, except where acknowledgements and references are made to prior research. This dissertation results from a research trajectory that evolved through several published works authored by the candidate during the doctoral period. While some sections draw on this previously published material, the thesis integrates and contextualizes these publications through introductory and connecting chapters, presenting an original synthesis and reorganization of concepts to provide theoretical background, methodological grounding, and research motivation.

Furthermore, in addition to the works directly included in this dissertation, investigating user interaction and collaboration tools the design preferences were conducted in collaboration with members of the research team.

Parts of the text have been linguistically refined with the aid of AI-based tools, but all conceptual and structural contributions are original and developed by the author.

List of Papers Written by the Author

The following articles, of which I am the author or co-author, form the scientific and methodological basis of this dissertation and are cited in this thesis:

- Fashion showroom in metaverse[1]
- Mixed tangible catalog[2]
- MR-CoCo[3]
- Magic [4]

Acknowledgements

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Chapter 1

General Introduction

The industrial and commercial landscape is experiencing a rapid diffusion of immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Within the broader paradigms of Industry 4.0 and Industry 5.0, these technologies promise new modes of product communication, configuration, and collaboration. Small and Medium-Sized Enterprises (SMEs), which constitute the backbone of European manufacturing, face structural constraints (cost, skills, and integration) that often prevent them from reaping these benefits at scale [5], [6]. In B2B scenarios, where negotiation dynamics and multi-stakeholder decision-making are central, the lack of established methods to support social interaction and tangible evaluation further hinders adoption [7], [8].

From a scientific standpoint, prior studies have demonstrated that immersive environments can enhance engagement and improve product comprehension. However, two limitations remain pervasive: (i) the sensory gap—particularly the absence of reliable tactile cues in visual-only experiences, which is critical in sectors like fashion; and (ii) the social gap—limited evidence and reusable methods for pair or group configuration and negotiation in immersive scenarios.

This thesis directly addresses these two gaps by proposing tools and methods that converge immersive visualization, social collaboration, and tangible interaction, tailored to SME constraints [9], [10].

1.1 Problem Statement

Despite the proliferation of XR toolchains, three intertwined problems limit effective adoption in industrial B2B contexts [9], [11]:

1. Sensory fidelity: Visual immersion alone is insufficient where material qualities (texture, weight, flexibility) drive evaluation and purchase decisions.
2. Collaborative decision-making: Product configuration is often a social process; yet existing XR systems remain primarily single-user or loosely collaborative, with few validated patterns for real-time negotiation, conflict mitigation, and shared agency in co-located settings.

1. General Introduction

3. Adoption and integration for SMEs: Cost, skill shortages, and unclear workflows hamper the transition from prototype to practice. Practical frameworks that connect XR systems to existing product data and routines are scarce.

1.2 Motivation

In business-to-business (B2B) contexts, particularly among SMEs, product evaluation and configuration still rely predominantly on traditional physical showrooms and circulating material sample kits. This model remains valuable, as it affords rich sensory inspection, enables the sharing of tacit knowledge among practitioners, and naturally supports face-to-face negotiation among multiple stakeholders. However, even in its most effective implementations, the physical showroom approach exhibits structural limitations that increasingly constrain scalability, timeliness, and decision quality.

First, there is "logistical", building, transporting, updating, and disposing of physical samples is costly and time-consuming, often leading to partial collection coverage, delayed updates, and limited personalization.

Second, there is a temporal rigidity: access depends on synchronizing multiple agendas in a specific place and time, which does not always match the cadence of design iterations or procurement cycles. Third, while physical samples do provide haptic fidelity, the decision process itself is typically "social".

Digital alternatives have grown in parallel, yet most visual-only presentations insufficiently capture tactile attributes (e.g., hand feel, texture, stiffness) that are decisive in material-sensitive sectors [12]. Moreover, many existing tools foreground individual exploration rather than shared, co-located, and co-configuration, offering limited mechanisms to coordinate turns, mediate conflicts, or make agreement states salient.

Finally, from an adoption point of view, SMEs face non-trivial barriers—hardware cost, workforce training, and integration with existing PIM (Product Information Management) and DAM (Digital asset management) pipelines—that complicate the transition from prototypes to everyday practice [13], [14]. As a result, organizations often oscillate between the convenience of visual digital assets and the trust afforded by tangible samples, without a unifying framework that reconciles sensory fidelity, social negotiation, and operational feasibility.

Within this landscape, the Covid-19 pandemic did not create new problems but acted as a stress test that exposed latent vulnerabilities [2], [12]. Travel restrictions, supply-chain disruptions, and the

intermittent inaccessibility of physical venues made dependence on showroom workflows particularly fragile. The disruption highlighted the need for hybrid, resilient arrangements capable of sustaining product communication and joint decision-making even when physical colocation is constrained or when sample logistics become temporarily infeasible. Accordingly, the pandemic should be read here as an accelerator rather than a motivation, it compressed timelines and clarified priorities, making evident that B2B evaluation models must remain effective under both ordinary and perturbed conditions.

Taken together, these observations motivate a program of research that does not seek to replace the traditional showroom, but to relocate it within an XR-enabled hybrid ecosystem that preserves its strengths while addressing its structural limits [2], [8]. Unlike much of the prior work on virtual showrooms that targets end-consumer (B2C) experiences [15], [16], our focus is the B2B showroom: integrating virtual presentations with tangible anchors (physical samples aligned with virtual content) to restore perceptual trust while supporting co-located negotiation and decision-making, with potential sustainability benefits through reduced transport and samples [2], [13]. Figure 1.1 illustrates the role of material swatches and option codes in current practice and how they can be coupled with MR to retain haptic cues while expanding virtual configurability.



Figure 1.1: Example of the garment with its color chart

The traditional approach by the resellers is to visit the distributor in person to perform showrooms with physical samples and materials [1]

1. General Introduction

Fig. 1.2.

This approach involves a large amount of disposable resources and transportation costs. B2B showrooms are crucial, as poor reseller decisions can immediately affect final sales, leading to client dissatisfaction, increased returns, and related costs and wastes [17].

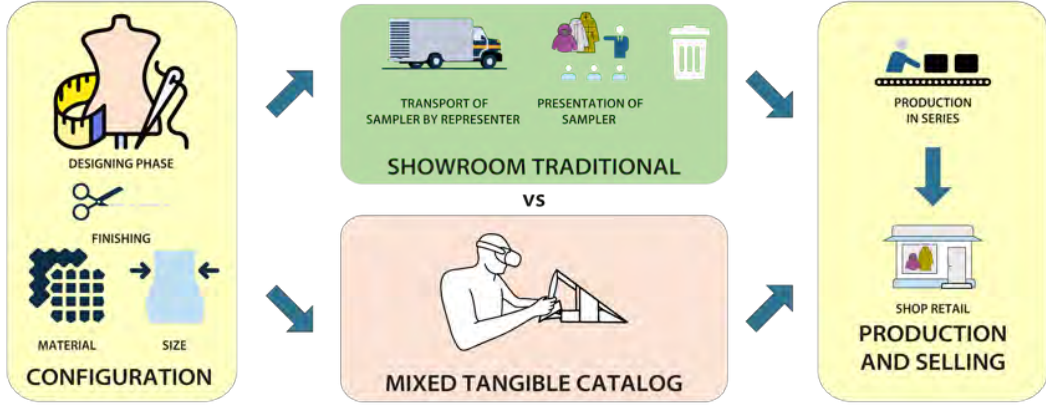


Figure 1.2: The fashion industry processes: **Left:** Product, Design, and Configuration; **Central:** Traditional approach (top) vs The novel Mixed Tangible Catalog (down); **Right:** Production and sales

On the other hand, current virtual showroom implementations do not integrate tangible aspects, but interaction with the material is essential, especially for B2B experts.

1.3 Objectives

The overarching objective is to increase the effectiveness (quality of decisions and evaluations) and accessibility (cost/skill feasibility and workflow fit) of XR for B2B product presentation and configuration in SMEs. The work pursues three specific objectives:

- **O1** — Immersive showrooms: Design and evaluate immersive environments for B2B product presentation that enhance visual engagement and support interactive exploration.
- **O2** — Social configuration tools: Define and validate co-located interaction patterns that support negotiation, agreement formation, and conflict reduction in pairs.
- **O3** — Tangible anchors: Develop and test tangible (physical) anchors synchronized with virtual content to reduce perceptual uncertainty and improve evaluation accuracy in material-sensitive domains.

These objectives translate into the following research questions:

- **RQ1 (Showrooms)** — To what extent do immersive showrooms improve aesthetic evaluation and user engagement relative to traditional 2D interfaces?
- **RQ2 (Social Co-configuration)** — In pair or group settings, how do tangible anchors and co-located coordination patterns affect agreement, decision quality, and the incidence of conflict?
- **RQ3 (Tangibility)** — Does coupling a physical haptic anchor with the virtual model reduce perceptual uncertainty and improve the accuracy of product evaluations compared to visual-only presentations?

1.4 Methodological Approach

This thesis is situated within applied industrial research conducted through collaborations with small and medium-sized enterprises (SMEs). Methodologically, it follows a research-through-design paradigm in which knowledge is generated by iteratively framing a domain problem, translating requirements into interactive XR artifacts, and evaluating those artifacts in use-oriented conditions. The goal is not to treat each prototype as an isolated demonstration, but to use successive design iterations as a structured instrument to surface requirements, breakdowns, and actionable design implications for immersive configuration systems in industrial contexts.

Industrial partners were selected through purposive sampling to maximize ecological validity and relevance for SME-oriented digital transformation. Selection criteria included: the presence of recurring configuration and decision-making activities in pre-sales or early design phases, the availability of product assets suitable for XR visualization, and the feasibility of engaging domain stakeholders in interviews, walkthroughs, workshops, and formative user sessions. This setting enables a consistent pipeline across case studies, combining domain inquiry with iterative prototyping and evaluation, where results are interpreted as feasibility, usability, and perceived value, complemented by task-level observations and standardized questionnaire benchmarks.

“The work spans two domains, fashion and recreational nautical, to intentionally stress-test XR configuration under different decision regimes. In fashion, configuration is driven by large product catalogs and frequent variant exploration, where users must quickly browse, compare, and communicate aesthetic and material choices while maintaining orientation

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within the catalog structure. In nautical configuration, decisions are constrained by the physicality of space, especially in compact interiors, making scale perception, clearance assessment, and collaborative spatial reasoning central to decision quality. Studying both domains allows the thesis to extract transferable design principles while also documenting domain-specific constraints that shape interaction design, visualization fidelity, and collaboration mechanisms in SME workflows.

1.5 Content of Use

The following sections introduce the two industrial domains and summarize their current practices, stakeholders, and decision constraints that informed the subsequent case studies.

1.5.1 Fashion Collaboration

For case studies in part 1, during the making of FSM, and part 2 for MTC.

Thanks to a collaboration with a partner company, EmmeEvolution s.r.l., which helped us in the implementation and user test, in fashion case studies. The company staff formed by (ten users (80% female, 20% male)), sales representatives, and retailers, participated in our user study.

1.5.2 Nautical collaboration

For case studies in Part 1, in case studies (Magic and MR-CoCo), we collaborate with partner company Neo Yacht s.r.l..

This company gives us assets (3D boat models), and interviews with workers to receive feedback and suggestions to create a virtual scenario.

1.6 Thesis structure

The dissertation is organized into three parts and follows the workflow in Fig. 1.3: starting from the B2B field analysis, moving to product presentation, and branching into two trajectories—**Social** and **Tangible**—that lead to the three artefacts.

Part I — Social Interaction: state of the art on immersive showrooms and co-configuration, followed by the design and evaluation of *FSM* Chapter 4, *MAGIC* Chapter 5, and *MR-CoCo* Chapter 6.

Part II — Tangible Interaction: limitations of visual-only approaches and the design/evaluation of the *MTC* system Chapter 8.

Part III — Conclusions: cross-case synthesis, limitations, sustainability considerations, deployment guidelines for SMEs, and future work.

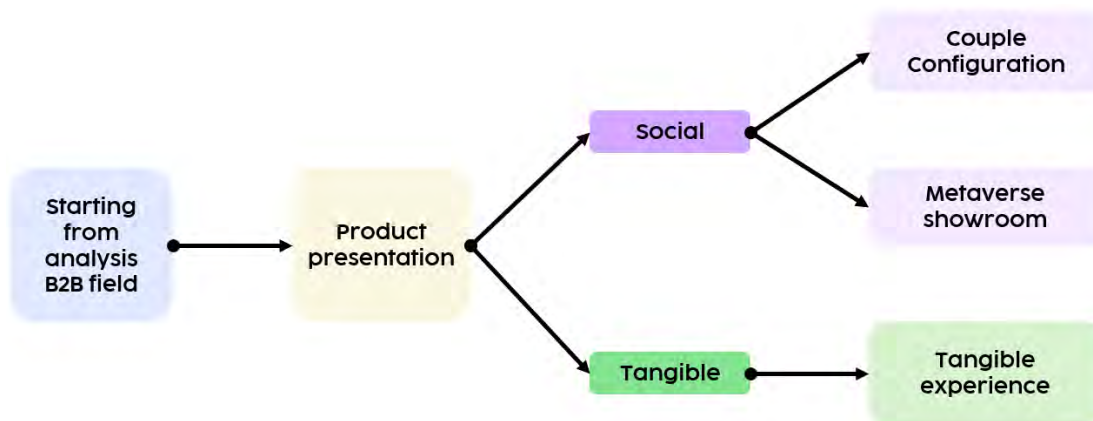


Figure 1.3: Workflow of this dissertation

Chapter 2

Related Work

This chapter provides a comprehensive review of the scientific literature pertinent to the development of immersive systems for small and medium enterprises (SMEs), with particular emphasis on social interaction, tangible interfaces, and product configuration within extended reality (XR) environments. The review is structured to systematically address the key theoretical and technological foundations that underpin this dissertation, critically examining existing contributions while identifying gaps that motivate the present research.

The chapter is organized as follows:

Section 2.1 examines the emergence of the Metaverse and virtual worlds as platforms for business applications, with particular attention to accessibility challenges for SMEs, including an analysis of technology acceptance models and organizational readiness factors.

Section 2.2 reviews product configuration systems in immersive environments, analyzing interaction paradigms, visualization techniques, and the evolution from traditional 2D interfaces to immersive 3D and mixed reality platforms.

Section 2.3 investigates co-located collaborative mixed reality, addressing spatial registration, networking architectures, state synchronization mechanisms, and multi-user interaction design, with particular emphasis on gaps in aesthetic customization and decision-making processes.

Section 2.4 surveys methods for subjective fabric evaluation in digital contexts, bridging material sciences and human perception, with attention to augmented tactile feedback systems.

Section 2.5 examines tangible user interfaces and their integration with virtual environments, exploring embodied interaction and the vMR-hR (visual Mixed Reality - haptic Reality) paradigm.

Finally, Section 2.6 synthesizes the identified gaps and articulates how this dissertation contributes to addressing them, with particular focus on social co-configuration, visual-haptic convergence, and SME adoption challenges.

2.1 The Metaverse and Virtual Worlds: From Concept to Implementation

The term "Metaverse" was coined by Stephenson [18] in the speculative fiction novel *Snow Crash*, envisioning a persistent, shared virtual environment inhabited by users represented as avatars. While initially a literary construct, the concept has progressively materialized through advances

2. Related Work

in networking, 3D graphics, and distributed systems. Contemporary interpretations of the Metaverse emphasize interoperability, persistence, user-generated content, and economic systems enabling virtual commerce [19]. The Metaverse can be broadly understood as a network of persistent, shared, and socially inhabited virtual spaces where users, often represented by avatars, can interact, create, and transact [20].

2.1.1 Business Applications and Enterprise Metaverse

To date, much of the discourse and experimentation around the Metaverse has focused on business-to-consumer (B2C) contexts, especially entertainment and retail, while business-to-business (B2B) use cases remain comparatively underexplored. Within fashion and adjacent industries, virtual and augmented reality have been investigated mainly to enhance store atmospherics, product presentation, and customer engagement [11].

Metaverse platforms can be classified into non-immersive worlds (e.g., Decentraland) and fully immersive, head-mounted display (HMD)-based environments (e.g., Spatial, VRChat), supporting both multiplayer scenarios with multiple concurrent users and single-player experiences wherein a lone user explores the virtual scene. Beyond consumer-oriented social platforms, the Metaverse paradigm is increasingly being explored for enterprise applications [21]. Virtual showrooms, training simulations, collaborative design sessions, and remote site inspections represent use cases wherein immersive virtual environments offer substantive operational advantages [19].

Recent empirical studies in the fashion domain illustrate diverse approaches to Metaverse-based product presentation. Ricci et al. [9] compared desktop virtual reality (DVR) and immersive VR (IVR) for a luxury handbag shopping task, reporting higher utilitarian and hedonic value in IVR, with comparable cognitive load but longer and more engaging sessions. Morotti et al. [22] studied an embodied voice assistant (Alexa), represented as a sphere-shaped avatar in a virtual shop, demonstrating that such guidance can improve outfit configuration and perceived usability. Lau's "Future Shop" concept [23] further illustrates how immersive visualization and interactive garment selection can increase purchase intention, interactivity, and hedonic shopping value in virtual apparel retail.

2.1.2 Technology Acceptance and Organizational Readiness

The Technology Acceptance Model (TAM) [24] and its extensions, including the Unified Theory of Acceptance and Use of Technology (UTAUT) [25], provide theoretical frameworks for understanding factors influencing adoption intentions. Perceived usefulness, perceived ease of

The Metaverse and Virtual Worlds: From Concept to Implementation

use, social influence, and facilitating conditions have been identified as key determinants of technology acceptance.

Extensions specific to XR technologies incorporate constructs such as perceived presence [26], cybersickness susceptibility [27], and perceived innovativeness [28]. Empirical studies reveal that hedonic motivations and experiential value play more prominent roles in VR/AR adoption compared to purely functional technologies [29], suggesting that the immersive and experiential qualities of Metaverse platforms may constitute significant adoption drivers beyond traditional utilitarian considerations.

Organizational readiness for XR adoption encompasses not only technical infrastructure but also managerial commitment, change management strategies, and provision of adequate training [30]. SMEs often exhibit constrained absorptive capacity—limited ability to assimilate and exploit external knowledge [31]—necessitating targeted support mechanisms such as innovation intermediaries, pilot programs, and collaborative ecosystems [32].

2.1.3 Barriers to SME Adoption

Despite the potential benefits, the adoption of Metaverse technologies by SMEs remains limited. Economic barriers include the capital expenditure required for hardware (HMDs, workstations) and software licenses [33]. Technical barriers encompass integration complexity, particularly with legacy systems, and the scarcity of in-house technical expertise capable of developing and maintaining immersive applications [34].

Organizational barriers, including resistance to change, risk aversion, and lack of strategic vision regarding digital transformation, further impede adoption [35]. Knowledge barriers—manifested as limited awareness of available technologies, unclear return on investment (ROI), and absence of relevant case studies—compound these challenges [32].

The democratization of Metaverse access for SMEs necessitates solutions that lower barriers across these dimensions: economically accessible platforms, simplified authoring tools, integration frameworks for legacy systems, and evidence-based demonstrations of business value in contexts representative of SME operational realities.

2.1.4 Research Gap in B2B Metaverse Deployments

In summary, B2C studies in product presentation-oriented Metaverse and XR retail chiefly inform constructs such as engagement, presence, perceived quality, and purchase intention. However, there remains limited evidence of B2B-oriented Metaverse deployments evaluated through controlled user studies and decision-centric metrics. This gap motivates

2. Related Work

the present work’s emphasis on co-located, instrumented collaboration and on hybrid pipelines that connect immersive presentations to tangible evidence and enterprise data.

2.2 Product Configurators in Extended Reality

Product configuration systems enable customers to customize offerings according to individual preferences, selecting from predefined options pertaining to materials, colors, features, and dimensions. In traditional e-commerce contexts, such systems are typically implemented via 2D web interfaces [36]. The integration of configurators with immersive XR environments offers enhanced spatial understanding, photorealistic material representation, and more engaging interaction experiences [37].

2.2.1 Evolution from 2D to Immersive Configurators

Product configuration systems have evolved from static web-based interfaces to more dynamic 3D and immersive platforms. Traditional 2D configurators typically allow users to customize aspects such as materials or colors, but often lack spatial immersion or support for collaborative workflows [38], [39].

Recent advancements have extended configurators into immersive VR, enabling users to interact with 3D models in more engaging ways. For instance, Jin et al. [40] introduced a VR-based product configurator that improves user engagement by providing an interactive environment for collaborative decision-making. However, these VR-based approaches often focus on scaled product representations, limiting real-world spatial alignment and interaction fidelity.

Mixed Reality (MR) approaches integrate virtual elements into the user’s real-world environment, providing a more immersive and contextually grounded experience. Unlike traditional VR-based systems, which often rely on asynchronous feedback or remote collaboration, MR enables synchronous co-located interaction. By leveraging spatial anchors and dynamic interfaces, contemporary MR configurators overcome common challenges in prior tools, such as physical misalignment and asynchronous feedback observed in systems like Arkio [41] and those described by Fages et al. [42].

This integration of real-time collaboration and spatial awareness marks a significant advancement in MR-based product configurators, addressing gaps left by systems that emphasize either physical or virtual worlds without ensuring synchronized co-location.

2.2.2 Interaction Metaphors for Configuration

Traditional graphical user interfaces (GUIs) map poorly onto three-dimensional immersive spaces. Alternative interaction metaphors developed for XR configurators include: (1) spatial menus positioned proximate to configurable components [43], (2) ray-casting selection coupled with radial or pie menus [44], (3) gestural commands invoking configuration options [45], and (4) tangible proxy objects serving as physical controls [46].

Each approach presents trade-offs concerning precision, learnability, and cognitive ergonomics. Studies investigating user preferences reveal a general inclination toward spatially contextualized interfaces that minimize attentional switching between menu systems and the configured artifact [47]. The design challenge lies in balancing intuitiveness for novice users with efficiency for experienced operators, while maintaining consistency with established interaction conventions.

2.2.3 Multi-User Collaborative Configuration

Collaborative product configuration, wherein multiple users jointly define specifications, introduces additional complexities about shared state management, conflict resolution, and mutual awareness. Scientific research addresses multi-user collaboration predominantly from a social perspective, emphasizing the role of VR in design review and group decision-making dynamics, ultimately leading to greater process efficiency. Mixed Reality (MR) facilitates collaborative prototyping between designers, ergonomists, and end-users [48].

Recent systems have begun addressing the technical challenges of multi-user immersive environments. CIDER [49] introduced an AR system enabling independent and conflict-free editing of shared scenes, analyzing the impact of commit strategies (forced vs. consensus-based) on collaborative dynamics and usability. Research by [50] examines how user roles and task complexity influence subjective perception while also exploring technical factors such as latency, which affects Quality of Experience (QoE) in long-range virtual collaboration.

In the nautical industry, BoatAR [51] exemplifies an AR-based configurator that simplifies remote boat customization, demonstrating potential for reducing logistics and inventory costs while showcasing how immersive technologies can address operational and economic challenges. Additionally, Favi et al. [52] addressed the functional arrangement of cockpit instrumentation in maneuvering areas, supported by evaluations of operational, ergonomic, and anthropometric aspects.

Despite these advancements, multi-user product configuration in VR

2. Related Work

remains underexplored, particularly concerning sustainability considerations and the role of advanced graphics in enhancing emotional engagement. Persistent challenges include high hardware costs and the lack of standardized user interfaces to ensure accessibility and intuitiveness for a broad audience [53]. Moreover, despite technological progress, the inherent complexity of VR tools often requires specialized expertise for effective integration into complex workflows, such as those typical of the nautical industry [54].

Future research should explore novel collaborative approaches that incorporate realistic graphics and avatar support, enhancing spatial perception and ergonomic assessment in real-world industrial scenarios, with particular attention to the unique requirements of SME contexts where resource constraints and workflow integration challenges are more pronounced.

2.3 Co-located Multi-User Mixed Reality Systems

Co-located collaboration in MR environments, wherein multiple users occupy the same physical space while interacting with shared virtual content, represents a distinct modality with unique affordances and challenges [55]. Unlike remote collaboration systems relying exclusively on network-mediated communication, co-located configurations preserve face-to-face interaction, nonverbal cues, and direct physical presence, potentially enhancing coordination efficiency and mutual understanding.

Co-located Mixed Reality offers significant advantages for collaboration by establishing a shared spatial frame of reference and mutual visibility of gestures and gaze, which can improve grounding, reduce deictic ambiguity, and facilitate joint action [56]–[58]. The design of these environments is non-trivial; studies on user positioning (e.g., side-by-side vs. face-to-face) reveal trade-offs between accessibility and interference [59], [60], while research extending Fitts' Law to multi-user VR highlights how proximity and occlusion affect performance [61], [62]. Furthermore, investigations of collaborative tasks such as escape rooms underscore the importance of communication channels that support direct communication and distributed problem-solving beyond simple text or audio [63].

2.3.1 Spatial Registration and Shared Reference Frames

A fundamental prerequisite for co-located multi-user MR is the establishment of a shared spatial reference frame [64]. Users' individual tracking systems must be mutually registered such that virtual content appears consistently positioned and oriented relative to the physical environment. Techniques for achieving spatial alignment include: (1) external tracking

infrastructure (e.g., OptiTrack, Vicon) providing a common coordinate system [65], (2) shared natural feature tracking, wherein all users' devices detect and localize the same physical markers or objects [66], and (3) cloud-based spatial anchors [67] enabling device-independent persistence of virtual content registration.

The accuracy and stability of spatial registration directly impact user experience, as misalignment manifests as perceptual inconsistencies (e.g., virtual objects floating above surfaces, interpenetration with physical obstacles) that disrupt immersion and task performance [68]. Contemporary systems must balance registration precision against computational overhead and initialization complexity, particularly in resource-constrained SME deployment scenarios.

2.3.2 Networking Architectures and State Synchronization

Real-time multi-user systems necessitate low-latency state synchronization across devices to ensure consistent visualization of shared virtual content [69]. Networking architectures include: (1) client-server models, wherein a centralized server maintains authoritative state and disseminates updates to clients [70], and (2) peer-to-peer approaches, wherein clients communicate directly, potentially reducing latency but complicating conflict resolution [71].

Interpolation and extrapolation techniques, dead reckoning, and interest management [72] are employed to mitigate the perceptual artifacts arising from network latency and jitter. The choice of networking topology and synchronization strategy depends on application-specific requirements concerning scalability, latency tolerance, and consistency guarantees, with co-located scenarios typically prioritizing low latency over extreme scalability.

2.3.3 Collaborative Interaction Design

The design of collaborative affordances—visible cues indicating the manipulability of shared objects, permission models governing access rights, and feedback mechanisms confirming action outcomes—profoundly influences collaborative efficiency and user satisfaction [60]. Empirical studies reveal that explicit mechanisms for coordinating attention (e.g., pointing gestures, gaze indicators) and communicating intent (e.g., verbal commands augmented by visual annotations) enhance mutual understanding and reduce coordination overhead [73].

Collaborative interaction in MR environments encompasses diverse modalities: simultaneous manipulation of shared objects, turn-taking protocols mediated by explicit locking mechanisms, and parallel activities wherein users work on independent subtasks within a shared space.

2. Related Work

The design of appropriate collaboration patterns must consider task characteristics, user expertise, and social dynamics to optimize both objective performance metrics and subjective experience quality.

2.3.4 Gap in Aesthetic and Decision-Centric Collaboration

While existing studies have advanced functional and technical aspects of collaborative MR, significant gaps remain in understanding aesthetic customization and commercial decision-making processes. Much of the existing literature has focused on functional tasks [74] or remote collaboration, often overlooking the nuanced, interactive decision-making processes essential in real-time aesthetic customization. For instance, explorations in multi-user AR assisting co-located users with room layouts [74] noted challenges in interaction fluidity but did not focus on aesthetic or design-oriented judgment.

This gap persists in both academic taxonomies and commercial tools. Taxonomies classifying AR collaboration [75] provide useful analytical lenses, yet few systems instrument the aesthetic and commercial decision-making typical of B2B configuration (e.g., explicit states for proposal, comparison, shortlisting, and final consensus). Similarly, commercial solutions like Arkio [41] demonstrate the potential for co-located architectural design but remain constrained by preset asset libraries and limited customization capabilities.

The present research addresses this gap by focusing on co-located collaborative product configuration scenarios involving aesthetic judgment and commercial decision-making, with particular attention to the unique requirements of SME contexts in fashion and nautical industries.

2.4 Subjective Fabric Evaluation in Digital Contexts

In fashion and textiles, material interaction is central to quality judgment; virtual showrooms that omit tangibility face well-documented limitations in conveying material properties accurately. Subjective hand (handle) assessment by trained experts remains a cornerstone of textile evaluation, with established procedures that elicit perceived attributes through direct manipulation of physical swatches [76].

Empirical comparisons between real-touch protocols and virtual simulations highlight discrepancies in perceived stiffness, bulk, compressibility, and micro-texture; these differences can be magnified in contexts where negotiation and consensus-building among multiple stakeholders unfold. Bridging traditional tactile assessment and virtual experiences thus requires hybrid approaches that bring real haptic cues into instrumented

immersive sessions, particularly when multiple decision-makers must reach agreement on material selections.

2.4.1 Augmented Tactile Feedback Systems

Given the limitations of purely visual fabric representation, researchers have explored augmented tactile feedback as a complement or alternative. Tactile displays employing vibrotactile actuation [77], electrotactile stimulation [78], or deformable surfaces [79] aim to simulate fabric textures through controlled sensory stimulation.

The challenge of reproducing the nuanced tactile characteristics of textiles—particularly the complex interplay of mechanical properties manifested during grasping, stretching, and rubbing—remains formidable. Current haptic technologies can approximate certain aspects of textile hand feel but fall short of reproducing the full richness of physical fabric interaction, particularly for expert evaluators with highly calibrated tactile discrimination abilities.

Hybrid approaches combining physical fabric samples (tangible proxies) with virtual visualization of coloration and pattern [80] offer pragmatic compromises, preserving authentic tactile information while enabling digital manipulation of visual attributes. Such approaches recognize that complete tactile simulation may be neither technically feasible nor economically justified for many application scenarios, and that strategic integration of physical and virtual modalities can achieve acceptable user experience within practical constraints.

2.5 Tangible Interaction and Haptic Integration

Tangible User Interfaces (TUIs) [46] embody digital information and functions through physical objects, enabling direct manipulation and leveraging users' sensorimotor skills developed through real-world interaction. The integration of tangible elements within XR environments blurs boundaries between physical and virtual modalities, offering enhanced realism and embodied engagement [82].

Tangible interactions focus on designing physically interactive and manipulable interfaces that afford natural engagement. The essence of tangible interaction lies in creating intuitive ways to engage with digital content through physical manipulation. Compared to interactions with purely digital interfaces, tangible interactions tend to be more captivating and memorable, potentially reducing cognitive load and enhancing task performance through exploitation of well-practiced sensorimotor skills [10]. Tangible user interfaces supported with physical samples, conceived as an alternative or complement to purely visual interfaces,

2. Related Work

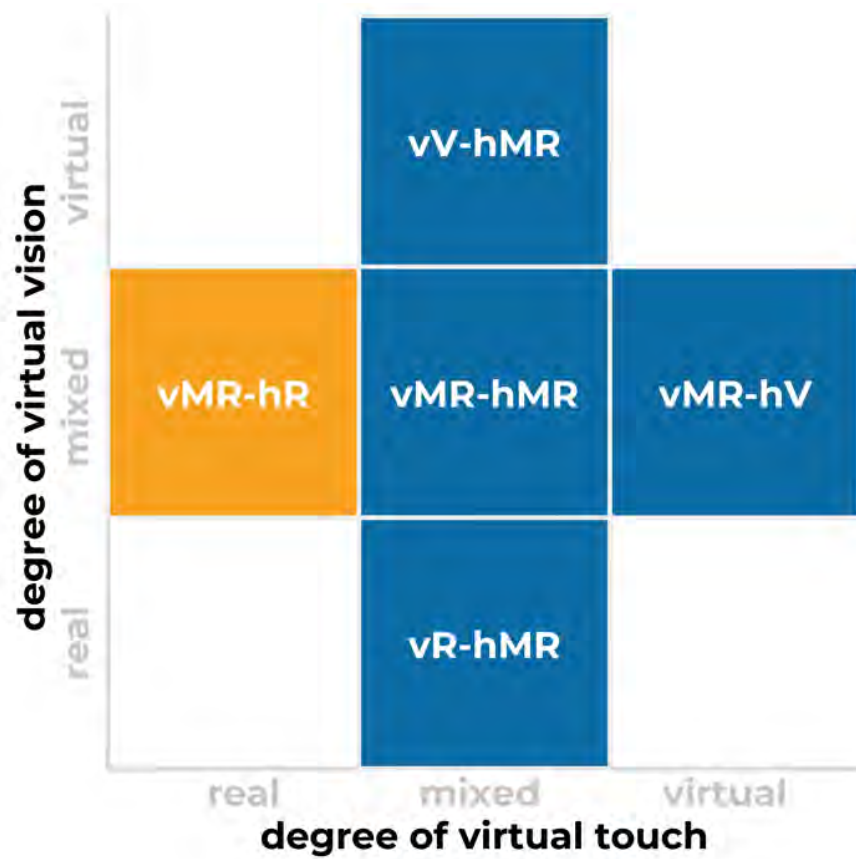


Figure 2.1: This study uses the real haptic and virtual vision (vMR-hR) approach, highlighted in orange as defined by Jeon et al. [81] grid.

aim to reintroduce the interactive richness associated with physical items into engagements with digital content.

2.5.1 The Visual Mixed Reality and Haptic Reality Paradigm

Although the topic of touching physical materials while experiencing virtual visualization is not extensively discussed in the literature, Jeon et al. [81] provide a useful conceptual framework through their "continuum" of virtual touch and virtual vision. This continuum is represented graphically as a grid with nine blocks: the x-axis represents the "degree of virtuality in touch" while the y-axis indicates the "degree of virtuality in vision" (Figure 2.1).

This classification centers on the potential of interactions in Mixed Reality, particularly the fusion of visual and haptic components. The block investigated in the present work is designated "visual Mixed Reality and haptic Reality" (vMR-hR), in which the user interacts with real objects while perceiving mixed (physical and virtual) visual content,

highlighted in orange in Figure 2.1. It is important to emphasize that this definition of "haptic reality" refers to touching actual physical objects and should not be confused with the common definition of haptics, which typically refers to the use of artificial haptic display devices.

The vMR-hR paradigm offers particular advantages for applications requiring authentic material assessment, such as fabric evaluation in fashion showrooms, where the complex tactile properties of textiles are difficult to reproduce artificially but can be preserved through integration of physical samples with virtual product visualization.

2.6 Research Gap and Positioning of This Work

The preceding review reveals substantial progress in the technical capabilities of XR systems and growing interest in their application to industrial contexts. However, critical gaps persist, particularly concerning the deployment of immersive technologies within resource-constrained SME environments and the design of interaction paradigms that balance technological sophistication with usability and social sustainability.

2.6.1 Limited SME-Focused Research

Existing literature on immersive product configuration, collaborative MR, and virtual showrooms predominantly reports studies conducted within large corporations or research laboratories [37]. SMEs face distinct challenges—including limited budgets, lack of specialized personnel, and tighter integration requirements with existing non-digital workflows [34]—that are insufficiently addressed by solutions developed for large enterprises.

Research investigating the transferability of XR technologies to SME contexts remains sparse. Studies demonstrating pragmatic deployment methodologies, cost-benefit analyses grounded in SME operational realities, and evaluation of systems designed explicitly to minimize technical complexity are needed to inform evidence-based adoption decisions [32].

While technical performance (rendering quality, latency, tracking accuracy) has received extensive scholarly attention, the social and organizational dimensions of XR adoption remain comparatively underexplored. Questions concerning workforce impacts, skill requirements, acceptance barriers among non-technical users, and strategies for inclusive design have not been systematically investigated in industrial XR contexts.

2. Related Work

2.6.2 Sustainability and XR Adoption

The discourse on sustainability in technology adoption extends beyond environmental and economic dimensions to encompass social sustainability, the equitable distribution of opportunities, well-being, and agency among stakeholders [83]. In the context of immersive technologies for industrial applications, social sustainability considerations include workforce impacts, accessibility, digital literacy, and the psychological effects of prolonged XR usage.

The acceptance that technological deployments enhance rather than diminish human well-being, agency, and equity in XR design methodologies represents a nascent area requiring substantial further research. This dissertation addresses this gap by foregrounding human-centered design principles and empirically evaluating not only task performance but also user comfort, collaboration quality, and subjective experience.

2.6.3 Gap on Tangible Interaction in Product Configuration

Although tangible interfaces have been extensively studied in educational and creative applications [84], their application to industrial product configuration—particularly in hybrid configurations integrating physical material samples with virtual product representations—remains limited. The specific challenge of bridging tactile fabric evaluation (critical in fashion and textile industries) with digital product customization has received minimal attention.

Furthermore, empirical evaluations comparing tangible versus purely virtual approaches in realistic configuration scenarios, accounting for prolonged usage durations and cognitive fatigue, are scarce. This dissertation contributes novel tangible interface designs tailored to SME fashion showroom contexts and provides controlled experimental evidence regarding usability, user acceptance, and practical deployment considerations.

2.6.4 Gap on Co-located Collaborative Configuration

While remote collaboration systems for VR have been extensively investigated [55], co-located multi-user MR configuration scenarios—wherein collaborators share physical proximity while jointly customizing products—represent a less explored configuration. The unique affordances of co-location (preserved nonverbal communication, spatial awareness through peripheral vision, ease of reference to physical artifacts) and associated design challenges warrant dedicated inquiry.

This dissertation systematically investigates co-located collaborative product configuration through purpose-built testbeds, employing mixed methods (quantitative usability metrics, qualitative observational data) to characterize interaction patterns, collaboration dynamics, and design implications. The resulting contributions advance understanding of how spatial co-presence influences collaborative decision-making in mixed reality contexts.

2.6.5 Synthesis: Three Intertwined Gaps

Synthesizing the foregoing analysis, this dissertation addresses three intertwined gaps that span technical, methodological, and organizational dimensions:

- **SME adoption gap:** Limited design-for-deployment guidance connecting XR prototypes to SME workflows (integration with existing data/assets, training effort, cost envelopes) and to sustainability outcomes (e.g., reduced physical samples, decreased travel requirements for showroom visits).
- **Social co-configuration gap:** A lack of validated, reusable interaction patterns for co-located, pair-based product configuration in XR (including proposal, shared controls, and consensus mechanisms) and a shortage of decision-centric metrics (agreement time, consensus stability, conflict events) to evaluate collaborative effectiveness systematically.
- **Visual–haptic convergence gap:** Insufficient empirical evidence on whether and how tangible anchors (real material samples synchronized with virtual garments/products) reduce perceptual uncertainty and improve evaluation accuracy relative to visual-only setups, particularly in contexts requiring expert material assessment.

2.6.6 Contributions of This Research

This research addresses the identified gaps through a design research methodology [85] encompassing iterative development of novel systems (Fashion Showroom in Metaverse, MAGIC, MR-CoCo, Mixed Tangible Catalog), rigorous user-centered evaluations, and critical reflection on design principles. The contributions encompass:

1. **Pragmatic XR Solutions for SMEs:** Development of cost-effective, technically accessible immersive platforms demonstrating

2. Related Work

feasibility for resource-constrained organizations, with explicit attention to deployment considerations including hardware requirements, integration complexity, and training burden.

2. **Social Interaction in XR:** Empirical investigations of collaborative dynamics, spatial awareness, and trust-building in co-located multi-user MR configuration scenarios, yielding validated interaction patterns and decision-centric evaluation metrics applicable to B2B product customization contexts.
3. **Tangible Interaction for Fabric Evaluation:** Novel hybrid interfaces integrating physical material samples with virtual product visualization, evaluated in authentic fashion industry contexts, providing empirical evidence on the efficacy of the vMR-hR paradigm for material-intensive product categories.
4. **Human-Centered Design Frameworks:** Methodological contributions concerning inclusive design, usability assessment, and integration of social sustainability principles in industrial XR development, with particular emphasis on stakeholder engagement and iterative refinement processes suitable for SME contexts.

By bridging technical innovation with grounded consideration of organizational and human factors, this dissertation contributes actionable knowledge supporting the responsible and effective adoption of immersive technologies by small and medium enterprises within the Made in Italy ecosystem and beyond. The work demonstrates that XR technologies, when appropriately designed and deployed with attention to social sustainability and pragmatic constraints, can deliver substantive value to SMEs while enhancing rather than displacing human expertise and agency.

Part I

Social interaction

Chapter 3

Methodology for Social XR

Social XR refers to the study and design of immersive environments where the interaction between multiple users plays a central role. In contrast to individual virtual experiences, social XR emphasizes the collaborative dynamics that emerge when several actors engage simultaneously with a product or a task. Within this perspective, immersive technologies are not only visualization tools but also platforms for negotiation, cooperation, and joint decision-making.

In industrial settings, like B2B collaboration and configuration, the user experience goes beyond passive observation. Customers, suppliers, and designers participate in interactive processes, with decisions being made collectively and often requiring coordination and compromise. This is especially true for product configuration, where various stakeholders must align on design choices, materials, or finishes. In these cases, social presence and the ability to share a common reference frame are essential for the success of the process.

This part of the thesis focuses on two main research domains:

- **Immersive showrooms in the metaverse**, which explore how virtual environments can enhance B2B product presentation, reduce the reliance on physical samples, and provide a sustainable alternative to traditional showrooms.
- **Collaborative configuration in pairs**, which investigates how two users can jointly configure a product in XR, examining negotiation patterns, agreement strategies, and decision quality.

The aim is to understand how immersive technologies can support not only the visual and functional representation of products, but also the social processes that underpin configuration and purchasing decisions. This part combines a review of the state of the art with the presentation of two case studies. Both are conceived to evaluate how XR can be applied to real-world B2B contexts where collaboration and negotiation are central.

3.1 Research Scope and Questions

This part addresses two complementary objectives of the overall program:

O1 – Immersive showrooms

3. Methodology for Social XR

O2 – Social configuration tools (see Objectives in the General Introduction).

Accordingly, we investigate:

RQ1 (Showrooms): To what extent can immersive B2B showrooms improve visual assessment compared to traditional solutions such as 2D images and physical presence?

RQ2 (Social Co-configuration): In pair or group settings, how do co-located coordination patterns (e.g., proposal/lock, turn-taking, shared controls) affect agreement, decision quality, and conflict incidence?

3.2 Case Studies

We analyze three case studies that demonstrate varying degrees of social interaction and system capabilities in B2B settings:

- The use of immersive technologies by SMEs.
- Different methods for product presentation and configuration.

Each case study targets a specific industry, investigating how the integration of social and tangible interactions enhances user experience, decision-making, and sustainability.

3.2.1 Fashion product presentation

Fashion Showroom in the Metaverse (FSM) a fully virtual showroom for fashion B2B product presentation. It explores how controlled immersive environments can reduce reliance on physical samples while sustaining decision-relevant judgments by professional users (Detailed in Chapter 4).

3.2.2 Yacht configurator

Collaborative VR Configurator (MAGIC) configurator in the nautical domain, enabling co-located pairs to explore and configure a yacht, focusing on social presence and negotiation mechanics in a high-fidelity immersive setup (Detailed in Chapter 5).

Couple MR Configurator (MR-CoCo) a mixed-reality couple configurator for yachts that extends the pair-based configuration paradigm to MR, emphasizing shared agency, turn-taking, and decision traces with real-world spatial referencing (Detailed in Chapter 6).

Chapter 4

FSM Fashion Showroom Metaverse

The project involves the development of a Fashion Showroom Metaverse (FSM) for the B2B fashion sector, aimed at facilitating interaction between retailers and the sharing of business projects. The system design process begins with the identification of user needs, which come from the fashion sector and operate in a B2B context. Next, user requirements are defined, which include the presentation of garments and the configuration of materials.

The conceptualization phase of the FSM involves the design of a virtual showroom where retailers can view and interact with garments while company representatives present collections Figure 4.1. The experience is developed multiplayer mode, with users represented by avatars.

The virtual showroom is designed to be used exclusively by the retailer, replicating the interaction typical of a physical meeting. The interaction actions are those traditionally used in the B2B, necessary for selecting products for purchase. These include viewing the entire catalog and its color chart, although they do not allow you to see the different color versions of a single product or the various configurations available.



Figure 4.1: Concept of "Fashion Showroom in the Metaverse" (FSM) that includes user floor view and garment visualization.

4. FSM Fashion Showroom Metaverse

4.1 Showroom design

The virtual showroom spans 20x10 meters, recreating the traditional interaction between the retailer and the company representative. The retailer can move freely around the room, staying seated to minimize cybersickness issues. This seating arrangement mirrors traditional interactions in a physical showroom while maintaining comfort during extended VR sessions [86].

The virtual room adopts a futuristic style, inspired by the fashion manufacturer's branding guidelines. Key elements, such as the mannequin displaying the garment, are strategically placed to ensure optimal visibility and interactivity Figure 4.2.

The area for the mannequin wearing the garment is elevated because for correct visibility (i.e., light blue dot) is positioned in front of the seat at 2.30m, a height of 45cm, and represented by a female body with predefined somatic features (height 170cm; total black outfit). On the sides of the mannequin, are panels indicating the description of the garment materials and the name. The interface (i.e., blue dot). The seating area for the retailer (i.e., red dot). The company representative (i.e., green dot).

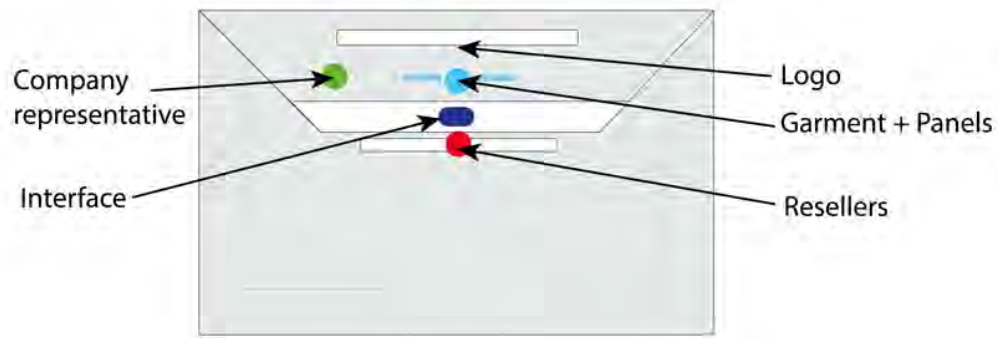


Figure 4.2: Fashion Showroom in the Metaverse layout.

4.2 3D virtual user interface design

The reseller can interact with the mannequin through a user interface, placed on the desk Figure 4.3, and interact through the avatar's hands. The interface is made of 3D buttons, divided into two groups. The first group consists of two elements at the top, designed for color change with colored spheres according to the color chart. The second group consists of the remaining consists of four sub-areas elements at the bottom:

- Left macro-area: Mannequin control: go close to the mannequin;

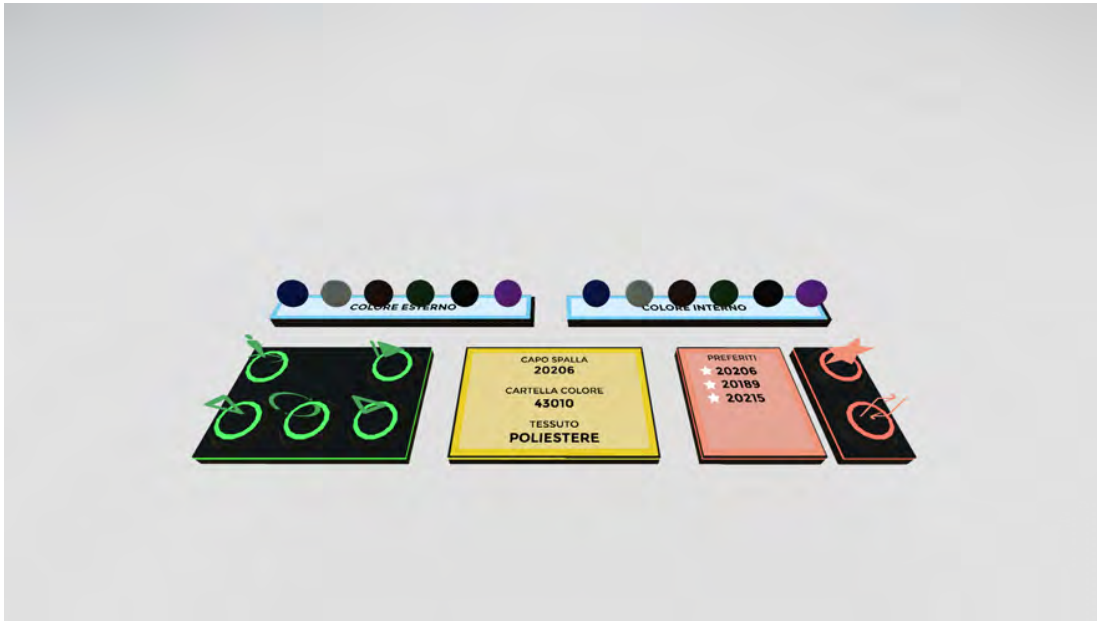


Figure 4.3: The virtual user interface.

start the fashion show; rotate the mannequin; change garments with the next/previous button.

- Center macro-area: Information: the display of garment name and related technical information (color chart and material).
- Right macro area: Favorite garments: List of saved garments and button for saving the garment and comparing multiple garments.

4.3 Design of experiement

4.3.1 Setup

The software architecture is based on VRChat [87] used to host the metaverse; Ready Player Me is a platform that allows for the creation of custom humanoid avatars. VRChat is an application installed on the Oculus headset through the integrated store and requires an Internet connection to be used in multiplayer mode. For access to all the mentioned platforms, one must have a dedicated account. For the virtual world creation phase, Unity Engine is used as the editor, and by taking advantage of the SDKs provided by VRChat, it allows the loading of the virtual world from Unity to VRChat. A Meta Quest 2 was used for testing.

4. FSM Fashion Showroom Metaverse



Figure 4.4: Experimental Setup: The real user interacts with the virtual scene through HMD.

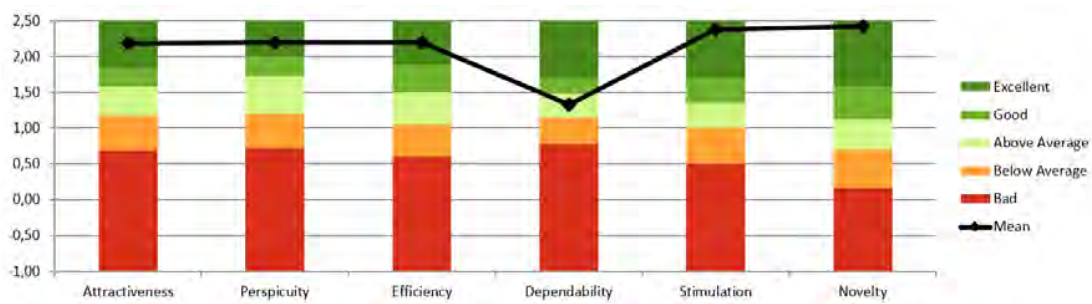


Figure 4.5: UEQ scales results with 5% confidence intervals error bars.

4.3.2 Procedure

Before the test, users received a briefing from a research assistant, through a presentation, that trained them about the experience, and HMD, and explained the VR operations (see Fig. Figure 4.4). The search assistant assisted users within the virtual scene, through an HMD.

4.4 Validation and Results

We evaluate the user experience through a User Experience Questionnaire (UEQ) [88]. The UEQ consists of 26 adjective-based semantic differential elements. Using six criteria (attractiveness, perspicuity, efficiency, reliance, stimulation, novelty) UEQ aims to better understand how users view the system. We compared the two UEQ datasets using the UEQ analytic tool utilizing a baseline data set made up of information from 21,175 participants in 468 studies on a variety of issues Figure 4.5.

The results obtained represent user feedback related to the user experience measure Figure 4.5 regarding the FSM. The five dimensions of Attractiveness, Perspicuity, Efficiency, Stimulation, and Novelty delivered “Excellent” values, while the De-pend-ability dimension delivered an “Above Average” value. Dependability usually refers to how much the

	Conclusion					
	Mean	Std. Dev.	N	Confidence	Confidence Interval	
Attractiveness	2,183	0,722	10	0,447	1,736	2,631
Perspicuity	2,200	0,753	10	0,467	1,733	2,667
Efficiency	2,200	0,599	10	0,371	1,829	2,571
Dependability	1,325	0,958	10	0,594	0,731	1,919
Stimulation	2,375	0,592	10	0,367	2,008	2,742
Novelty	2,425	0,602	10	0,373	2,052	2,798

Table 4.1: Confidence intervals (p=0.05) per scale

user feels in control of the interaction. Therefore, this result may depend on the fact that not all users were familiar with VR and had ever performed a task in VR. Some users (n=2) reported feeling dizzy and perceiving a sense of nausea. These represent symptoms of cybersickness, probably caused by the position (sitting) and weight of the Oculus Quest 2. Despite this negative aspect, all users expressed their involvement and engagement in being immersed in the virtual environment and seeing themselves embodied in an avatar.

4.5 Conclusion

The FSM solution demonstrates that the Metaverse can effectively support B2B product presentations while addressing sustainability challenges. This study, while preliminary with a small sample, affirms the potential of virtual fashion showrooms to overcome traditional showroom limitations, especially in terms of transportation costs.

Chapter 5

Magic

The Multi-user Advanced Graphic Immersive Configurator (MAGIC) is a collaborative, cross-platform solution designed for configuring complex, high-value products such as yachts, providing an immersive and scalable customization experience. MAGIC integrates multi-user functionalities with high-quality, photorealistic rendering, enabling a seamless configuration experience, even on lower-performance hardware.

This system advances research in immersive technologies, particularly by addressing the limitations of traditional 2D visualization systems, which often fail to engage customers in the B2B environment effectively. By offering an intuitive and immersive interface, MAGIC bridges the gap between complex CAD models and customer expectations, allowing users to engage with a product in real-time, visualize configurations, and make informed decisions.

This study includes a real-world case study conducted in a shipyard, where MAGIC was tested in a professional setting, contributing to both scientific research and promoting eco-sustainability in product design. The research demonstrates the feasibility of immersive VR tools in high-value product configuration, and MAGIC serves as a foundation for future innovations in the sector.

The key contributions of this research are:

- The development of MAGIC, a VR-based collaborative configuration system featuring real-time optimized photorealistic rendering.
- A practical case study of MAGIC applied in a shipyard, where it was used to configure sailing yachts and gain valuable user feedback.

5.1 Implementation

To implement collaboration, the users are embodied with digital avatars and provided with synchronized tools. A maximum of 10 participants can simultaneously use the following interactive features (Viewer Menu, see Figure 5.1):

- **Transform:** Allows selecting an object or assembly prepared for mobility, dragging in 3D space, and repositioning it.
- **Measurement:** Allows performing measurements to support space evaluation.

5. Magic

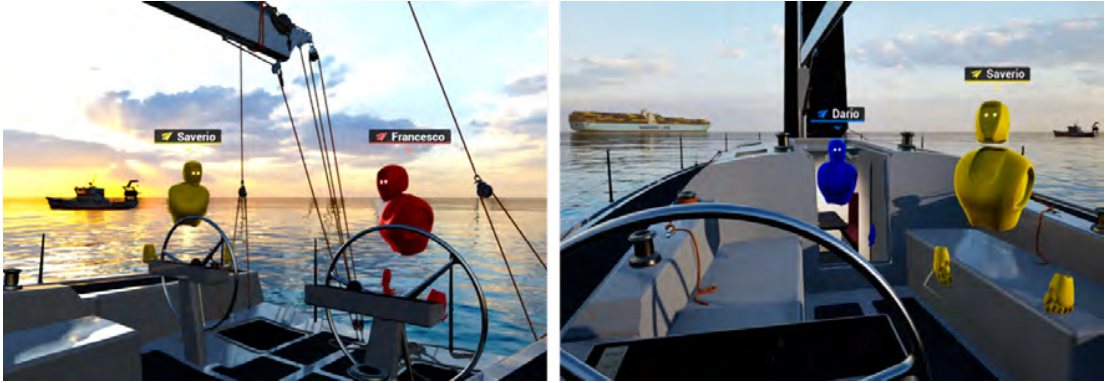


Figure 5.1: Multi-user VR configuration of a highly customizable yacht using MAGIC in a three-person shared session: Yellow and Red users evaluate the optimal distance between the helms (left), while the Blue user observes the deck from the hatchway (right).

- **3D Cut Volume:** Allows modeling, moving, rotating, and scaling a cutting volume to dynamically inspect cross sections of the model.
- **Bookmark:** Allows creating quick-access points to the scene, facilitating access to key elements of the model.
- **User Scale:** Manages the avatar scale to access an overall view of the model or move quickly through space.
- **Annotation:** Allows creating 3D text boxes for comments and annotations.
- **Snapshot:** Allows taking snapshots to validate the arranged configuration.

Unreal Engine 5 (UE5) is chosen for the VR implementation due to its versatility, scalability, and advanced integrated programming tools. With technologies like *Nanite* and *Lumen*, this game engine can provide high-quality visual experiences and manage complex, high-resolution geometries with dynamic lighting.

MAGIC is an extension of **Collab Viewer**, a cross-platform template provided by UE5 and designed for collaborative experiences, with excellent flexibility for integrating custom controls through Blueprint (BP) programming.

A dedicated BP logic has been implemented to allow the configuration of aesthetic variants, supported by photorealistic materials and algorithms for simulating interior furniture components, aimed at validating the ergonomics of the yacht's confined loft spaces.

Using a raycast targeting logic and activating the command with the dedicated button on the controller, the user can easily cycle through material variants Figure 5.2 and interact with the yacht's internal and external components, without the need for an overlaying menu. This approach is chosen to prioritize the usability and simplicity of the interface.



Figure 5.2: Material variant permutation example in real time: from striped marine fabric (left) to petrol leather (right).

In the scene, the user can move using the teleportation metaphor Figure 5.3 left or quick access points (Bookmarks) to explore the model and access off-board PoV for an overview of the configured yacht Figure 5.3 right.



Figure 5.3: Teleport ray cast (left), position Bookmarks (right) for quick access to key locations (e.g. off-board tender view)

At the start of a collaborative session, the initial user (*Host*) enables the server, allowing participants (*Clients*) to access the shared scene. Each *Client*, equipped with their own headset and computer, can join the session remotely by connecting to a shared network (Wi-Fi or VPN).

In basic multiplayer solutions, only the *Host* has the authority to edit the scene on the server and share it with *Clients*. Although default

5. Magic

template features are provided with appropriate programming measures, implemented functionalities (e.g., material changes, animations, etc.) require tailored multi-user logic to allow all users to actively interact with the scene during the session.

Immersive elements such as spatial sound effects and dynamic environmental content (e.g., waves, boats in motion Figure 5.4) can be added to enhance emotional engagement and the overall quality of the experience. By means of volumetric sound occlusion, the pitch of waves and motor noises is reduced when an object is positioned between the sound source and the avatar, allowing users to experience a quieter and cozier environment once inside the loft. In addition, automatic exposure is enabled in the scene to ensure a smooth and realistic transition between the yacht's interior and exterior, where sunlight might otherwise appear overly bright or dazzling.



Figure 5.4: Environmental and narrative content: moving trawler with spherical engine noise (left); Cargo ship in the background (right).

5.2 Research Questions

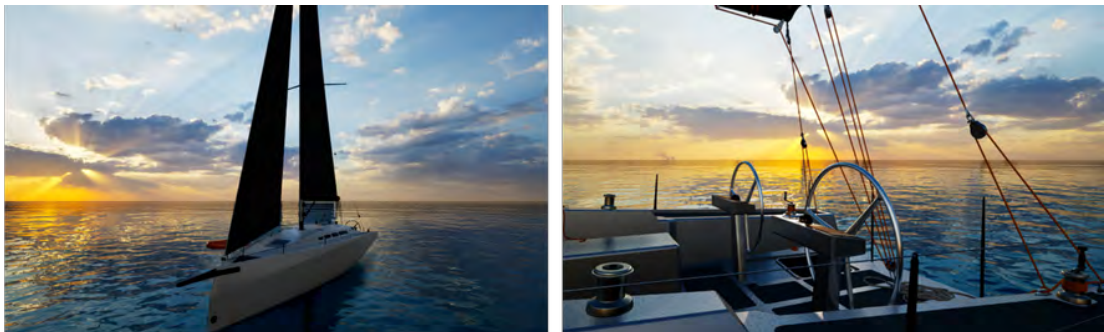


Figure 5.5: Photorealistic dynamic environment provided by MAGIC in runtime: showcasing a photorealistic yacht view from afar (left) and an immersive onboard perspective toward a vibrant sunset (right).

In addition, we designed and implemented realistic and dynamic environments, such as breathtaking marine scenarios, including open seas (Figure 5.5), ports, and coastlines to enhance user engagement and create an emotional impact during the purchase process.

We address the following Research Questions (RQs) with a user test in a controlled setting:

- **RQ1:** Does MAGIC ensure an adequate level of usability?
- **RQ2:** Does MAGIC enhancement the sailboat configuration experience?
- **RQ3:** Do advanced graphics impact immersion and realism for the configuration process?
- **RQ4:** Do environmental scenarios and additional content contribute to user engagement?
- **RQ5:** Does demographic data or prior VR experience affect the system's usability?

5.2.1 Participants

Participants were recruited through a social call distributed via the university mailing list including students, PhD candidates, and researchers from Engineering and Industrial Design faculties at the Polytechnic University of Bari, as a representative sample of users with different background for evaluating system's usability.

Thirty volunteers participated in the tests (age of 24.20 ± 4.62 , min=18, max=32), with a gender distribution of 63.3% male (19 users) and 36.7% female (11 users). The male prevalence is in line with the current preference of real clients, while the age is younger to provide insights into future customers. To create a multi-user scenario, the subjects were divided into 15 couples according to booking order, with the members of each couple not necessarily knowing each other.

5.2.2 Setup

The tests were conducted in a controlled environment using Oculus Meta Quest 2 and 3 HMDs connected to two side-by-side laptops with different technical specifications:

- **Asus ROG** with an Intel Core i7-7700HQ processor, 16GB of RAM, and an NVIDIA GeForce GTX 1070 graphics card
- **Acer Aspire 5** with an AMD Ryzen 7 5700U processor, 16GB of RAM, and an AMD Radeon RX Vega 8 graphics card.

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These two different setups allowed the feasibility and compatibility of devices with varying system specifications and operational conditions.

5.2.3 Procedure

The test duration of 25 minutes is estimated according to the company's experience, as valid to perform an initial configuration of the yacht. Before the test, users are introduced to the research topic and provided with training (5 min) on the VR commands, with a total test duration set to 30 minutes. Users, however, can interrupt the test at any time. The participants are asked to role-play as potential customers of the yacht model in an interactive and consensual configuration (Figure 5.6 left). During the collaborative session, users are co-present in the same laboratory and connected with two synchronized hardware to a shared scene through a Wi-Fi network (Figure 5.6 right).



Figure 5.6: Double setup paired test (left image), collaborator visualization in the shared scene; the field of view of the female participant (right image).

The users define materials, the nautical components, and interior furniture, analyze spaces using the inspection tools, and interact with dynamic elements of the scene to explore the model and assess the ergonomic suitability. During the test a scientist monitors users' actions to ensure safety and assistance.

5.2.4 Metrics

The configuration experience for each pair enabled the collection of data through the following metrics:

- User **Age**, user **Gender**, user previous **VR Experience** (yes/no)
- **Success Rate**: Measures the effectiveness of the VR configuration process in terms of percentage of successful couple sessions

- **Early exit:** Number of couples that quit the session before the planned test time
- **SUS [89]:** Standard questionnaire for evaluating system usability
- **Open-ended Feedback:** Evaluation of the implemented features, the level of immersion, graphical rendering, and emotional impact, including any improvement suggestions

The analysis of demographics such as age, VR experience, and gender may provide valuable insights into factors influencing usability. Below is a concise explanation of their potential impact:

- *Age:* Older users, who may resemble the actual customer (e.g., ship owners), could prioritize configuration feasibility from a purchasing perspective, while younger, tech-savvy users might offer insights to improve features and enhance gamification.
- *VR Experience:* Experienced users might focus on advanced features and provide technical feedback on immersion and interactivity, while inexperienced users could highlight accessibility gaps and the learning curve.
- *Gender:* Gender might influence interaction preferences, such as task approach and priorities, ensuring that the system design is inclusive and appealing to all user groups.

5.3 User Feedback and Results

The results of the user tests were assessed using various metrics, providing valuable insights into the system's usability, performance, and user satisfaction. Feedback was collected in the following key areas:

- **Graphics and Immersion:** The visual quality and immersion of the system were highly rated. Users commented that the realistic rendering of objects and materials made them feel as if they were physically present in the yacht. One participant stated: "The graphics exceeded my expectations; it felt like I was actually aboard the yacht."
- **Interaction and Customization:** The real-time interaction with and customization of the yacht's components was praised for its intuitiveness. However, some participants requested a wider variety of materials and textures to increase customization options.

5. Magic

- **Navigation and Controls:** The controls were generally intuitive, although some users expressed the need for greater freedom of movement. Seven participants found the teleportation method difficult to use in tight spaces, and others mentioned challenges with selecting smaller objects remotely.
- **Functional Suggestions:** Users suggested improvements, such as a more precise locomotion system, clearer training, and haptic feedback to signal avatar-object collisions. A few participants also reported physical discomfort and dizziness, likely due to the weight of the headset and occasional lag.

The System Usability Scale (SUS) score was 80,82, indicating that the system's usability is above the acceptable threshold of 68. This score reflects the overall positive reception of the system, with 83.3% of participants scoring above the threshold, categorizing MAGIC as a usable application for product configuration.

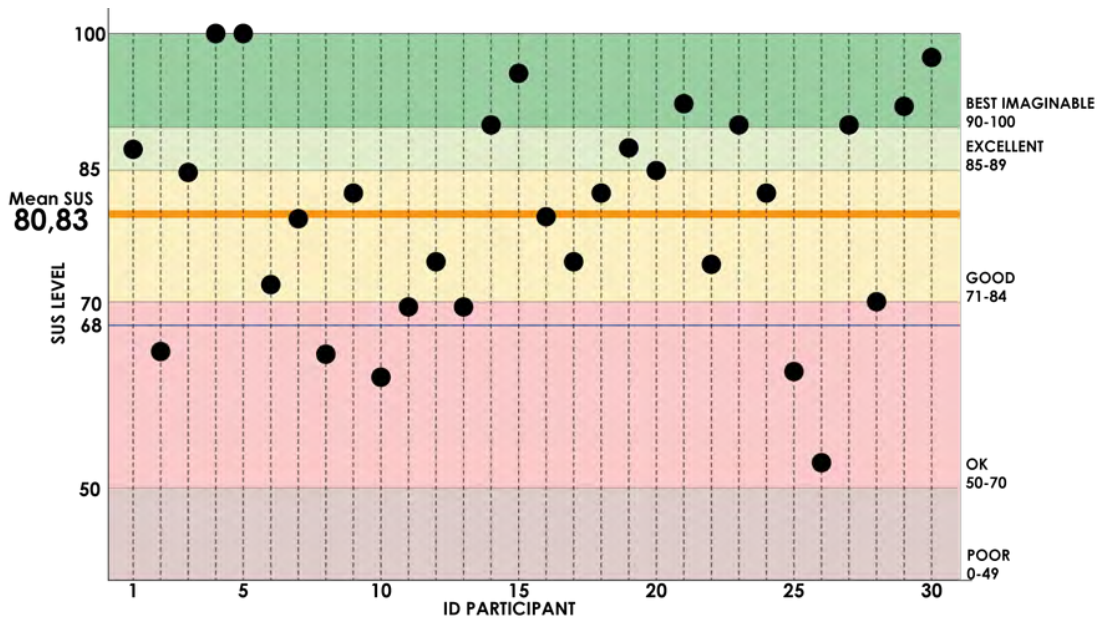


Figure 5.7: Distribution of individual SUS scores, with the SUS mean (orange line), the "Acceptable threshold" (blue line), and the range covered by the scores (min=52.2, max=100).

5.4 Discussion

With a success rate of 100%, all couples found agreement upon a final configuration within the set test duration. This outcome highlights the feasibility of the system in supporting collective decisions in a dynamic

and immersive environment. Only one couple quit the session before the estimated time, as one of the participants needed to attend a university class. Therefore, it can be considered a statistical outlier, unrelated to any system interface design issue or episode of cybersickness, supporting the assertion that the 25-minute session was properly estimated.

To further investigate the distribution of individual SUS scores, potential correlations are analyzed to provide a comprehensive examination of their relationship with sample parameters such as age, gender, and prior experience with VR devices.

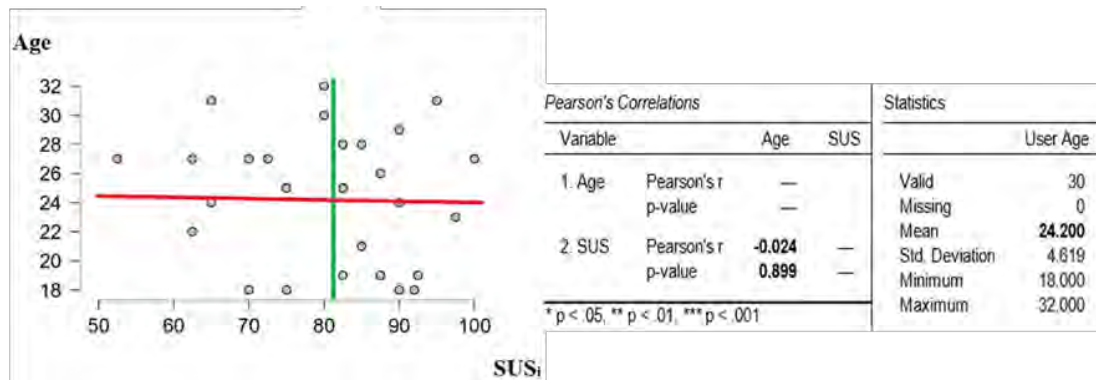


Figure 5.8: SUS-Age Correlation diagram with a negative slope ($r = -0.024$) (Regression line shown in red, and the SUS mean=80,82 marked in green).

No significant correlation is found between users' demographic data and the distribution of usability scores, which appear largely random, thus ruling out a functional dependency between these two parameters (Figure 5.8).

The slope ($r = -0.024$) of the regression line indicates a weak, negative correlation, showing that as participants' age increases, the SUS score tends to decrease slightly.

However, since the $p\text{-value} = 0.899 \gg *p (< 0.05)$, it can be concluded that this correlation does not hold statistical significance.

Similarly, the correlation between gender and SUS scores is negligible (?? left), with a percentage difference of 1.38% between the average values assigned by each category. Remarkably, the scores of male participants exhibit a greater deviation.

Regarding VR familiarity (Figure 5.9 right), experienced users provided scores within a broader range compared to non-experienced participants, even though the average results are similar (percentage difference $< 0.3\%$). This might indicate that experienced users conducted more technical and informed evaluations, while non-experienced participants

5. Magic

offered valuable insights into the system's impact on end-users without specific expertise.

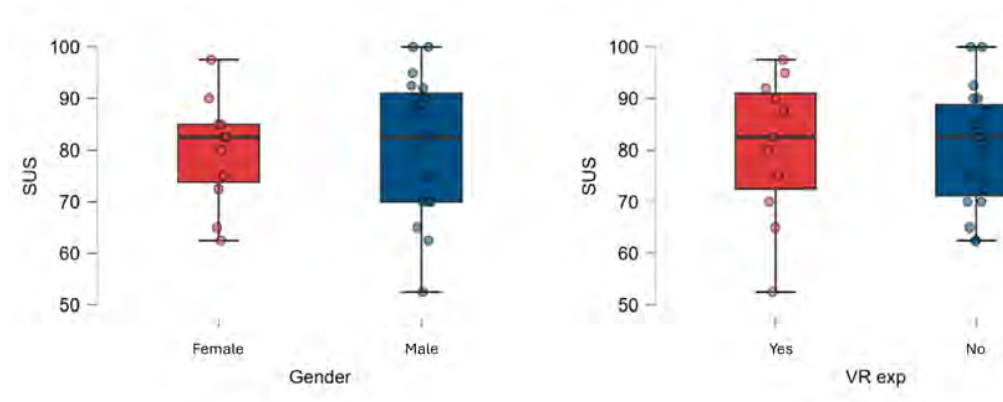


Figure 5.9: Distribution of SUS scores based on user gender (left image) and prior experience with virtual reality (right image).

The feedback indicates that the experience was generally perceived as immersive, engaging, and well-executed, with a graphical and interactive system that exceeded users' expectations. However, targeted improvements in customization, navigation, and technical optimization could address the issues that emerged, making the overall experience even smoother and more satisfying. With a greater variety of options, a more intuitive control system, and a more dynamic environmental context, this application could reach an even higher level.

Following the results analysis, it is possible to attempt to answer the RQs:

- **RQ1:** Supported – MAGIC's usability falls within the "acceptable" range on the SUS metric.
- **RQ2:** Partially supported – MAGIC is feasible for sailing yacht configuration, but improvements in navigation and collision systems are required for effective space evaluation.
- **RQ3:** Supported – Photorealistic graphics are essential for a convincing digital preview.
- **RQ4:** Supported – Additional content significantly enhances the experience.
- **RQ5:** Not supported - Demographic data or VR experience does not significantly affect the SUS score, but further investigation with a wider sample is needed.

5.5 Limitations

While the results are promising, there are several limitations that could guide future improvements. The current sample consists mainly of younger participants, limiting the diversity and generalizability of the findings.

Additionally, while the teleportation method was useful for rapid movement, some users found it frustrating, particularly in confined spaces. Future developments could include alternative locomotion methods, such as joystick-based movement or more refined teleportation mechanisms. However, it is important to consider the trade-offs between reducing motion sickness and enhancing navigation freedom.

5.6 Conclusion

MAGIC demonstrates the viability of using VR technology for product configuration, offering a collaborative, immersive solution that aligns with the needs of high-value product industries such as the maritime sector.

The feedback received highlights the system's strengths, including its graphics and immersive qualities, as well as areas for improvement, particularly in navigation and customization. As technology advances, tools like MAGIC will become even more relevant in industrial design, offering new ways for users to interact with and configure products remotely.

Chapter 6

MR-CoCo

Mixed Reality Couple Collaboration (MR-CoCo) is an innovative mixed reality (MR) product configurator designed to facilitate real-time collaboration between two users, here presented through a sailboat customization case study. MR-CoCo provides an immersive, dual-user platform where participants can collaboratively configure a virtual model, selecting materials and visualizing the results in real-time. The primary advantage of MR-CoCo lies in its seamless integration of virtual elements with the physical world, promoting engagement through hand-tracking interactions and real-time feedback.

The testbed is highly modular, allowing the platform to support various product types and configuration scenarios, ranging from complex industrial applications to simpler product designs. This modularity enables MR-CoCo to be easily adapted for diverse retail environments, creating a flexible tool for collaborative workflows.

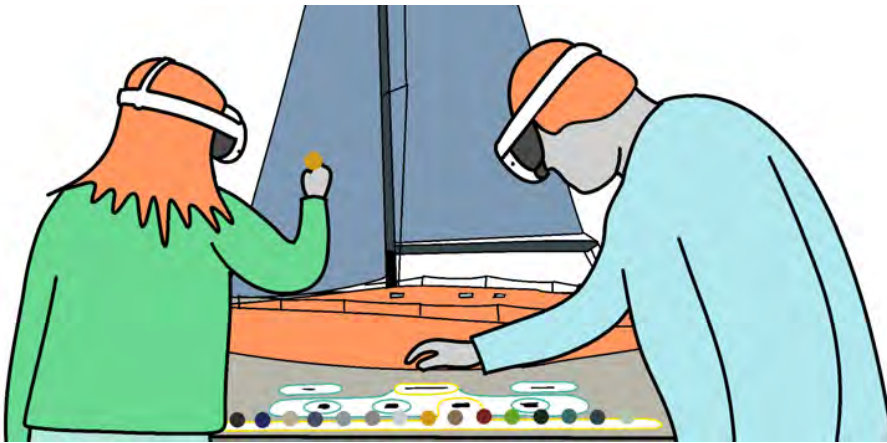


Figure 6.1: **MR-CoCo testbed:** Co-located Couple Product Configurator in Mixed Reality. Two users (couple) simultaneously configure a virtual sailboat on a physical table, manipulating and customizing materials through the interaction with draggable UI spheres within the mixed reality environment.

MR-CoCo is a MR product configuration application designed for couples Figure 6.1. It leverages augmentation to display 3D product visualizations and a 3D interface in a real-world context. The primary function of the system is to provide a shared 3D user interface that allows both users, in the role of collaborative customers, to configure

6. MR-CoCo

the material combination on a virtual 3D model and receive a real-time shared preview. Despite the virtual nature of the scenario, the advantage of augmentation lies in preserving a strong sense of presence in the real world (e.g., a store, meeting room, or showroom), enhancing the collaborative experience.

The MR-CoCo platform was conceived as an extremely modular and adaptable test bed, capable of supporting numerous configuration scenarios that go beyond specific use cases or product types. Thanks to this modular architecture, it is possible to test collaborative workflows in the most diverse retail environments, abstracting assets and logics specific to each scenario.

MR-CoCo enables rapid adaptation to different case studies by the following steps:

1. Import CAD model into Unity MRCOCO project and insert inside the “MODEL HERE” node hierarchy;
2. Import or create the configuration materials (e.g., texture, colors, etc.);
3. Customize UI (labels and icons) according to the desired theme Figure 6.2;
4. Connect the material widget (3D UI spheres) to the material in the model by unity inspector.

6.1 Interface design

The MR-CoCo interface was designed with a user-centered approach, focusing on natural, intuitive interactions to foster collaboration. Unlike traditional MR systems that rely on controllers, MR-CoCo emphasizes hand tracking as the primary interaction method. This design decision allows for a more fluid, immersive experience where users can manipulate the virtual model directly with their hands, simulating real-world interactions.

The interface is structured into three hierarchical rows, each providing different levels of control over the product configuration process:

1. First Row:

- *State Control Button (Left)*: This button toggles between internal and external views of the product, allowing users to switch perspectives and explore different aspects of the model.
- *Category/Group Selection (Right)*: Enables users to select the primary category or group of configurable elements for the model, facilitating the process of material selection.

2. **Second Row: Subcategory Selection:** This row enables the user to select specific subcategories of configurable objects, providing finer control over customization.
3. **Third Row: Color Palette:** Users can select predefined colors from a palette and drag them onto target components to modify their appearance in real-time.

TOP VIEW

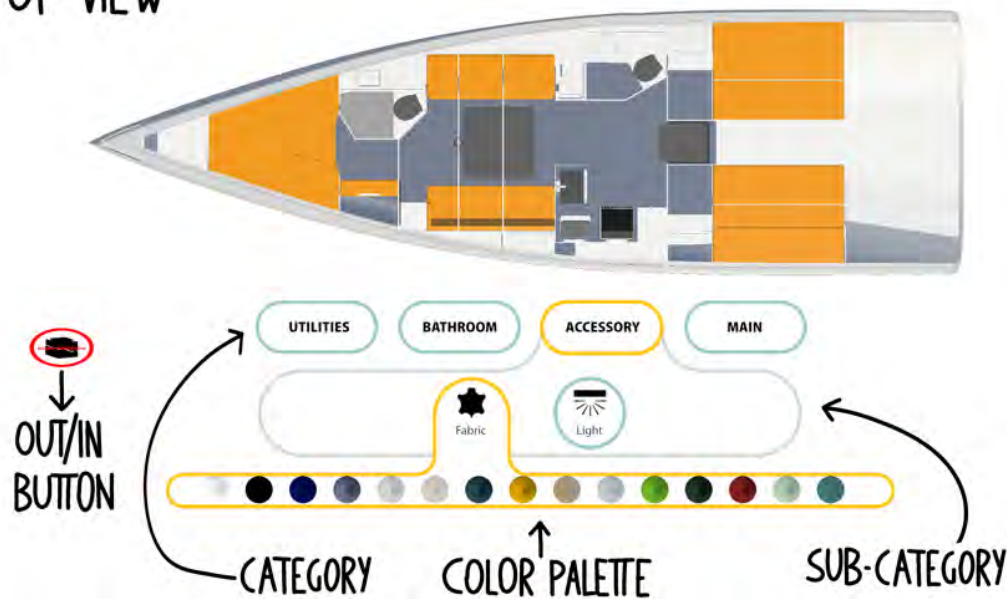


Figure 6.2: **MR-CoCo interface** (Top view): The interface features a three-row menu for category selection, subgroup refinement, and color application. A side button allows users to toggle between internal and external views of the model.

6.1.1 Interactions

User interaction in MR-CoCo is designed to rely primarily on hand tracking, with the controller being used solely for initial co-location setup. The system's interactions are as follows:

Selection of UI:

- *User Interface Interaction* Users can interact with UI elements using hand gestures, specifically through index finger gestures. The controller is used only for the initial space anchor setup phase. After the setup, interactions are facilitated through hand tracking. The custom script "Toggle" is used to synchronize the activation and deactivation of the interface when interacting with the index finger.

6. MR-CoCo

- *Perspective Switch interaction:* Users can toggle between internal and external views of the product being configured. This perspective switch enhances user understanding of the space and supports collaborative discussions by offering different perspectives on the model.

Material configuration: The system enables users to apply predefined colors to various components of the virtual model in real-time. This feature facilitates collaborative exploration of material combinations, enabling users to jointly determine the final configuration. Users apply colors by selecting a color sphere via a "pinch" gesture and dragging it onto the corresponding target component. Upon collision with a configurable surface, the color is applied in real-time, and audio feedback confirms the successful application. The "Photon Grabbable Object" component script and the custom "DraggableSphere" script ensure that the sphere behaves appropriately within the virtual environment and that the color change is synchronized between both users.

6.2 System Design

MR-CoCo is designed to provide real-time, multi-user collaboration within a shared MR environment. The system architecture consists of two primary components: the software component for managing real-time interactions and the hardware component for tracking user positions and integrating MR devices Figure 6.4.

6.2.1 Software

MR-CoCo is implemented using Unity (version 6000.0.37f1 LTS), leveraging the Meta XR Interaction SDK for interaction and OVR passthrough visualization.

Shared Spatial Anchor The software utilizes Unity's Shared Spatial Anchors (SSA) ¹ to align virtual elements with the physical environment, ensuring precise positioning within the shared workspace ². The calibration process is aided by the passthrough view on the HMD, providing a stable and intuitive reference surface. For calibration, it uses a "Gizmo" to anchor the virtual scene to the real-world environment, facilitating seamless integration between virtual and physical spaces Figure 6.4.

Multi-User Environment The system employs Photon Unity Networking (PUN) to ensure real-time synchronization of the 3D scene between users. By using the PhotonView component, scene elements are

¹<https://github.com/oculus-samples/Unity-SharedSpatialAnchors>

²<https://developers.meta.com/horizon/documentation/unity/unity-spatial-anchors-overview/>



Figure 6.3: **Couple Interaction in Shared VR Environment:** From the first user's perspective, the second user configures the color of the virtual sailboat via the shared user interface, which is rendered simultaneously.

shared between participants, allowing for low-latency interaction and maintaining consistency in the shared MR experience [90]³.

6.2.2 Hardware

The MR-CoCo testbed is deployed on the Meta Quest 3 devices, which display the MR scene. The devices are configured to operate in passthrough mode, allowing real-time integration of the physical and virtual worlds. While the system can run in standalone mode, for research purposes, the "Editor Mode" in Unity is used to facilitate debugging and monitoring of the application by the experiment moderator Figure 6.4.

6.3 Design of Experiment

This study represents an initial testing phase within the MR-CoCo testbed, which is designed for continuous research and iterative development. This section outlines the research questions, the experimental setup, the participant couples, the procedure, and the metrics. We selected the boat configuration because it represents a complex, highly customizable product. In contrast, simpler products typically do not require such advanced visualization tools, according to current industry practices. We aimed to evaluate the benefits of immersive configura-

³<https://www.photonengine.com/pun>

6. MR-CoCo

tion in contexts where traditional methods fall short due to product complexity.

6.4 Research questions

We addressed the following research questions, divided into three categories:

RQ1: *Co-Located Collaboration:* Does co-located user collaboration affect interaction in MR environments?

RQ2: *Configuration - Couple Decision Making:* Does MR-CoCo improve decision-making during couple-based product configurations?

RQ3: *Usability:* How do users evaluate the usability of MR-CoCo according to the SUS scale?

6.5 Setup

The experiment was conducted in a dedicated meeting room, chosen to ensure sufficient physical space and minimize external interference. The room offered adequate lighting and acoustic conditions to support verbal communication between the couple. Its dimensions allowed comfortable side-by-side standing positions, crucial for co-located interaction and shared access to the physical table used as the spatial anchor.

A real table was positioned at the center of the room, serving as the physical reference for the SSA. This ensured the accurate alignment and stability of the virtual 3D sailboat model across both headsets. The use of a large, stable surface (minimum recommended size: 180 cm x 100 cm) contributed to enhancing co-presence, natural hand gestures, and ease of calibration during the setup phase.

MR-CoCo hardware setup is composed of two PCs used for the experiment are as follows:

PC A: Intel Core i7-7700H, 16 GB RAM, Nvidia GTX 1070 GPU.

PC B: Intel Core i7-13620H, 16 GB RAM, Nvidia RTX 4060 GPU.

And two Meta Quest 3 devices in passthrough mode to enable mixed visualization of the physical and virtual worlds, and two computers with different hardware specifications to support the MR devices Figure 6.4.

Both PC were connected via the same Internet network, enabling real-time synchronization of virtual environments between the devices. Each PC is connected to MR devices via wired links for real-time debugging "*unity editor mode*". This methodology helps research assistants when debugging during experiment scenes, allowing users within the virtual scene to resolve bugs or problems.

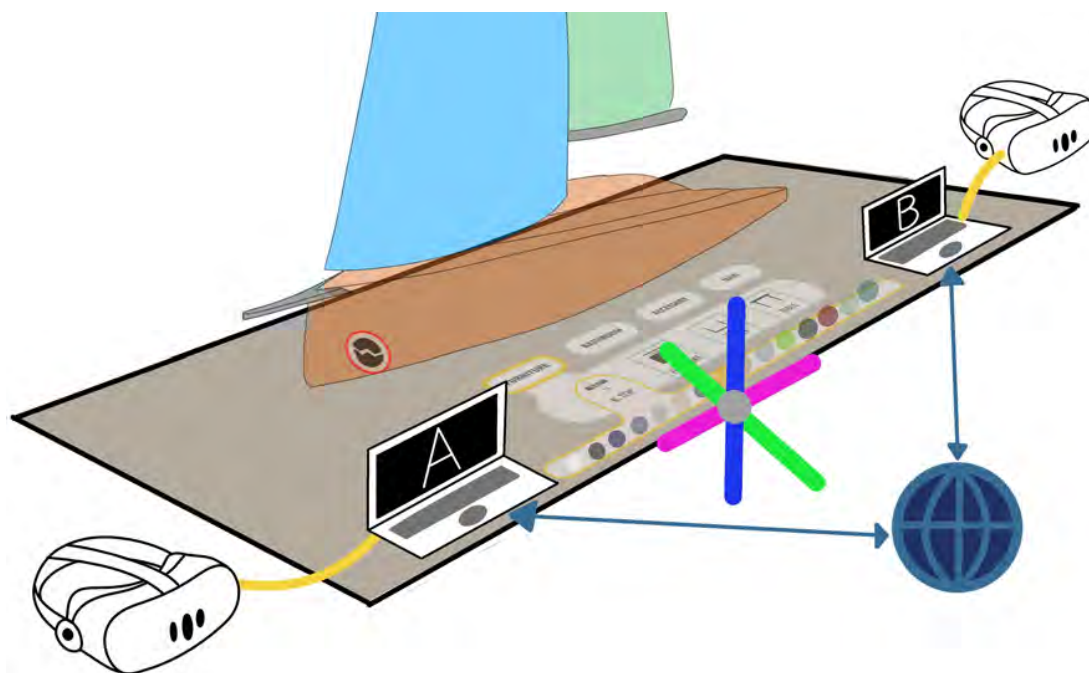


Figure 6.4: **MR-CoCo Testbed Architecture:** Two PCs (A and B) and two HMD viewers are synchronised on the same network via the Photon PUN platform. The SSA is displayed directly on the actual table, allowing users to align the scene and ensuring a smooth and perfectly coordinated experience between the viewers displaying the synchronised scene.

6.6 Procedure

The experiment was approved by the institutional ethics committee. To evaluate the benefits of the MR-CoCo testbed, we conducted a user study through qualitative metrics. The experiment was performed in a co-location collaboration with the simultaneous participation of two people. The devices were tested to minimize any physical discomfort associated with prolonged HMD use, ensuring a comfortable and safe experience. The research assistant introduced the experiment, monitored user interactions, took notes during the experiment, observed the couples' actions, and intervened if technical problems or interaction difficulties arose. The steps of the experiment are divided into the following steps Figure 6.5.

Task Presentation: The couples were briefly introduced to the task and asked to stand side-by-side Figure 6.6, then they were asked to wear HMDs so that the research assistant could start the scene.

Spatial anchor setup phase: Each user calibrated the scene by positioning the "gizmo" at a predefined corner of the physical table,

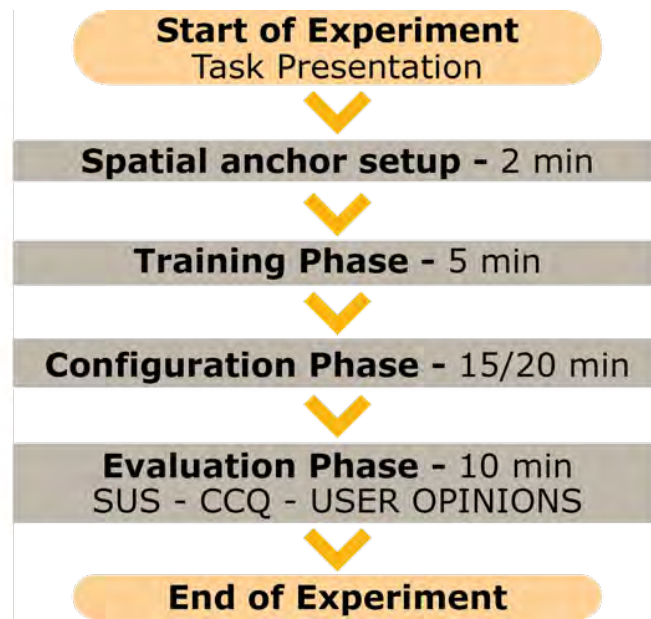


Figure 6.5: **Procedure:** divided into 4 steps to be performed for the procedural task to be carried out correctly

ensuring accurate alignment of virtual elements within the shared environment.

Training phase: During this phase, the couple familiarized themselves with the MR-CoCo interface and learned how to use the main configuration functions. Users first select the "cube" button and then choose the color that appears on the list, dragging it to the cube to change its color. After this step, when the couple understands how the UI works, they start the main experiment of the sailboat configuration.

Configuration phase: In this phase, the couple simulates a purchase scene and configures a sailboat to reflect mutual preferences by collaborating in MR, being in the same room, side-by-side Figure 6.6. During the activity, users can view the product from all angles, ensuring a comprehensive understanding of its characteristics. Verbal communication between the couple is permitted, allowing open discussion on the operations.

Evaluation phase: Finally, each user completed separately the questionnaire to evaluate their configuration experience, focusing on elements such as system usability, level of collaboration, and perception of the MR environment. At the end of the experiment, the couple was asked to provide their feedback orally.

6.7 Couple Participants

Voluntary adult participants were recruited via a publicly available online form disseminated through social media platforms. Eligibility criteria included: (1) being at least 18 years of age, and (2) the ability to participate with another adult (a friend or colleague), as the study required dyadic participation. This approach was adopted to reduce communication barriers and foster spontaneous collaboration, aiming to ensure relational and communicative homogeneity within each couple. The final sample consisted of 48 participants (24 males, 24 females), aged between 20 and 40 years ($M = 27.20$, $SD = 4.42$), organized into 24 couples. Gender composition of the couple was balanced: 8 male-male, 8 female-female, and 8 mixed-gender couples. Participants were selected based on prior familiarity with technology. Among the 32 individual users (from the 24 couples) who reported experience with MR, 18 had previously used MR applications. Self-assessed MR proficiency was reported on a 7-point Likert scale (1 = novice, 7 = expert), yielding a mean score of 4.42 ($SD = 2.03$).

6.8 Metrics

Here, we describe the metrics collected to evaluate the testbed MR-CoCo.

Co-Presence Couple Questionnaire We used an enhanced co-presence configuration questionnaire (CCQ) featuring additional questions on configuration, couple decision-making, and collaboration, using a Likert scale (1 lower to 7 higher) [91].

This metric evaluates the degree of connection and synchronization the couple felt, focusing on mutual awareness, engagement, and the ability to interpret each other's nonverbal cues. The couple provided ratings ranging from partner presence and communication to evaluation of configuration choices, supporting the MR-CoCo application. **System Usability Scale - SUS** Each user of the couple compiles the SUS questionnaire separately [89]. We used the SUS questionnaire, which consists of 10 questions (Likert scale: 1 = strongly disagree, 5 = strongly agree). We then calculated the SUS value for each participant, ranging from 1 (poor) to 100 (best imaginable). **Couple Opinions** Finally, open-ended questions were administered to collect couples' qualitative impressions and suggestions about MR-CoCo.

6.9 Results

The MR-CoCo experiment, conducted with 24 couples (48 participants), provided valuable insights into the usability and effectiveness of the

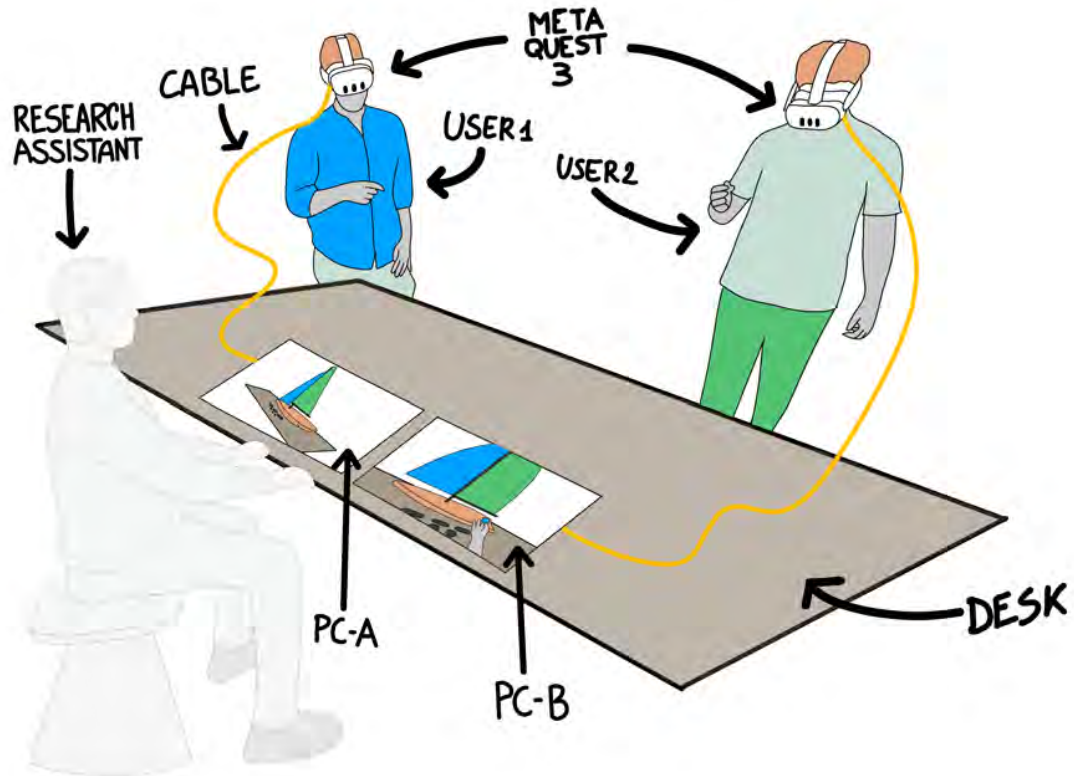


Figure 6.6: **Experimental setup:** The research assistant (left) monitors from the PCs (A+B), the actions of each user as they interact with the sailboat model in MR. The couple is side-by-side as they complete the configuration task.

system for collaborative configuration.

6.9.1 Co-Presence Configuration Questionnaire Results

The Co-Presence Configuration Questionnaire (CCQ) measured the participants' sense of presence, communication, and collaboration Figure 6.7. The average score for this category was 5.60 (SD = 0.23), indicating strong co-presence and collaboration during the task. High scores were observed in categories such as Harmony (A4) and Collaboration (A7), while the lowest score was in Usability (A6), highlighting areas for further improvement in interaction fluidity.

6.9.2 System Usability Scale (SUS) Results

The SUS score averaged 79.06 (SD = 14.32), indicating a "Good" usability level Figure 6.8. The system was generally well-received, but five users reported challenges with interface usage, particularly in interaction accuracy. The feedback suggests that further improvements in gesture

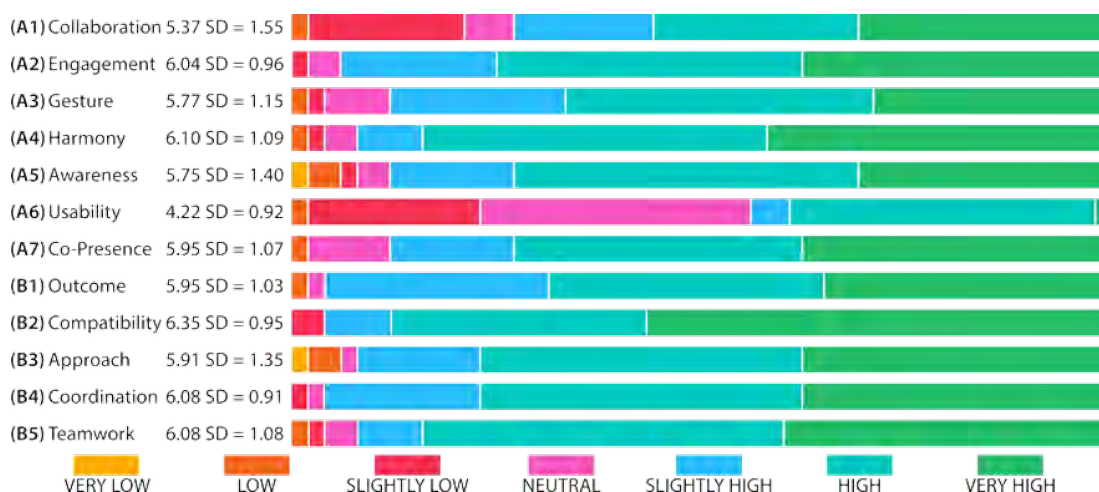


Figure 6.7: **Co-Presence Configuration Questionnaire**: Matrix displaying the frequency of user responses, with categories ranging from very low to very high. On the left are the names of the analyzed categories and the mean value. The distribution captures all user preferences within the minimum to maximum range.

recognition and interface design are needed to reduce the learning curve and enhance the overall user experience.

6.9.3 Co-presence Configuration

The results of the CCQ indicate that MR-CoCo effectively supports collaboration between couples. High scores in Harmony (A4) and Collaboration (A7) suggest that the couple felt a strong sense of connection and teamwork during the experiment. The ability to sense reactions and interpret gestures (A1, A3) further contributed to a positive interaction experience.

However, the lower rating in Usability (A6) indicates that the fluidity and naturalness of interaction were not optimal. This could be due to technological limitations, unfamiliarity with the system, or initial difficulties in coordinating actions. Addressing these factors could enhance the overall user experience.

In decision-making, the couple demonstrated a high level of agreement on the final configuration (B2) and were generally satisfied with the collaborative process (B3). The variability in responses to B3 suggests that while many found collaboration beneficial, some couples may have preferred working individually. Future iterations of MR-CoCo could explore adaptive mechanisms that accommodate different collaboration styles.

Regarding support and facilitation, MR-CoCo was rated highly

6. MR-CoCo

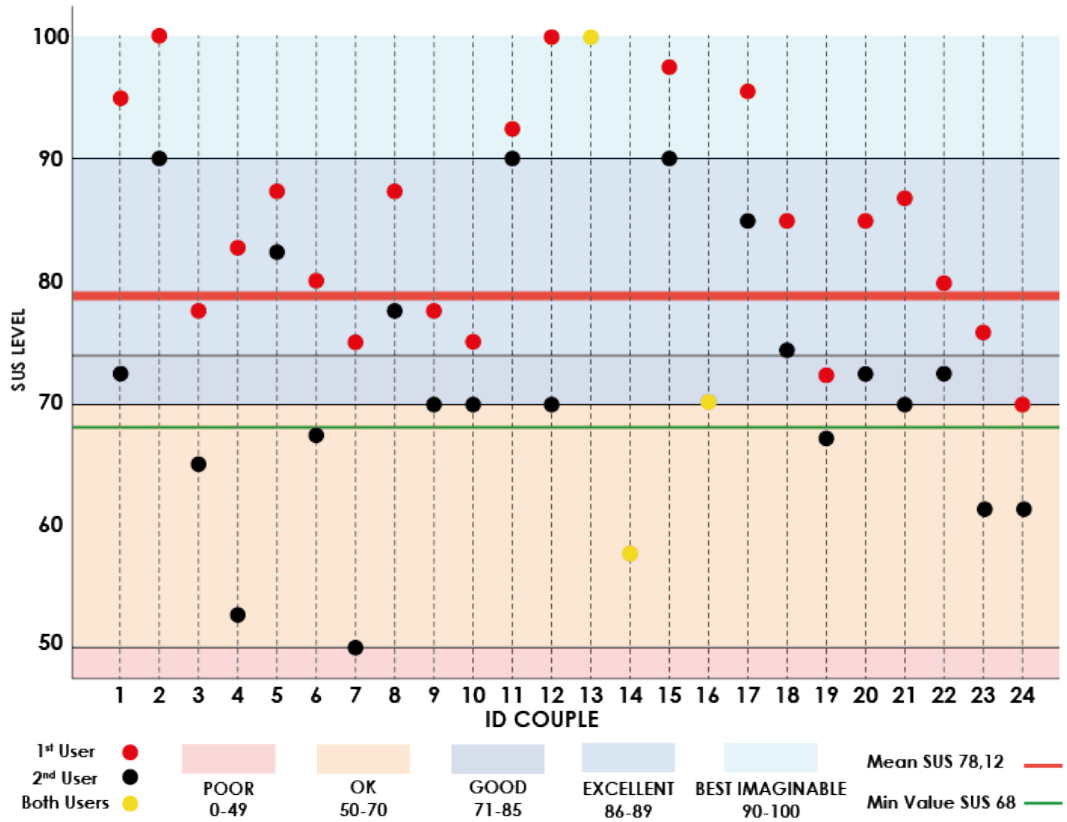


Figure 6.8: **SUS results:** A score distribution plot showing the validation of the X-axis (0-100) and user couples on the Y-axis. Each column represents the individual usability scores for each couple member. A red LINE indicates the average SUS score, while a gray bar highlights the minimum score. Four colored sections represent the SUS rating categories: Excellent, Good, Acceptable, and Poor.

in terms of coordination and teamwork (B4, B5), highlighting its effectiveness in structuring collaborative efforts.

6.9.4 System Usability

The SUS results indicate that MR-CoCo was generally well-received, with an average SUS score of 79.06, classifying it within the 'Good' usability range. However, the presence of five users with scores below the average suggests that usability challenges require further investigation.

The color-coded SUS categories in Figure 6.8 reveal that most participants rated the system in the range (70-90), entering at least "good" (71-85) and "excellent" (86-89) scores. Only 3 users rated it as 100 (best imaginable), and one user rated it as 50 ("poor").

The variance in SUS scores highlights differences in user experience,

particularly for those less familiar with MR environments. The two extreme outliers—Couple 12 (SUS = 40) and Couple 3 (SUS = 95)—suggest that while some participants found the system overall easy to use, others struggled with its interface and interaction design. One of the main issues identified was related to the "grabbable" functionality: when users did not perform the correct hand gesture (e.g., pinching) to interact with the color spheres, they were unable to apply changes to the product effectively. This led to some frustration, particularly among less experienced users. These users may have encountered difficulties due to unclear onboarding procedures, a complex navigation system, and challenges in adapting to MR interactions.

The lower-scoring users' feedback suggests a need for refinement in user training, gesture recognition, and the clarity of the interaction flow. Future iterations of MR-CoCo will focus on simplifying the onboarding process, improving gesture recognition accuracy, and providing clearer feedback during interactions to reduce the learning curve and improve usability for all users. Overall, the variance in SUS scores underscores the need for ongoing improvements in training, interface design, and system feedback mechanisms to streamline the user workflow and ensure a consistent experience across users with varying levels of familiarity with MR environments.

6.9.5 Couples' Opinions

Open-ended feedback from couples provided valuable insights into the strengths and limitations of MR-CoCo, offering key areas for improvement. Overall, users appreciated the system's ability to facilitate real-time collaboration, intuitive interaction, and immersive experiences. However, various challenges emerged related to cooperation, usability, interaction, visualization, and system limitations.

Cooperation and Communication One of the most frequently mentioned improvements was the ability to preview a partner's choice before applying it. This feature would enhance mutual awareness and coordination in shared decision-making. The feedback suggests that stronger visual cues and clearer communication channels could improve co-presence and facilitate smoother interactions between users.

Usability Enhancements Usability concerns focused on the need for a more flexible visualization system, additional customization options, and clearer feedback mechanisms. Users suggested the ability to manually rotate models for better inspection, expanding the available color and texture options, and integrating a zoom function for better visibility of small objects. Furthermore, couples requested a confirmation or

6. MR-CoCo

review step at the end of the configuration process to solidify choices and enhance engagement.

Additionally, experienced sailboat users highlighted the importance of displaying key specifications such as length, anchor details, and tank capacity. While MR-CoCo was designed for collaborative configuration, incorporating relevant product data could enhance decision-making, especially for users familiar with technical specifications.

Interaction Refinements Qualitative feedback indicated challenges with hand tracking accuracy during color selection, highlighting a need for improved gesture precision and interface ergonomics. The couples also reported that identifying configurable elements was sometimes unclear, due to limited prior knowledge of sailboat components or unclear UI labels. Further refinements, such as contextual tooltips or interactive labels, could support user understanding.

Visualization and System Limitations Users noted discrepancies in graphic rendering quality due to variations in computer graphics hardware, highlighting a limitation that affects system consistency. Enhancing graphical optimization and standardizing visual fidelity across different hardware configurations would help mitigate these discrepancies.

Mobility restrictions due to the tethered setup were also noted, with some users expressing concerns about cable limitations. While necessary for observational purposes, exploring wireless or alternative tracking solutions could enhance user freedom and comfort.

Furthermore, participants' feedback revealed difficulties in identifying configurable elements, primarily due to unfamiliarity with nautical terminology. While button icons were designed to alleviate this issue, further refinements, such as interactive labels or contextual tooltips, could enhance clarity.

User Suggestions User feedback also highlighted several suggestions for enhancing immersion and interaction. Some participants expressed interest in experiencing environmental elements, such as simulating the water level or the sailboat's actual dimensions, to enhance their spatial understanding. Others suggested an option to highlight configurable elements dynamically to streamline the interaction process.

Regarding training, participants recommended a structured sequence with numbered steps to provide clearer guidance. In addition, some users preferred an avatar representation of the partner in augmented mode rather than seeing them with the HMD. This preference suggests that integrating avatar-based representations could improve social presence and engagement in collaborative tasks.

The feedback from open-ended questions underscores the importance of refining MR-CoCo's usability, communication, and visualization

features to enhance co-presence and collaborative decision-making. Addressing the identified challenges through improved interaction design, expanded customization options, and enhanced training processes will help streamline the interaction and increase confidence during decision-making.

6.9.6 Limitations

Despite the positive outcomes of MR-CoCo, several limitations were identified that impact user experience and the overall system effectiveness:

Human Factors: Initial interaction with MR was challenging for many users, negatively affecting early experience, but performance improved with training, leading to more autonomous configuration, better task execution, and a deeper understanding of the system. Participants completed the task in about 15 minutes, faster than the expected 20–25 minutes. Outcomes were also influenced by communication within the couple, how control over configuration was shared, and how task responsibilities were distributed. Future work could integrate AI to analyze conversations and track user movements. The assistant's lack of direct access to the MR scene limited spatial awareness; an in-scene observer with an HMD and pointing tools could improve guidance and coordination.

Technical Issues: The cabled HMD constrained user movement and reduced immersion. Mesh rendering limitations required a direct PC connection, preventing fully independent use of the HMD, while the PUN synchronization cap of 1000 objects caused delays when syncing objects. The system also could not handle user occlusion, preventing users from seeing others' actions; implementing avatars would make interactions more visible and provide a more natural representation of user behavior.

6.10 Conclusion

MR-CoCo addresses a gap in the literature by introducing a novel mixed reality-based collaborative product configurator. By combining MR with real-time interaction and immersive visualization, MR-CoCo enhances collaborative decision-making, exemplified in the context of configuring a luxury sailboat. The results show that the system supports more engaging and seamless interactions, improving collaboration among users during configuration tasks. This approach not only strengthens communication but also increases user engagement and perceived satisfaction compared to traditional, individual configuration tools.

Furthermore, MR-CoCo highlights the potential of immersive technologies to enable mass personalization. Through shared, collaborative

6. MR-CoCo

decision-making, users reported greater confidence in their choices and a more positive perception of the configured product. These findings emphasize the advantages of MR environments, where synchronized interactions enhance both user experience and satisfaction throughout the configuration process.

Chapter 7

Discussion on Social Interaction in XR

The study aims to evaluate various approaches to social interactions in immersive environments, with a particular focus on the adoption of advanced technologies such as virtual reality and mixed reality within SMEs. These studies allowed for the investigation of product presentation and collaborative configuration processes.

User Engagement The results from the immersive configuration and showroom sessions demonstrated a significant increase in user engagement compared to traditional methods. The VR experience notably enhanced the visual perception of the products, reducing the perceived distance between the user and the virtual object, creating a sense of physical proximity. Despite these positive outcomes, the absence of tactile feedback remains a key limitation, especially in industries like fashion and boating, where the texture and feel of materials are essential for informed purchasing decisions.

Collaboration and Negotiation Dynamics The integration of collaborative tools such as proposals and shared interfaces has proven to be highly effective in streamlining the product configuration process. The ability for users to simultaneously interact with the model and share their views in real time has significantly reduced conflicts and facilitated faster, more informed decision-making. This was especially evident in the MR-CoCo study, where a couple of configurations benefited from the shared experience.

However, some social dynamics remain challenging, particularly in managing conflicts between users and synchronizing actions in real time. Future iterations should focus on refining conflict resolution mechanisms and improving real-time synchronization to ensure smoother interactions, especially for users working in a collaborative environment.

Technological aspects and limitations While the proposed solutions demonstrate strong potential, graphics performance and user interface robustness remain critical issues. Device usage exposed problems with rendering smoothness and episodes of cybersickness. Nevertheless, the results confirm the novelty of the approach, although interaction reliability received lower ratings, likely due to participants' limited familiarity with VR technology.

7. Discussion on Social Interaction in XR

Summary In conclusion, the adoption of immersive technologies such as VR and MR in SMEs, particularly for B2B product presentations and collaborative configuration, holds great potential to transform business processes. These technologies offer a more efficient, sustainable, and interactive approach compared to traditional methods. However, to achieve a fully satisfying user experience, further development is required, particularly in integrating haptic feedback and improving usability for non-expert users.

Part II

Tangible interaction

Chapter 8

Methodology for Tangible solution

Following the exploration of social interaction in immersive environments, this part of the thesis shifts the focus toward physical interaction. While previous studies examined how users collaborate and make shared decisions in virtual spaces, the next phase investigates how tangible elements and real material engagement can complement those experiences and extend them beyond the purely visual dimension.

Despite the advantages of immersive visualization, the absence of physical touch remains a critical limitation—especially in fields such as fashion and design, where texture, weight, and material perception are central to product evaluation. Building on the findings of the social XR experiments, this section explores how hybrid physical–digital systems can reconnect immersive design with material reality, supporting more sustainable, sensory-rich, and meaningful experiences.

According to Milgram and Kishino (1994), MR is related to the ‘reality-virtuality continuum’, as it is a technology that mixes real and digital data. MR is a very flexible technology as it can add 2D/3D multimedia, customized narratives, and gamification to reality to provide more immersive and engaging experiences [92].

However, the scientific knowledge of MR for fashion showrooms is limited in terms of case studies and the variety of application sectors, and it mostly addresses the final customer (B2C), which is just the final part of the industrial process.

Currently, there is a limited understanding of how to craft an MR Metaverse experience, with case studies predominantly centered on the end consumer (B2C) [9]. Yet, the fashion industry typically follows a process involving a distributor before reaching the final client. Fashion producers traditionally showcase their collections to distributors in person through showrooms each season. Unlike end consumers, who are adapting to digital representations, these showrooms are highly technical, with users often requiring direct contact with materials. Presently, Metaverse designers face challenges in accessing knowledge and guidelines, with case studies often restricted in terms of product variety and quantity. Furthermore, the focus tends to be on B2C experiences, neglecting the B2B distributor process. However, even distribution has an environmental footprint that can be mitigated by embracing Metaverse digitalization, offering a pathway for a more sustainable and resilient fashion B2B sector.

8. Methodology for Tangible solution

The metaverse is defined as "*a virtual-reality space in which users can interact with a computer-generated environment and other users.*" It is a virtual social space that is a candidate to occupy people's recreational and working time [7].

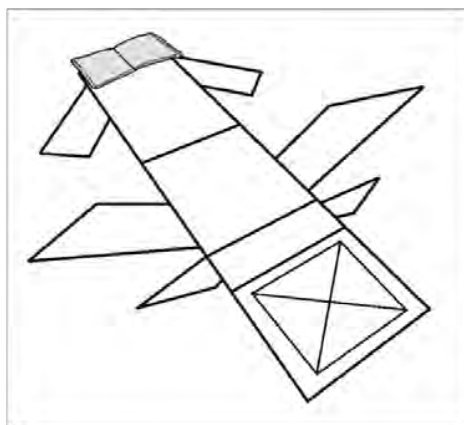
Apart from being the future of shopping for end users, the Metaverse can also improve the B2B fashion industry process.

The development and evaluation of the Mixed Tangible Catalog (MTC) highlight how physical interaction can meaningfully complement immersive visualization in industrial contexts. By merging real samples with digital augmentation, the system provides a bridge between material perception and virtual representation, allowing designers and clients to experience the product both sensorially and conceptually. Beyond its functional role as a sustainable and modular exhibition tool, MTC demonstrates that tangible interfaces can foster a more embodied and ecologically conscious approach to design communication. This outcome reinforces the thesis vision that future XR ecosystems should not replace materiality but reinterpret it—integrating touch, collaboration, and sustainability into the digital workflow.

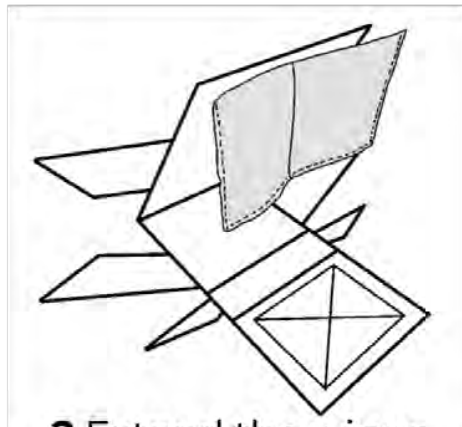
Chapter 9

Mixed Tangible Catalog

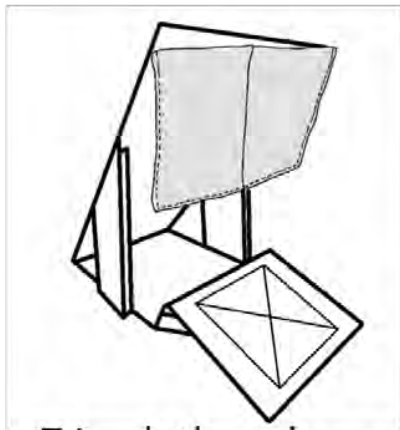
For this hybrid solution that combines physical and virtual elements. Catalog is a scaled tangible prototype; the Mixed Tangible Catalog is augmented with digital overlays in Mixed Reality (MR). This approach aims to overcome the limitations of purely virtual systems by reintroducing tactile interaction, enabling resellers to manipulate real material samples while visualizing garments and configurations in MR.



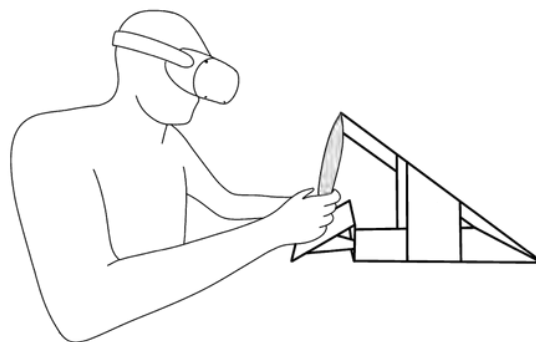
1 Open the MTC Stand



2 Extend the wings



3 Lock the wings



4 MTC Stand is ready to use

Figure 9.1: MTC Stand: Instructions for opening and usage

The Mixed Tangible Catalog (MTC) experience is a novel system that combines two key elements: a physical demonstrator, the so-called MTC Stand, and an MR App using an HMD to visualize and configure

9. Mixed Tangible Catalog

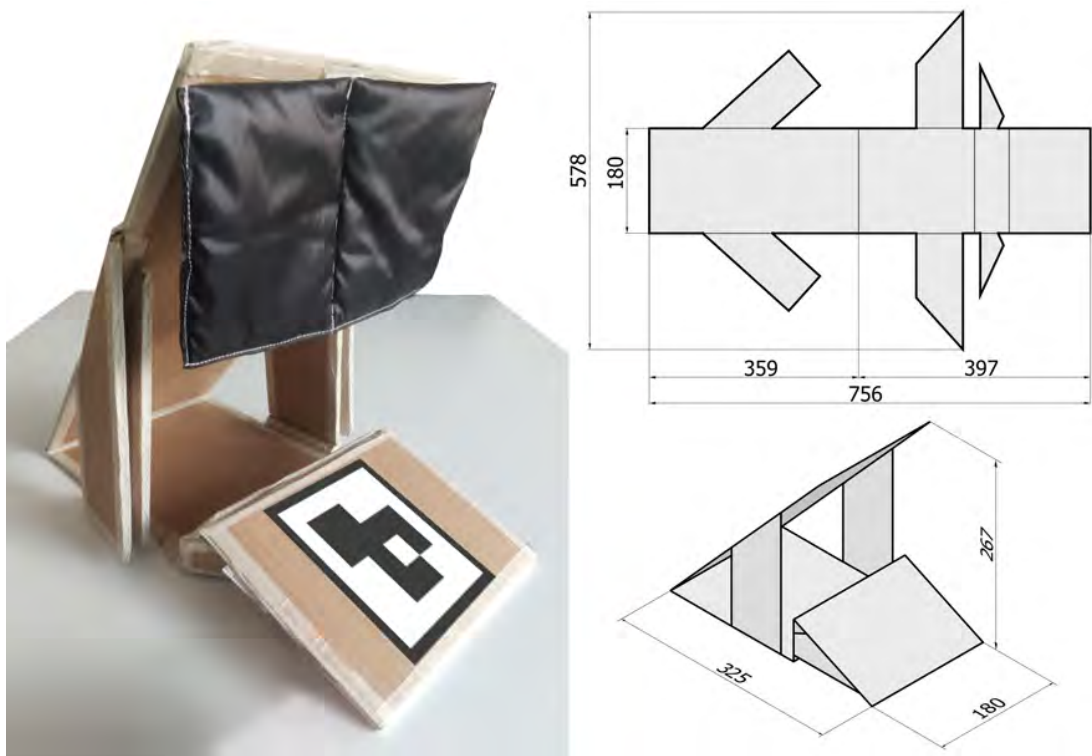


Figure 9.2: Left: MTC Stand with the material sample attached by Velcro and the AR marker placed at the bottom of the object for tracking by the viewer. Right: Technical drawing of the MTC Stand in the flattened open version and the isometric view with the overall dimensions.

a virtual catalog Fig. 9.1 Fig. 9.3.

We implemented the MTC from the results obtained from the previous work, which highlights the impact of physical touch in the B2B process. Another crucial requirement in MTC implementation was creating a transportable system that optimizes the time aspects. Both of these key aspects are lacking in the literature and are not fully addressed. Several applications implement tactile feedback (real touch / haptic gloves) with different costly setups and not standardized. In this work, we discussed the physical touch and not a touch input device since the company requested to further analyze a real touch interaction. This method ensures that the tactile sensation is as accurate and realistic as possible, eliminating the limitations often associated with haptic devices. The realism of touching actual garments during the MR sessions significantly enhanced their overall experience and engagement with the showroom.

The main idea is to transfer the traditional showroom to the metaverse and deliver the MTC Stand to the reseller by physical mail, with an optimized collection of physical material samples as the bare minimum

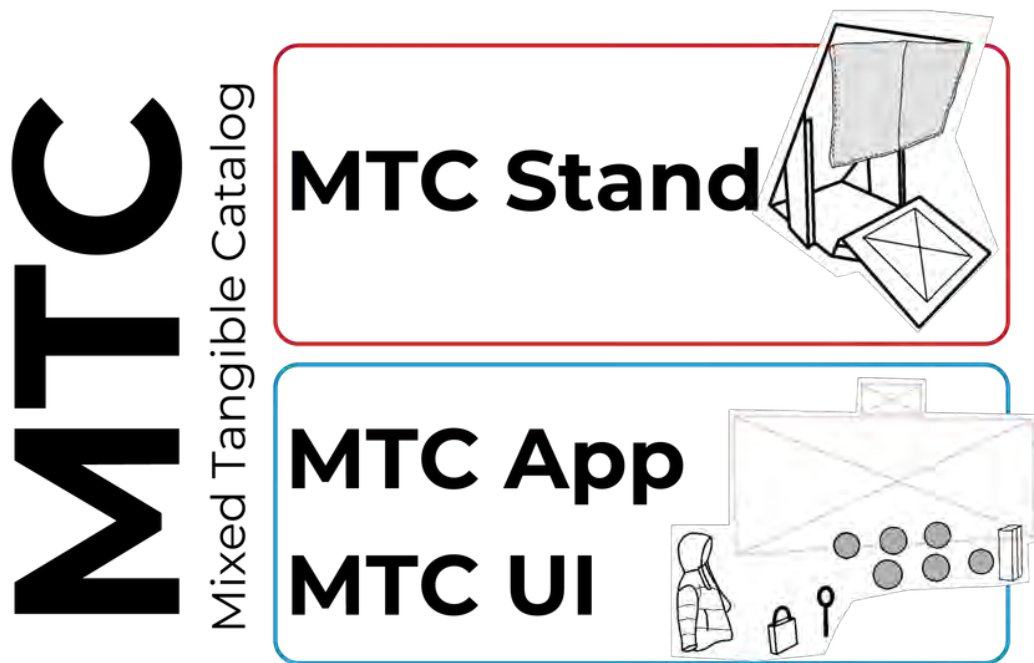


Figure 9.3: Explanation of the MTC system consists of MTC Stand, physical sample, and MTC App + MTC UI.

to represent the full collection with mixed reality augmentation.

The user (retailer) runs the MTC App in combination with the MTC Stand through the HMD to experience the virtual showroom and interact with the mixed materials. The MR App intuitively and interactively enriches the physical sample with colors and textures through hand gestures.

9.0.1 The MTC Stand

The MTC Stand is a physical cardboard display made by laser cutting a large sheet of cardboard and then folding it to form a stable geometry. Using nesting and automation, it is very economical and recyclable. Because it is lightweight and foldable, it is cheap to deliver worldwide. MTC Stand is a collector of selected material samples. It is designed with a compact form factor to enable user interaction without causing significant desk clutter. It enables a tangible experience of observing the garments. The use of physical material samples is motivated by their feel, while colors and textures are added by the MR application and simulation of real garments.

Creating an MTC Stand is straightforward and can be substituted with a virtual alternative, offering a sustainable and often cost-effective solution in the long term. This substitution minimizes environmental

9. Mixed Tangible Catalog

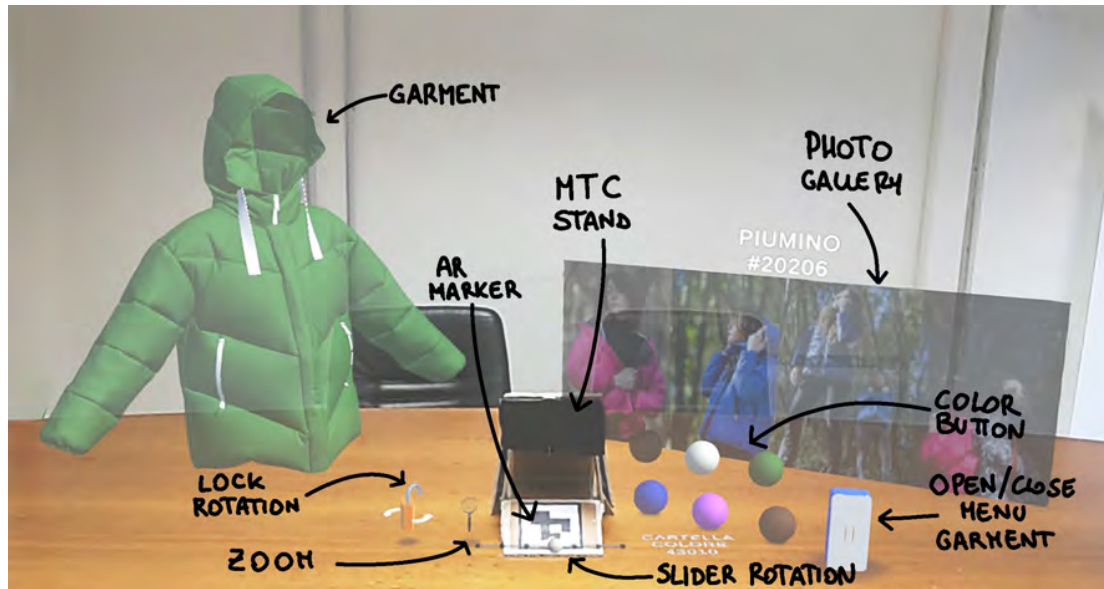


Figure 9.4: MTC, user interface layout with the placement of virtual & real elements: MTC Stand with sample material, Virtual Garment, MTC App interactive controls (lock rotation, magnifying lens, varied colored spheres)

impact, as employing an MTC Stand typically results in multiple product versions and subsequent collections. Utilizing this method contributes to a more eco-friendly catalog production process compared to conventional workflows Fig. 9.2.

To use the MTC Stand, the first step is to open the cardboard, then fold the main part and the wings and fasten them with Velcro Fig. 9.1. The dimension of the MTC Stand, when it is folded, measures 400 mm, and when open measures 756mm extended. The open structure is made to allow positioning and to store the material sample. The width of the MTC Stand is 180 mm and height of the MTC is 267 mm and the depth is 325 mm Fig. 9.2.

MTC features a specific inclination in its front part, which proves useful for positioning the AR marker to calibrate the scene through the HoloLens.

The MTC Stand contains a sample of material shared by other garments, making this process convenient for all products made in the same way. When displaying other garments with different material characteristics, the MTC Stand's material can be changed and replaced with other material samples, thus changing the perceptual qualities.

9.0.2 The MTC UI

The MTC's UI development starts with an examination of Tangible User Interfaces (TUIs), a key aspect of the chosen methodology. The implementation of TUIs was custom-designed to integrate seamlessly with the MTC and the HoloLens HMD, providing users with an exceptionally interactive MR experience. MTC Stand with binary marker is read from the HoloLens, users can physically move the entire interface within the virtual space.

Furthermore, our approach allows the use of hand gestures and raycast in case a user is unable to interact with three-dimensional buttons placed in the virtual model, making the user experience even more immersive and intuitive <https://learn.microsoft.com/en-us/windows/mixed-reality/design/cursors>.

We designed the user interface of the MTC respecting the narrow FOV of the HoloLens, dividing it into three control areas: on the left side of the user, the clothing option; on the right side, the color chart, and the return to the menu button. We designed an array of other control buttons with different capabilities. These buttons for the garment function consist of two interactions: one shaped like a "padlock," which locks the garment's automated rotation and position, and the other shaped like a "magnifying glass," which scales the garment.

The UI buttons that are dedicated to the color chart are simple sphere 3D icons. The menu button has an icon shaped like a cabinet. We chose a slider for garment manipulation to rotate the garment and avoid any possible error in the task.

9.0.3 The MTC App

We implement the MTC App using Unity 3D software for the reseller that can utilize an HMD to run the MTC App in combination with the MTC Stand to experience the virtual showroom and interact with the mixed materials. Unity software connects to the Mixed Reality Toolkit (MRTK) package to develop the MTC App for HoloLens.

The physical sample is enriched by colors and textures by the MR application intuitively and interactively through hand gestures. The MTC App requires dedicated MR hardware, such as the Microsoft HoloLens 2 device destined for AR applications. This optical HMD has a transparent panel that projects virtual images, allowing simultaneous viewing of the real environment. It is equipped with sensors to track the user's eye and hand movements and includes a camera for displaying binary markers. The use of the binary marker is necessary to calibrate the position of the MTC on the desk when the application is started.

9. Mixed Tangible Catalog

Another feature of the HoloLens headset is the direct hand interaction that allows the user to physically click the virtual button; this type of interaction provides intuitive interface navigation and control.

9.1 Focus group design

We followed the focus group as part of the research method that involves end users in the development and evaluation process [93]. This methodology offers a rich and in-depth picture of the respondents' opinions, perceptions, and experiences, thus providing a detailed analysis of the key elements inherent in the context under study.

Focus group is an informal way to assess the requirements and users' opinions. This process requires a group consisting of a moderator who asks the questions, a facilitator who relates between the company and the moderators, and finally, an assistant in charge of recording the actions performed by the users Fig. 9.5.

A focus group needs a minimum of six members, in addition to moderators, to be executed effectively. This approach works well for determining user interface problems and requirements analysis. It offers insights into user experiences and preferences by revealing unscripted user reactions and illuminating group dynamics Fig. 9.6.

We aimed to create this group of industry fashion experts to participate in the product discussion to maximize the benefits of focus groups. It was necessary to address research design issues at both the project and group levels.

We set the following research questions:

- **RQ1:** The MTC improves product presentation vs traditional showroom.
- **RQ2:** MTC improves users' perception and usability vs traditional showrooms.
- **RQ3:** The physical sample makes it easier for users to understand the virtual product vs traditional showroom.

9.2 Setup

Our current operating setup fosters a comfortable room environment, allowing participants the freedom to engage in interactive conversations guided by the moderators.

In our focus group setup, the following hardware and setup are required: the MTC Stand, a HoloLens 2 AR headset for launching the MTC App,



Figure 9.5: Photo from focus group session: In meeting room table with company staff and the moderator who explained the task during the focus group.

a PC for live streaming, and a monitor for displaying the user's field of view in the room.

9.3 Focus Group Procedure

As a first step, each focus group member presented themselves to each other.

Subsequently, the moderator elucidates the initial task, which involves expounding on the company's methodology. This stage is pivotal for validating the MTC concept and gathering information to shape and enhance the project. After grasping the business's procedures, we presented targeted and concentrated focus group objectives and research motivation.

Demo session: Following this, the presenter delves into the demo session, providing an overview of the task to the fashion expert (task chapter). In this phase, the moderators introduced the MTC, and then each fashion expert used the MTC App by talking aloud.

Explaining Task: The moderator starts before the test and receives the instructions from the operator. The procedure commences by introducing the task and the test.

The main task of the user is to control the entire scene of the experiment, visualize the virtual garment, and configure it (change colors and rotate the garment) while interacting with the MTC Stand by interacting with the actual garment samples.

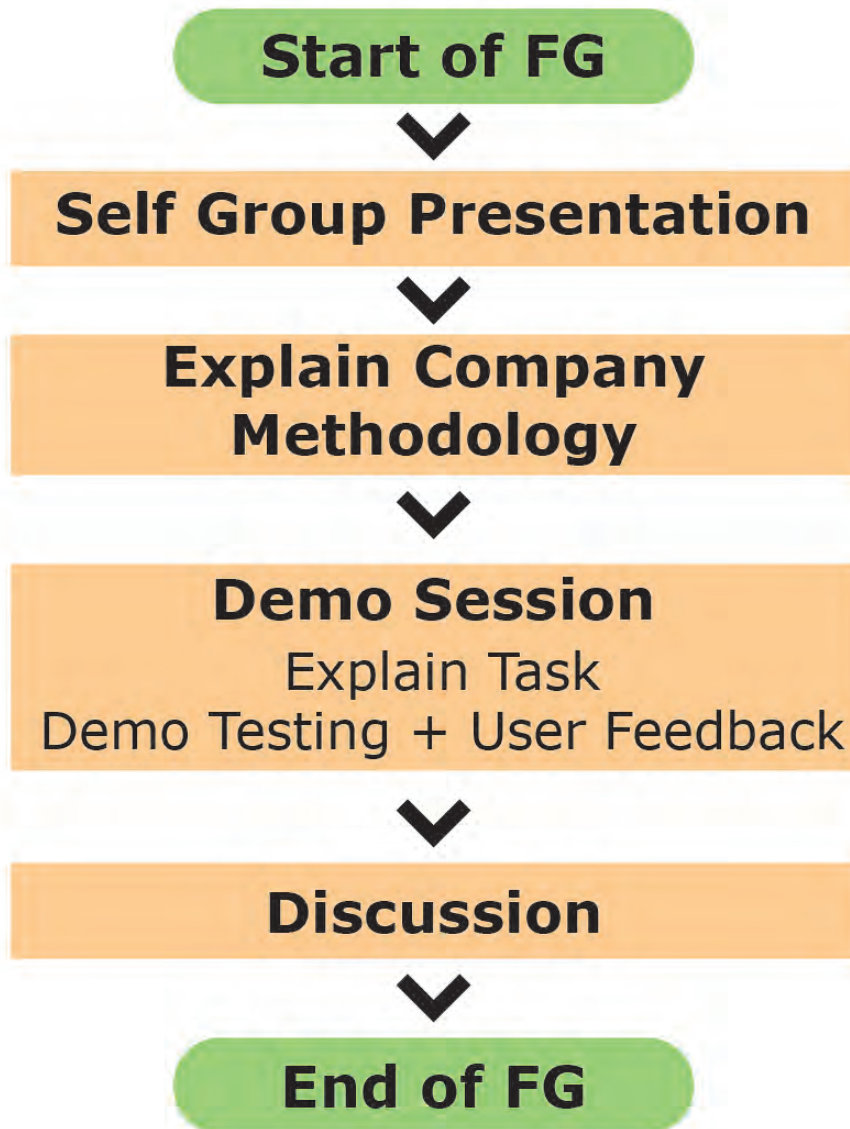


Figure 9.6: Focus group study flowchart; divided into four blocks: 1. Self group presentation, 2 Explanation of the company's methodology, 3. Demo Session (explaining the task, demo testing, and user feedback, and 4. Discussion.

Demo Testing: After the explanation of the task, we subjected the MTC App to a test procedure. The demo consisted of evaluating the application of the MTC using the HoloLens2 device Fig. 9.7.

First, the moderator launches the MTC App on HoloLens2. Then, the user positioned themselves in front of a desk. The assistant helped the user wear the HoloLens2 correctly and ensured their eye distance

was set correctly so their vision was clear.

Each participant is asked to look at the MTC Stand marker which will start the interface. The virtualization of the interface is started by the user by scanning the binary marker on the MTC Stand. Then, the moderator helps the participant in the initial phase and how to interact via gestures. At this point, users can open the sampler menu and select the first garment on the left.

After the user chooses the first garment and has the option to set it with the color present, the operator instructs the user to open the "cabinet" located on the right side of the scene. Next, the tester will have the opportunity to customize the virtual garment, including choosing the desired color. In the next configuration step, the tester will be required to physically touch the sample material on the MTC holder.

Other required functionality includes the ability to lock automatic garment rotation, adjust garment size, and perform manual rotation using the appropriate slider. During demo testing, the user's point of view is replicated on a large screen so that all other fashion experts and moderators can see the users' actions. Thus, all parties concerned were able to gain a greater grasp of the application and related procedures.

USER FEEDBACK During demo testing, the users provide feedback to the entire focus group, which the assistant diligently records. By using the "thinking aloud" technique, testers were able to provide real-time feedback by talking with the moderators [93].

The practice of vocalizing feedback proves advantageous for the focus group, as it fosters a collective understanding of the application and facilitates assistance in its subsequent usage. This approach ensures that the group comprehensively grasps the functionality of the MTC App.

As the Fourth step: When all fashion experts have used the MTC App, they are asked about the experience, with a discussion to capture complete and individual feelings through group interviews and discussions about the application. This work is experimental; the evaluation of the MTC's effectiveness serves as a starting point for the user study.

9.4 Metrics

The focus group procedure included qualitative questions about processes, best practices, and issues. An experimenter acquired the comments through paper and audio-video records. The use of qualitative techniques offers a unique insight into opinions and values, which is particularly effective in exploring attitudes and experiences for several consumer-focused marketing initiatives [94].

9. Mixed Tangible Catalog



Figure 9.7: The user uses the MTC Stand and in the background the mirroring of what they see

9.5 Results

The total time taken for the focus group, including explanations and breaks, was 4 hours. The application's explanation phase and the assigned task took 10 minutes, including the questions asked by the participants. The average time taken by each user was approximately 10 minutes, including the time spent accommodating the viewer to ensure maximum comfort for each person and the eye calibration performed individually by each participant.

The overall feedback from users after the focus group indicated that the platform currently has a higher level of usability than the traditional one (RQ1). It is suggested that the MTC App could be integrated more synergistically into the company's activities. Fashion experts stated that MTC augmented the garment perception and usability by combining the digital and physical since the traditional showrooms lack this ability (RQ2, RQ3).

In addition, a skill and comfort gap in interactions was noted, with

younger users (up to 35 years old) adapting more easily than the remaining test audience. Some fashion experts were hesitant or shy toward the platform, while others manifested more immediate interaction with the technology.

9.5.1 Feedback analysis

The feedback received from the users after using the demo was generally very optimistic, with the comments referring mainly to the UI and the ability to interact and virtually display garments. Based on the results of the analysis, the following modifications are suggested to improve the application:

- **Simplify the visual aspect of UI buttons.** The controls should be larger and easier to locate. They should also be placed closer to the point of interest.
- **Improve visibility to help users locate commands.** This is related to the narrow FOV of the device; commands could be moved and highlighted when the user approaches them.
- **Provide better explanations of UI commands.** Explanations could be displayed on the screen or could be provided through a tutorial.

Moreover, it was appreciated that the ease of interaction with the garment and visual interface and the tactile feedback. We here listed feedback received from each fashion expert user:

- **User1** stressed the added value for the recipients of the experience, emphasizing dematerialization and integration of touch sensation as positive elements.
- **User2** appreciated the innovative and engaging visualization of the sample garments, comparing them to "plaster models".
- **User3** reported that the use of raycast (a mode in which one can interact with virtual objects intuitively through manual control) may require further training to fully exploit this functionality.
- **User4** found the experience useful and functional in the B2B context.
- **User5** reported the value of the tactile element.
- **User6** suggested that the current application could be used to the fullest as an integration.

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Users raised some critical issues regarding the interface, indicating difficulties in clicking elements of the interface. These challenges are attributed to unfamiliar interaction with the technology, generating stress and frustration toward users who were unable to interact in time, more training and improvement of the UI emerged as solutions to mitigate these problems. Among the difficulties reported were finger interaction and slider pinch for manual rotation of items.

There was also a request to eliminate the animation from the magnifying glass which contributed to complicating the experience. A recurring problem during the test was the need to recalibrate the device's eyes at the change of each user testing the app. This resulted in the app being restarted, and thus in slowdowns and with the risk of commands disappearing from the field of view due to the tracks being influenced by the user's actions since users already found the app open on the device.

To complete the user feedback phase for possible implementations and solutions, all information was collected and grouped into GUI, Functionality, Technology, and Additional features lists:

GUI:

- Simple commands to improve overall usability.
- A double-layer approach to simulate sleeve touch is a proposed solution.
- To facilitate interaction, merge elements closer together.
- Vertical development of elements.
- The placement of the color chart under the garment.
- Indicate the activation of a button.
- Increasing the size of the trigger for buttons is recommended.
- The addition of a material legend is suggested to improve the experience.

Functionality:

- Centering the head to the scene is recommended, taking into account the limitations of the field of view.
- Ability to move the head via controls.
- Targeted training on actions to be taken to accelerate the process of familiarization with the environment.
- The ability to lock the rotation of the head with the hand.

Technology:

- Implementation of voice commands could simplify interaction.
- The use of new devices such as the Meta Quest 3 or Apple Vision to use better color rendering than the color rendering of HoloLens 2 and provide better tracking accuracy.

9.6 Discussion

Our article focuses on applying existing MR technology in the fashion industry, particularly in B2B showrooms.

No new solutions are introduced in graphics, but the novelty lies in improving the user experience by seamlessly integrating real and virtual samples, thus improving decision-making processes, reducing costs, and minimizing waste through MR.

The demonstration consists of gathering feedback from the group after analyzing the MTC, on the usability and functionality of the application. The research results have real-world applications, helping practitioners evaluate retail communication and marketing methods for successful digital fashion marketing. In addition, designers and developers of AR and VR retail technologies can discover direction and inspiration for future improvements.

9.6.1 Limitations

The main limitations are inherently related to the device employed. The first limitation concerns the technology used to display the head in high quality. This is because the HoloLens device has render limitations and, consequently, projects in high definition due to the transparent panel used. The second limitation factor is the need for the user to perform hand gestures correctly for them to be recognized effectively. This limitation is inherently related to the device, which is not state-of-the-art in hand recognition, thus constituting an element that affects the application's overall performance. The third limitation is the intensive use of the device by many people. During our focus group, we had only the real material sample which was black, therefore even though the user changed the virtual garment color the sample was always visualized as black.

A technical limitation of the HoloLens device is related to the reduced FOV, which may not display the scene elements correctly. To compensate for this, the elements were arranged so that the user with a reduced head movement could see the elements correctly in full, as in the case of the main product. The device needs to be calibrated before it may be used.

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This process is particularly frustrating and time-consuming and affects the device's battery life.

Another limitation concerns a problem encountered during demo testing when users' actions were streamed wirelessly to a second screen. This configuration made it difficult to explain the application to other testers clearly and concisely. It must be made clear that the first part of the experience went smoothly, and the users could watch the operator's application presentation; this phase was not a complete failure.

9.7 Conclusion

In conclusion, the Mixed Tangible Catalog (MTC) represents a significant step forward in creating more interactive, immersive, and sustainable showroom experiences. By combining physical samples with digital augmentation, the MTC enhances the way resellers interact with products, making the configuration process more intuitive and engaging.

Part III

Conclusion

Chapter 10

Discussion & Conclusion

This dissertation has explored how immersive technologies can be leveraged to make the metaverse accessible and effective for small and medium-sized enterprises (SMEs), with a particular focus on the B2B fashion and nautical sectors. Through the integration of **social interaction** and **tangible interaction**, three main contributions can be highlighted:

- The design and validation of *Immersive B2B showrooms*, exemplified by the Fashion Showroom in the Metaverse (FSM), which demonstrated how virtual environments can reduce the need for physical samples while enhancing engagement and sustainability. This approach extends previous work on virtual retail environments [9], [11] by addressing B2B-specific requirements and incorporating sustainability metrics absent in prior consumer-oriented studies.
- The development of the *Collaborative configurator* for pair product configuration in Mixed Reality, which provided evidence on how co-presence and negotiation models influence decision quality and usability. While prior research has examined remote collaboration in VR [55], [73], this work contributes empirical evidence on co-located MR configuration, addressing the gap identified by [64] regarding spatial registration challenges in multi-user scenarios.
- The introduction of the *Mixed Tangible Catalog (MTC)*, a hybrid solution that combines physical material samples with Mixed Reality augmentation, offering an integrated visual-haptic experience that responds to the limitations of purely virtual showrooms. This tangible approach aligns with theoretical frameworks on embodied interaction [46], [82] while addressing the specific challenge of fabric evaluation identified in textile industry literature [95], [96].

Taken together, these contributions extend the literature on XR for industrial applications by characterizing, through formative single-condition evaluations, how immersive tools can support SMEs in digital transformation and how specific design choices shape sensory fidelity and collaborative decision-making. Because the case studies do not include experimental baselines, the evidence should be interpreted as feasibility, usability, and perceived value, triangulated with task-level observations

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and standardized questionnaire benchmarks, rather than as causal improvements over existing workflows. This framing motivates future controlled comparisons against the traditional system (2D DAM/PIM) and conventional showroom practices to quantify relative gains.

Sustainability Given the central role of sustainability in this work, future developments will also target a more direct reduction of material and process waste, beyond the already demonstrated savings in transportation. In particular, MTC can be extended to support virtual prototyping and iterative product refinement in immersive environments, enabling companies to test variants, fit, and aesthetics without producing physical samples. This shift toward fully digital design workflows can substantially reduce sample waste, shorten development cycles, and limit the overproduction of prototypes that never reach the market.

The sustainability benefits of the MTC are already evident, as it lowers the environmental impact of traditional showroom practices while offering a cost-effective and scalable solution for fashion companies. Future work will therefore focus on improving gesture recognition, enhancing the user interface, and broadening MTC support to additional product categories, with the explicit aim of maximizing reuse of digital assets and minimizing reliance on physical artefacts throughout the design and presentation pipeline.

In the MAGIC case studies, the sustainability assessment concentrated on reducing transport-related costs and environmental impact. CO₂ emissions were computed for yacht transport over distances of 1,745 km and 960 km, taking into account both the transport vehicle and the yacht mass. Using standard fuel consumption rates, annual round-trip trips to both destinations were estimated to generate approximately **116.6 tons of CO₂**. This figure highlights the substantial environmental burden associated with conventional transportation and quantifies the potential gain offered by immersive, remotely accessible alternatives.

By limiting or eliminating the need for physical travel, immersive systems such as FSM and MAGIC can significantly reduce transport-related costs and emissions, thereby supporting more environmentally sustainable business models. These findings reinforce the importance of evaluating greener transport solutions and implementing compensatory measures, as well as accelerating the adoption of immersive technologies that can structurally reduce the environmental footprint of these operations Figure 10.1.

10.1 Limitations

Despite the positive outcomes, several limitations must be acknowledged:

Route/Assumptions	Units	Bari-Düsseldorf	Bari-Genoa
Distance (Round Trip)	[km]	3490	1920
Yacht Weight (Displacement)	[kg]	5600	
Heavy-duty vehicle weight (avg)	[kg]	14500	
Total Weight	[ton]	20,1	
Diesel Consumption based on weight (avg)	[liters/ton/km]	0,4	
Diesel Consumption (avg)	[liters/km]	8,04	
Total Fuel consumption	[liters]	28059,6	15436,8
Average CO2 emissions	[kg/liters]	2,68	
Route CO2 Emissions	[kg]	75199,7	41370,6
Total CO2 Emissions	[ton]	116,6	

Figure 10.1: Total CO₂ emission estimated on two round trip to main trade fairs

- **Technological constraints** The performance of XR systems remains strongly dependent on hardware characteristics, such as field of view, hand-tracking accuracy, and graphical rendering. These factors affected user experience, particularly in the case of less experienced participants. These limitations reflect broader challenges in XR hardware development documented by [97], [98], with recent advances in display technology [99] not yet fully addressing vergence-accommodation conflicts that impact prolonged usage.
- **Human factors** The novelty of XR led to initial difficulties in usability for some users. Learning curves, susceptibility to cybersickness, and interpersonal dynamics influenced the outcomes of the experiments. Cybersickness susceptibility, documented extensively in VR literature [27], [100], remains a significant barrier to XR adoption, with individual differences in susceptibility [101] requiring tailored mitigation strategies. This formative evaluation approach [102], [103] prioritizes iterative refinement over statistical generalization, aligning with research-through-design methodologies [85] where ecological validity is traded for depth of insight during early-stage system development.
- **Methodological scope** The studies presented were conceptual presentations to experts from partner companies and pairs of users, which limits the generalizability of the results. Furthermore, the

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evaluations were conducted in controlled environments and did not take into account all the variables typical of real industrial contexts.

- **Integration issues** Although FSM, MR-CoCo, and MTC were validated independently, their integration into existing industrial workflows still requires adaptation, training, and infrastructural support from companies.

10.2 Future direction

Based on the results and limitations that emerged, it is possible to identify several directions for future research and development, such as comparisons between different case studies/scientific literature:

- **Enhanced multimodal interaction** Integrate more advanced haptic interfaces, voice commands, and AI-driven assistants to provide more natural and accessible interactions. Recent advances in haptic rendering [104] and pseudo-haptic techniques [105] offer promising avenues for enhancing tactile feedback without requiring specialized hardware, potentially lowering adoption barriers for SMEs.
- **Scalability and deployment** Extending the prototypes to larger samples and diverse industrial sectors (e.g., automotive, interior design, aerospace) will allow validation of the proposed approaches in real-world conditions. Cross-sector generalization requires addressing domain-specific requirements [37], with particular attention to configuration complexity [36] and stakeholder heterogeneity varying across industries.
- **Remote and hybrid collaboration.** While this thesis emphasized co-located interaction, future research should explore remote collaborative scenarios, where XR can support distributed teams and international supply chains. Hybrid collaboration models [106], combining co-located and remote participants, present unique design challenges regarding awareness mechanisms [107] and the asymmetry of experience between physical and remote collaborators.
- **AI integration** The adoption of intelligent agents for guiding configuration, suggesting alternatives, or mediating negotiation could further improve decision-making and reduce conflicts. Intelligent assistance in configuration tasks [38], leveraging machine learning for recommendation systems and constraint satisfaction, could

complement human decision-making while addressing the complexity identified in multi-criteria optimization scenarios [39].

- **Sustainability assessment** A quantitative evaluation of the environmental benefits of immersive showrooms, such as reduced transport and material waste, should be carried out to provide stronger evidence for SMEs considering adoption.

In conclusion, this doctoral research demonstrates that the integration of immersive visualization, social collaboration, and tangible interaction can transform the way SMEs approach product design and communication within the emerging industrial Metaverse. By combining technological innovation with human-centered design principles [108], [109], the proposed systems show how XR can evolve from a purely visual medium into an embodied, collaborative, and sustainable environment. This convergence of digital and physical creativity not only enhances accessibility and inclusivity [110], but also contributes to the shaping of a more resilient and competitive industrial ecosystem [33], [35] where design processes become shared, experiential, and environmentally conscious [83].

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