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# Designing and Evaluating XR Cultural Heritage Applications Through Human–Computer Interaction Methods: Insights from Ten International Case Studies

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**Abstract**

Advanced three-dimensional extended reality (XR) technologies are highly suitable for cultural heritage research and education. XR tools enable the creation of realistic virtual or augmented reality applications for curating and disseminating information about cultural artifacts and sites. Developing XR applications for cultural heritage requires interdisciplinary collaboration involving strong teamwork and soft skills to manage user requirements, system specifications, and design cycles. Given the diverse end-users, achieving high precision, accuracy, and efficiency in information management and user experience is crucial. Human–computer interaction (HCI) design and evaluation methods are essential for ensuring usability and return on investment. This article presents ten case studies of cultural heritage software projects, illustrating the interdisciplinary work between computer science and HCI design. Students from institutions such as the State University of New York (USA), Glasgow School of Art (UK), University of Granada (Spain), University of Málaga (Spain), Duy Tan University (Vietnam), Imperial College London (UK), Research University Institute of Communication & Computer Systems (Greece), Technical University of Košice (Slovakia), and Indiana University (USA) contributed to creating, assessing, and improving the usability of these diverse cultural heritage applications. The results include a structured typology of CH XR application scenarios, detailed insights into design and evaluation practices across ten international use cases, and a development framework that supports interdisciplinary collaboration and stakeholder integration in phygital cultural heritage projects.

**Keywords:** extended reality; cultural heritage; usability; pedagogy; museum exhibits; DoE

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## 1. Introduction

Cultural heritage (CH) sites and artifacts have long presented challenges for preservation, analysis, collaboration, representation, and sharing, particularly with the limitations of traditional 2D research, documentation, display, design, and evaluation methods. Before the advent of digital tools, maintaining accurate records of CH required painstaking efforts that often fell short of capturing the richness, complexity and protection of artifacts and sites. Today, however, extended reality (XR) technologies—encompassing virtual reality (VR), augmented reality (AR), mixed reality (MR), 360-degree scanning technologies, and Artificial Intelligence (AI)—offer transformative possibilities for CH preservation and sharing by creating 3D digital representations and visualizations. CH XR applications are a subset of Digital CH (DCH) applications.

These CH XR innovations enable accurate representation and documentation using virtual replicas. Local sharing of augmented CH artifacts and sites, and remote sharing of virtual replicas of CH artifacts and sites, open new avenues for collaboration and immersive exploration. Additionally, virtual AI-powered tutors can significantly enhance engagement, motivation, and learning outcomes. These AI avatars can be integrated into XR environments to provide personalized, effective, and scalable educational experiences. Many studies have supportive evidence for using XR for learning and exploring. For experiencing CH, XR could have an extensive impact on museum design, education, and tourism.

Studies have measured learning retention in users interacting with XR-based cultural heritage applications and found them to outperform traditional methods. The researchers found that students learn more than twice as much in less time when using an AI tutor, compared with the active learning class [1]. They also found that students feel more engaged and more motivated.

VR and AR experiences have been found to positively influence user attitudes, enhance cultural understanding, and encourage historical exploration [2–5]. Early childhood education significantly shapes future success, enhanced by technology [6]. Interactive games with touchscreens and animations promote engagement and learning [6,7]. XR aids in preserving and sharing cultural knowledge, allowing users to create and retain cultural memories through immersive experiences [8,9]. High tourist satisfaction is noted with portable VR and AR systems [10].

Research has shown that integrating XR tools, such as virtual reconstructions and AR overlays, significantly increases user engagement by providing immersive and interactive experiences. For example, gamified elements in XR applications have been found to emotionally and physically engage users, creating stronger connections with cultural content [11].

Applications that combine visual, auditory, and tactile interactions lead to higher retention rates of historical and cultural knowledge [12]. XR technologies significantly enhance engagement and learning outcomes in CH contexts. The integration of gamification in virtual tours, as examined by Pescarin et al. [13], has been shown to increase authenticity and user involvement. Furthermore, Liu et al. [14] emphasized the importance of understanding user experience (UX) to optimize educational XR applications for CH, employing bespoke evaluation methodologies. Studies such as Ref. [15], on Experience–Technology Fit (ETF), highlight how mixed reality (MR) characteristics and voice user interfaces (VUIs) impact user satisfaction and learning retention. Additionally, projects like "Past Has Ears" [16] demonstrate the potential of multisensory XR experiences in cultural preservation by recreating acoustic environments to enhance immersive engagement. Together, these findings provide compelling motivations for creating a widely accessible XR–AI-powered pedagogy. This can significantly enhance learning outcomes, and they present a compelling case for its broad adoption in learning environments.

Digital technologies have facilitated the shift from a solitary, "lone scholar" model of CH analysis and knowledge sharing via publications, to interdisciplinary remote collaboration, allowing for unprecedented reach and precision in the DCH preservation and sharing domains. With a future of continuous real-time data sharing and near-ubiquitous internet access, users can engage with XR-based DCH experiences that bridge physical and virtual worlds, almost from anywhere, anytime.

Examples like "Metaverse Seoul" [17] and Madrid's 360-degree virtual tour demonstrate how these technologies expand access and engagement. Advanced XR technologies not only create realistic replicas that enhance learning [18–21], but they also address the previously found shortcomings in graphical detail and simulation quality that limited the use of early VR applications in education [22–24]. Furthermore, XR enables interactive, shared experiences that traditional methods simply cannot provide [25,26], while also improving accessibility for individuals with unique needs [27] and supporting the representation of complex historical and cultural information [28–30].

XR-based tools have democratized access to cultural heritage by enabling virtual visits to inaccessible sites. For example, the CHISel platform allowed collaborative annotation of artifacts, ensuring that users worldwide could engage with digital reconstructions regardless of physical limitations [31]. The PLUGGY platform showed that XR applications emphasizing user-generated content and community interaction can foster a sense of ownership and active participation among users, broadening the reach of cultural heritage projects [32]. These examples showcase the ability of XR technologies to democratize access to CH, evidenced by the fact that these applications reach diverse audiences. Mediascape XR [33] enables real-time interaction with digital artifacts via social VR, effectively overcoming geographical barriers. Cardoso [34] further demonstrated the potential of tangible user interfaces (TUIs) to create affordable and accessible smartphone-based XR experiences, particularly benefiting individuals in remote or underserved areas. Applications such as the 'Museum Time Machine' [35] and the Seowon UNESCO World Heritage AR guide [35] exemplify how AR applications can provide immersive, interactive ways to explore and understand architectural evolution and historical narratives.

The media project 'Valle d'Aosta', reported by Nardi [36], illustrates how digital storytelling and innovative media can preserve and promote local heritage while strengthening cultural identity and community engagement. Although developed in 2016, its approach remains relevant today and could be expanded through Web3 technologies, including blockchain and Non-Fungible Tokens (NFTs), to authenticate and protect digital heritage content and foster decentralized participation and exchange. Technology acceptance of blockchain and NFTs remains uneven due to steep learning curves and financial barriers, despite the digital revolution significantly enhancing learning and information dissemination. This underscores the importance of creating user-friendly, transparent systems, using HCI methods in ensuring high usability. This is particularly important while digital learning media adoption continues to lag behind the pace of technological advancement [37–41].

Integrating CH XR and blockchain technologies into tourism and hospitality not only has the potential to enhance CH experiences, but can also help implement solutions for the United Nations' 17 Sustainable Development Goals (SDGs). Pre-visit virtual excursions allow exploration of virtual replicas of sites, reducing travel emissions (SDG 13: Climate Action) and ensuring accessibility for all, including those with disabilities (SDG 10: Reduced Inequalities). Gamified VR, AR, or MR quests, collecting CH-themed NFTs and DCH souvenirs, foster educational engagement (SDG 4: Quality Education) and drive economic growth (SDG 8: Decent Work and Economic Growth). Online–offline DCH activities can take tourism off the beaten track, and reduce overcrowding while providing digital rewards redeemable on-site for souvenirs, boosting local businesses (SDG 12: Responsible Consumption and Production).

AR-guided tours promote cultural understanding (SDG 11: Sustainable Cities and Communities), while post-visits encourage global sharing and partnerships for sustainable development (SDG 17). This holistic approach bridges economy, ecology, education, leisure, technology, culture, and sustainability. XR technologies have shown transformative potential in preserving CH through innovative tools such as digital twins, photogrammetry, and laser scanning. For instance, Banfi et al. [12] demonstrated the use of high-resolution 3D modeling to document fragile artifacts and archaeological sites, enabling non-invasive conservation practices. A notable example is the documentation of the Lamalunga Cave and Altamura Man, which utilized digital twins to facilitate remote analysis while avoiding physical damage to the site. Similarly, the PROMETHEUS project [42] highlighted XR-enabled multi-scalar web publishing, allowing for detailed digital preservation and public access to European architectural heritage.

Notable examples of how VR is successfully being used to promote and preserve cultural heritage are the British Museum's Bronze Age VR Experience, the Louvre's Mona Lisa VR Experience, the Pompeii VR Experience, Machu Picchu 360° Virtual Tour, the Acropolis of Athens Virtual Tour, the Nefertari's Tomb VR Experience, the Venice Biennale VR, and the Anne Frank House VR Tour. The British Museum developed a VR experience called "The Virtual Reality Weekend," allowing visitors to explore the Bronze Age in an immersive way, showcasing ancient objects and their historical context. The Louvre introduced a VR tour of Leonardo da Vinci's Mona Lisa, offering visitors an up-close and interactive experience of the iconic painting. VR technology allows users to explore the ancient Roman city of Pompeii as it existed before the eruption of Mount Vesuvius in AD 79. A 360° VR experience of the UNESCO World Heritage Site Machu Picchu offers users the chance to walk through the ancient Incan citadel remotely. The VR reconstructions of the Acropolis of Athens Virtual Tour allow visitors to experience the Acropolis and its monuments as they appeared in ancient Greece. An immersive VR experience developed by Curiosity Stream lets users explore the stunning tomb of Queen Nefertari. The Venice Biennale VR art exhibition uses VR to showcase virtual pavilions, art installations, and cultural performances. The Anne Frank House VR Tour provides a virtual tour of the secret annex where Anne Frank and her family hid during World War II.

The Picasso AR use case illustrates a Web3 phygital tourism app that merges cultural heritage (CH) learning, 3D visualizations, and XR for edutainment. Users can earn credits within the app, redeemable for perks at local CH sites, such as museum souvenirs or discounts at nearby restaurants and hotels. This model showcases how CH XR can support hybrid economies through multi-actor collaboration and token-based incentives.

Several organizations are actively developing Web3 CH XR applications. CyArk creates 3D models of endangered cultural heritage sites for preservation and education. Google Arts & Culture provides virtual museum and site tours to support global cultural access. The SITE Network promotes immersive XR tourism through a hybrid economy model, aiming to democratize travel and boost local tourism awareness via VR/AR experiences. The core of these experiences sees XR mix with blockchain to create an open interoperable spatial web. This permits users and their assets, memories, and souvenirs to move between experiences and act as a gateway to each destination that has purpose before, during, and after a visit. These initiatives demonstrate the power of VR in making cultural heritage more accessible and engaging to a global audience.

In summary, CH XR apps have an important role in preservation, tourism and hospitality:

1. Cultural Preservation: Modeling and sharing 3D virtual or augmented cultural artifacts assists in their preservation.
2. Physical Preservation: Viewing without physical interaction avoids wear and tear.

3. Digital Preservation: Building digital twins of artifacts enables them to be viewed and interacted with in a digital environment.
4. Crowdsourced Preservation: Democratizing access and sharing of CH information and digital twins globally via DCH platforms assists preservation.
5. Phygital Tourism and Hospitality: Innovating the way CH and DCH are used to share, enjoy, and organize viewing of local CH artifacts and CH site visits, and online DCH sharing, increases phygital tourism.

### *1.1. Human-Centered Design for Digital Cultural Heritage Extended Reality Applications*

HCD is a framework that focuses on designing systems and solutions around the needs, preferences, and limitations of users. It encompasses human–computer interaction (HCI) [43–45], user experience/User Interaction (UXUI) design [46–48], and Design Thinking/Design Doing methods [49–52].

The integration of Design Thinking [50] and user-centered design [53,54] principles is emphasized in various contexts, including web and mobile applications' engineering education [55]. This approach addresses the multifaceted nature of HCI education and prepares graduates for the evolving software development landscape. A concept-centric approach to software development, where concepts are explicitly represented and used to align products and communicate with non-engineering teams, has also been proposed [56]. This approach, while not VR-specific, underscores the importance of understanding the underlying concepts that shape user experience.

The current research reveals a lack of standardized UX design frameworks for XR cultural heritage applications. Although cases like Chilly Mo demonstrate the value of early Design Thinking methods, broader cross-case analysis is needed to establish best practices and generalizable guidelines.

HCD provides the overarching methodological approach for creating user-centered applications. HCI brings a scientific understanding of how humans interact with technology, providing empirical methods for usability testing and data-driven decision-making. UXUI translates these findings from usability testing into visually and interactively compelling, efficient, and effective designs. Design Thinking/Design Doing is a method developed by IDEO, the international design house, and emphasizes iterative, empathy-driven problem-solving processes that align with user-centered design and evaluation principles. Together, these disciplines form a multi-dimensional framework to designing technologies, particularly for complex, interactive systems like CH XR applications that depend on high precision and high accuracy.

HCD methods are versatile and adaptable to project-specific contexts, including budget constraints, user needs, usage scenarios, location, and prototype readiness. Early testing with low-cost prototypes is critical to refining UXUI design choices while minimizing costly errors later in development. Effective HCD relies on cross-disciplinary collaboration, enabling experts from various fields to communicate and work together to improve interfaces.

There are numerous HCD methods which have been developed by various researchers over time, such as persona creation, focus groups, interviews, and think-aloud testing during the design and mid-development phases. These methods are essential for gathering user insights and identifying pain points. An overview of the most popular methods is provided in Table A1 of Appendix C.

When innovating, there are situations where there are no known or established best practices, and this is where the HCD team and the UXUI experts need to tailor an existing HCD method or create a new one. Standard HCD methods are typically adapted to address specific HCI enquiries and UXUI requirements for each evaluation. For new technologies and interfaces, new methods need to be developed or existing ones adapted to specifically address the novel aspects that could affect the user. For instance, changes in system response, or the location for experiencing the CH XR app, or issues regarding the accurate merging of the real and virtual, can all negatively influence the UX. The setting of use changes per application, and with that, the methods of design and evaluation need to be adapted to take those differences into account when assessing the UX. This adaptation process is a skill that is learned over time by practicing on actual projects with real constraints.

A method like a questionnaire offers a generic structure, but its effective use lies in the 'tailoring process'—applying the method to a specific application or service by crafting questions that directly address the unique features under investigation. While the foundational aspects of the method remain consistent, such as knowing how to formulate clear and unbiased questions, selecting relevant end-users, determining appropriate timing and modes of administration, and analyzing responses, the content and focus of the questions must be adapted to the context. This tailoring is not a straightforward or codified procedure; rather, it is an experiential skill developed over time through repeated application and reflection, often guided by the insights of experienced practitioners. It is this largely invisible, practice-driven framework of development and process of adaptation that this investigation seeks to illuminate.

HCD methods are guidelines, generic, recommended ways of approaching the design of experiments (DoE). The methods and experiments are selected depending on the type of data that is required, the scenario of use, available time and budget, etc. The generic HCD methods are then typically tailored into a framework that is specific for each project deliverable and its requirements, including for each end-user type and scenario of use [15]. HCI experts may have to adapt an existing 2D UXUI development framework and respective methods to a 3D UXUI scenario of use, or they may have to develop a new method or a new framework for 3D development specifically. This tailoring of the DoE as a development framework involves iterative, hands-on practice with the DoE tailoring process. Exposure to learning the tailoring process in a real project is typically facilitated through experiential learning in research labs, via internships, and in real-world projects. The adaptability of the HCD methods ensures that HCD principles remain relevant and effective. This is especially important in the rapidly evolving domain of XR and other emerging technologies.

Critical points for applying HCD in the development of CH XR are as follows:

1. Quality and Usability: DCH systems must provide reliable interaction and information, and therefore, the interface design must achieve the highest usability and accuracy scores [14].
2. Human-Centered Iterative Design: The iteration of design, test, redesign, etc., with domain experts and representative end-users is essential for achieving accuracy in modeling high-precision information systems [15].
3. Correct HCD Method Selection: This is critical based on the development stage to avoid costly delays and negative experiences [16].
4. Developing New Evaluation Methodologies for CH XR: New methods are necessary for implementing and assessing novel use case scenarios for XR and related spatial computing technologies [17].
5. Developing New online–offline CH Sharing Solutions: CH XR applications provide new opportunities for CH tourism that allow the linking of gamified online CH experiences with preparations for in-person CH visits, on-location CH activities, and post-visit CH experience preservation and sharing and edutainment, including collecting DCH souvenirs and perks [57].

CH XR applications are complex applications that pioneer new technologies and approaches, that need iterative human-centered testing and development and carefully planned parallel evaluation studies. This is especially relevant for CH XR solutions, as recording and sharing cultural information requires maintaining accuracy and support for diverse users and their needs.

Conducting user evaluations with a large enough sample of individuals that represent the intended end-users, spanning different ages and different technical abilities, is another intentional step in order to infer quantitative empirical research using statistical analyses. In order to test the UXUI and infer generalizable user experience data, it is essential to select a random sample of participants that are representative of the intended end-users, which in this case would include a broad range of gender, age, and technological background. By engaging a diverse group under conditions similar to everyday use, designers gather authentic feedback on ease of use, pacing, and narrative clarity. Analyzing these responses helps pinpoint which elements resonate and which require further refinement. This cyclical approach of research, build, evaluate, and iterate is a hallmark of HCI because it minimizes wasted effort, guides improvements informed by real end-user responses, and provides tangible proof of concept, ultimately ensuring the application's relevance and appeal to actual users. It also shows how HCI can help inform design decisions, and empirical evaluation research results can inform the creation of universal guidelines for design that can be expected to be suitable for the general public, not only the participants in the sample.

Especially for newly proposed CH XR solutions with novel functionalities that may not have existed before, it is highly recommended to start with low-cost prototypes to demonstrate the added value of the proposed solutions before significant investments are made. Low-fidelity prototypes can be used to test UXUI before developing more costly mid- or high-fidelity versions, utilizing various HCI tools. Knowledge about user needs and best design solutions comes from testing rough prototypes, and informs further design decision-making during the development of the more detailed UI versions, through consecutive rounds of design–test–design–test iterations. Prototype evaluation addresses challenges early, prioritizes user needs, validates innovations, and supports continuous improvement, leading to a robust application and successful investment. Table 1 presents different degrees of prototype fidelity and test scenarios. Preliminary UXUI tests can be run even on low-fidelity sketches.

**Table 1.** Low-, mid-, and high-fidelity prototyping.

| Types of Prototypes | Description |
|---|---|
| 1. Low-Fidelity | A basic, non-functional representation of the product using simple visuals or mockups. Ideal for testing early concepts quickly and cheaply. |
| 2. Mid-Fidelity | A moderately interactive prototype with limited design and partial functionality. Balances realism and efficiency for broader user testing. |
| 3. High-Fidelity | A detailed and fully interactive prototype that closely resembles the final product. Best suited for final user validation before development. |

### *1.2. Key Contributions*

This article offers several key contributions to the field of cultural heritage (CH) extended reality (XR), with particular emphasis on human–computer interaction (HCI) and Human-Centered Design (HCD).

First, it presents ten curated CH XR use cases, categorized into four distinct application scenarios: In-Museum/On-Location, In-Home/School, Online Platforms, and hybrid (pre-visit, on-location, and post-visit) experiences. This spectrum forms a structured typology of phygital XR experiences, serving as a roadmap for cultural engagement in both single- and multi-user settings. Second, the article provides an in-depth account of UX/UI design and evaluation processes, highlighting mockups, prototypes, and iterative refinements. Unlike many studies that emphasize final products, this work foregrounds the creative and evaluative journey, offering rare transparency into how HCD and HCI methods are adapted to cultural heritage contexts. Third, it introduces a practical framework for Phygital Cultural Heritage Tourism App Development. Drawn from empirical insights, this framework guides interdisciplinary collaboration, team formation, user experience design, and evaluation across diverse contexts. Finally, the article offers a stakeholder analysis and role mapping, based on the collaborative work of researchers, professors, and students from multiple international institutions. This analysis captures the interplay of technical, cultural, educational, and economic factors involved in CH XR development and advocates for adaptive, participatory design approaches.

These ten CH XR projects were undertaken by XR researchers, professors, and students involved in these projects. The students who worked under the supervision of their respective mentors and professors contributed the results to various conferences, journals, research reports, and deliverables via their institutions and international projects.

In sum, this work contributes a practice-based roadmap that integrates scenario typologies, design processes, methodological transparency, and collaboration frameworks to advance human-centered CH XR applications.

### *1.3. Structure of This Document*

The Introduction Section provided the background story of the origins and relevancy of our work on the intersection of XR, CH, and DCH. Section 2 introduces the ten DCH XR use case studies. Section 3 is the Results Section, which presents the use cases applying the HCD methods for the development of DCH XR systems and summarizes what can be learned from these use cases. Section 4, the Discussion Section, provides an analysis of the findings, a CH XR stakeholder analysis, and recommendations for a framework for developing DCH XR for online–offline tourism and hospitality innovations involving all stakeholders. Section 5 presents the conclusions.

## 2. Ten Case Studies in Extended Realities for Cultural Heritage Preservation

Ten CH VR/AR use case studies are reviewed to analyze the development, design, and evaluation practices of these proposed CH XR applications, focusing on identifying best practices and how HCD was used to achieve usability in the different scenarios of use. Each use case highlights a specific design and evaluation method, and describes how development plans were put together to address the specific scenarios of use the novel applications intend to deliver. The following CH XR use cases are being reviewed:

1. Chilly Mo—This is a VR/AR app for toddlers introducing ancient civilizations like Persia through interactive storytelling and gamified cultural exploration. This is usable at home, in museums, or in schools and a great example of the Design Thinking/Design Doing process (empathize, define, ideate, prototype, and test). Additionally, it provides examples of a moodboard, a storyboard, persona descriptions (for a typical user and an atypical user), diagram of a Task Analysis, a Hierarchical Task Analysis, sketches as prototypes, and wire-frame (digital) drawings as prototypes for the proof-of-concept evaluations.

2. Cham Culture AR App—This is an AR app showcasing Cham ritual dances and musicians from stone reliefs, using QR cards for interactive storytelling in museums or educational settings. It is a great example of using a newly developed (Universal Design Principles (UDPs)) heuristic evaluation (HE) method for new technology (in this case, AR). The research was triangulated as follows: persona descriptions, (UDP) HE, and a System Usability Survey (SUS). The SUS is used to assess the attitude and opinions of potential new users about the new app. This use case has a video demo of the app prototype, available online.
3. Memories of Kellie—This is a desktop VR experience of Kellie Castle in Scotland, using an interactive narrative and atmospheric design to teach users about the site's layered history. It is a great example of empirical UX research into different emotions triggered by the design of the experience, based on a literature review to inform the hypothesis, a prototype design based on the hypothesis, and a questionnaire design and a test with representative end-users to get their feedback about the experienced emotions.
4. Fort Ontario AR Tour—This is an on-site AR-enhanced self-guided tour in a museum in upstate New York, allowing users to view historical imagery overlaid on physical locations using mobile devices. It is a great example of CW with representative end-users, and simultaneous observational data collection while the end-users do the CW in a real space, with the AR app on a mobile phone. The simultaneous collection of qualitative data (CW data and observational data) and quantitative data with a within-subject statistical DoE is useful; it allows for a rich, multifaceted (i.e., based on qualitative and qualitative data) analysis and deep understanding of both the user experience and measurable task improvement outcomes. A within-subjects design (where each participant experiences multiple versions or conditions) can more accurately attribute differences in user engagement, understanding, or emotional response to the experimental variables themselves rather than who the participants are. This is crucial when developing evaluation methods for cultural heritage XR, as it helps isolate what aspects of the design truly enhance learning, immersion, or cultural appreciation—insights that would be obscured if individual differences were not accounted for.
5. Hanging Gardens of Babylon—This is an AR and VR experience made with the Time Passport app, enabling users to explore a speculative reconstruction of the ancient Hanging Gardens from anywhere in the world. It is a great example of VR making it possible to do things that are not possible in the real world—in this case, visiting a cultural heritage site with artifacts that do not exist anymore in physical form. Additionally, it is a great example of using an A/B test—in this case, comparing an AR version with a VR version in terms of learning retention, with a between-subjects design. A between-subjects design is relevant to cultural heritage CH XR research because it allows researchers to test different versions of an XR experience across distinct groups of users, making it especially useful when the experience itself is likely to have lasting effects or when exposure to multiple conditions could bias participants. In CH XR, where the emotional impact, narrative immersion, or educational outcomes are central, experiencing one version might influence how a user perceives another, making within-subject comparisons less reliable. A between-subjects design avoids this carryover effect and enables cleaner comparisons between different design choices—such as interaction styles, storytelling approaches, or levels of historical accuracy—by ensuring that each participant only engages with one version. This design is particularly important when assessing first-time user impressions, which are often critical in cultural engagement contexts.

6. The Life of a House AR App—This is an on-site AR experience in Tallinn, Estonia, reconstructing the demolished Weigh House digitally with historical context and interactive storytelling. It is a great example of field-based research used to guarantee the ecological validity of the evaluation, and using qualitative data collection from in-depth interviews, with open-ended questions for evaluation with end-users during multiple phases of the development of the app, based on theme-based content analysis.
7. Fountain of the Lions—This is a museum-based interactive 3D experience at the Alhambra, Spain, letting users explore and manipulate a digital twin of the iconic fountain and its inscriptions. It is a great example of adapting the CW method to 3D, with the 3D CW example. It also uses 3D HE, and is already published in a conference paper.
8. CHISel Platform—This is a multi-user 3D annotation tool for experts to document, analyze, and collaborate on the restoration and study of digital heritage artifacts. It is a great example of a complex application still under development, and the use of the CW method, which was specifically developed for early stage evaluations on applications that may not be fully functional and not yet ready for testing with end-users.
9. PLUGGY Platform—This is a cultural heritage social curation platform, potentially Web3-enabled, for users and institutions to co-create and share cultural heritage stories through virtual exhibitions and immersive media. It is a great example of using a carefully created design and evaluation framework that consists of a triangulation of qualitative and quantitative data, i.e., a specially tailored questionnaire which may include the SUS questionnaire, the Net Promoter Score (NPS) questionnaire, and formative and summative evaluations, with multiple end-user types, for the collection of diverse end-user needs.
10. Picasso AR—This is a VR/AR interactive experience in Málaga, Spain, allowing users to engage in virtual dialogue with Picasso and learn about his life in immersive settings. It is a great example of the lean development philosophy and the Design Thinking/Design Doing methodology in action; using the lean MVP pitch deck and lean prototype, the prototype was validated with end-users, competitor analysis, and market research. It clearly demonstrates how a generic method—in this case, the structure and purpose of a pitch deck—must be tailored to fit a specific context or application. While the fundamental elements of a pitch deck remain the same (e.g., a problem statement, solution, market, value proposition, and call to action), the content and style need to be carefully adapted to the particular product or service being pitched.

The ten use case studies are organized into four application scenarios, each defined by its specific user context and technological setting. The In Situ (Museum/On-Location) category refers to applications used directly in museums or other location-specific cultural heritage sites. The In-Home/School category includes applications designed for use at home or in classroom settings, where teachers and learners engage with the content in a gameful manner. The Online Platforms category encompasses experiences accessed remotely via the internet, enabling multi-user collaboration, research sharing, and social engagement from anywhere. Finally, the hybrid pre-/post-visit and on-location category represents emerging XR solutions that combine digital and physical experiences, often incorporating blockchain and Non-Fungible Token (NFT) technologies to enhance cultural engagement and ownership. These four categories reflect key human–computer interaction (HCI) and Human-Centered Design (HCD) considerations, and support phygital experiences that connect digital cultural heritage with physical artifacts, local artisans, and tourism services. Table 2 shows a summary of the methods and maps the ten use cases to their respective scenarios.

**Table 2.** Overview of the ten XR cultural heritage case studies: application scenarios and HCD methods.

| Case Study # | Application Scenario | Application Type | Scenario of Use | HCD and Evaluation Methods (See Appendix C) |
|---|---|---|---|---|
| 1: Chilly Mo | In-Home/School | Entertainment and educational smartphone app, 3D interactive virtual environment of the Louvre Museum | Self-guided tour through cultural heritage events, costumes, sightseeing | Design Thinking process, persona description, medium-/high-fidelity prototyping, expert review |
| 2: Cham Culture AR | In-Home/School | AR smartphone/tablet app with QR cards | Viewing animations of rituals and costumes from ancient stone carvings | Persona description, SUS survey, prototyping |
| 3: Memories of Kellie | In-Home/School | Desktop PC app, 3D interactive virtual environment | Narrative | Persona description, UXUI testing, Agile methods |
| 4: Fort Ontario | In Situ (Museum/ On-Location) | AR smartphone app | Self-guided tour through a CH open air museum | CW with users, usability survey, think-aloud, observation |
| 5: Hanging Gardens of Babylon | Online Platforms | VR and AR educational tool | A/B test of historical learning (AR vs. VR) | Experimental design, memory retention test |
| 6: Weigh House Estonia | In Situ (Museum/ On-Location) | AR smartphone app | On-site visualization of reconstructed building | Theme-based content analysis, EMOTIVE framework, UXUI testing |
| 7: Fountain of the Lions | In Situ (Museum/ On-Location) | 3D computer graphics museum installation | On-site interactive exhibit | 3D cognitive walkthrough, 3D heuristic evaluation |
| 8: CHISel | Online Platforms | 3D collaborative annotation and restoration platform | Expert-only multi-user tool under development | CW with experts, think-aloud protocol, observational data |
| 9: PLUGGY Platform | Online Platforms | Web-based social media curation platform | Create/share CH XR exhibitions | Triangulated HCD framework, SUS, NPS, EMOTIVE, prototyping, expert reviews |
| 10: Picasso AR | Hybrid Pre-/ Post-Visit and On-Location | AR–AI location-based app | Chat with virtual Picasso; hybrid tourism UX | Lean MVP validation, persona interviews, pitch deck, prototype |

By using CH XR technologies, both amateurs and professionals can digitize and upload cultural content into shared XR worlds. This is demonstrated by the CHISel and PLUGGY platform app use cases. These 3D digital assets can then be collected, traded, sold, or reused, offering a marketplace for immersive experiences and interactive storytelling. This is demonstrated by the Chilly Mo and Memories of Kellie app use cases. This novel ecosystem creates new economic opportunities for local tourism activities providers and hospitality providers, such as developing a CH quest related to the Fountain of the Lions, or the Cham Culture app presented here, bringing tourism off the beaten track. This is highly relevant for cultural heritage because novel hybrid phygital CH XR experiences create new opportunities for collaboration between edutainment creators, local CH purveyors, and CH consumers, such as that demonstrated with the Picasso AR app use case. These experiences not only make heritage more engaging and accessible but also link preservation efforts with innovative revenue models, such as ticketed XR exhibits, branded digital content, or location-based AR storytelling. By embedding CH content into immersive, interactive formats, it attracts broader audiences and creates sustainable business models that support local stakeholders. This collaborative, economically viable approach ensures that heritage is not just preserved as static memory but actively lived, experienced, and valued in contemporary culture, such as the Hanging Gardens of Babylon development platform, Weigh House, and Fort Ontario app use cases. There are various stakeholders involved in creating these phygital use cases, requiring various configurations of teams of domain experts to collaborate in cross-disciplinary development team meetings. Together they have to define the user experience and the diverse technologies and cultural heritage assets which are going to be incorporated and how they are going to be experienced by the intended users. A framework for Phygital Cultural Heritage Tourism App Development, proposed to facilitate the collaboration process between the various CH XR domain experts, has been developed and is provided in the Section 4.

## 3. Results

This section presents the design and evaluation process of the ten CH XR HCI use case studies, focusing on the CH XR development and evaluation methods used, and the implementation outcomes. These ten use cases are more than creative applications of XR, AR, VR, Web3, or IoT in cultural heritage—they form a practical guide to applying the full toolkit of Human-Centered Design methodologies to take an idea from spark to system. Each demonstrates different stages of the design cycle and provides real-world examples of how interdisciplinary expertise is used to ideate, prototype, test, and validate.

### *3.1. In-Home/School*

#### 3.1.1. Case Study 1: "The Chilly Mo VR Application"

The Chilly Mo app is a proof of concept. The aim of the Chilly Mo VR application is to create an MVP to demonstrate educational and collaborative DCH experiences. The app aims to be a kid-friendly (i.e., from toddlers onwards) introduction to various cultural costumes and customs through exploring them via virtual museum tours [58] on a smartphone. Chilly Mo is intended to operate via a handheld device and as an interactive edutainment exhibit in the museum. It is designed for use in conjunction with visits to real museums, especially large museums such as the Louvre. It can be used in an individual or in a group setting, and under parental or teacher supervision [58]. The app aims to encourage children to go beyond mere entertainment while playing, and learn about different cultural events and customs. Toddlers, with parental guidance, can use the app to make an account, select their supporting language, select different civilizations, view the stories and costumes, and explore them in the VR environment using their own virtual embodiment (avatar) with the outfit of their choice. They can take virtual selfies in traditional costumes within the app. They can select and explore the different virtual spaces known as salons in the app, which can be viewed via their smartphone screens. Future exhibitions could cover the widest range of civilizations.

The Chilly Mo study used the five stages of Design Thinking/Design Doing—empathize, define, ideate, prototype, and test—to create the MVP and validate the prototype's perceived usability. Chilly Mo development followed the HCD principles, incorporating persona descriptions to represent typical user behaviors and needs [59]. The methodology integrated Design Thinking, which has been previously validated in the scholarly literature [60,61], to actively involve art therapists during the initial stages of feedback evaluation. This approach helps designers align on user characteristics and ensures comprehensive inclusion of user needs, adding depth to ideation discussions.

Extensive secondary research identified fundamental VR principles such as user comfort, intuitive navigation, spatial sound, 3D UI, feedback, and realistic interactions. Figure 1 shows some screen impressions. Usability testing refined the conceptual UXUI, and these results and the tested MVP were presented at academic conferences [23]. The design choices for the UI were based on research of interactive games for toddlers, integrating VR with user-friendly smartphones. Chilly Mo's design began with research on the benefits of interactive gaming in toddler learning, leading to an early-stage prototype using a Design

Thinking approach. The Chilly Mo app is utilizing some of the benefits of interactive gaming in toddler learning, and explorative learning in VR, to guide the use of their time and energy positively using the following concepts:

- VR applications enable exploring inaccessible historical sites and cultures [62].
- VR software experiences and gamification can effectively assist users in changing behavior and help them achieve desired positive behavior [61].
- VR experiences can help reduce anxiety in young children [63].


**Figure 1.** Mockups of Chilly Mo VR app smartphone screens to explore and show the design ideas for the "look & feel" of the app [6].

User Interactions

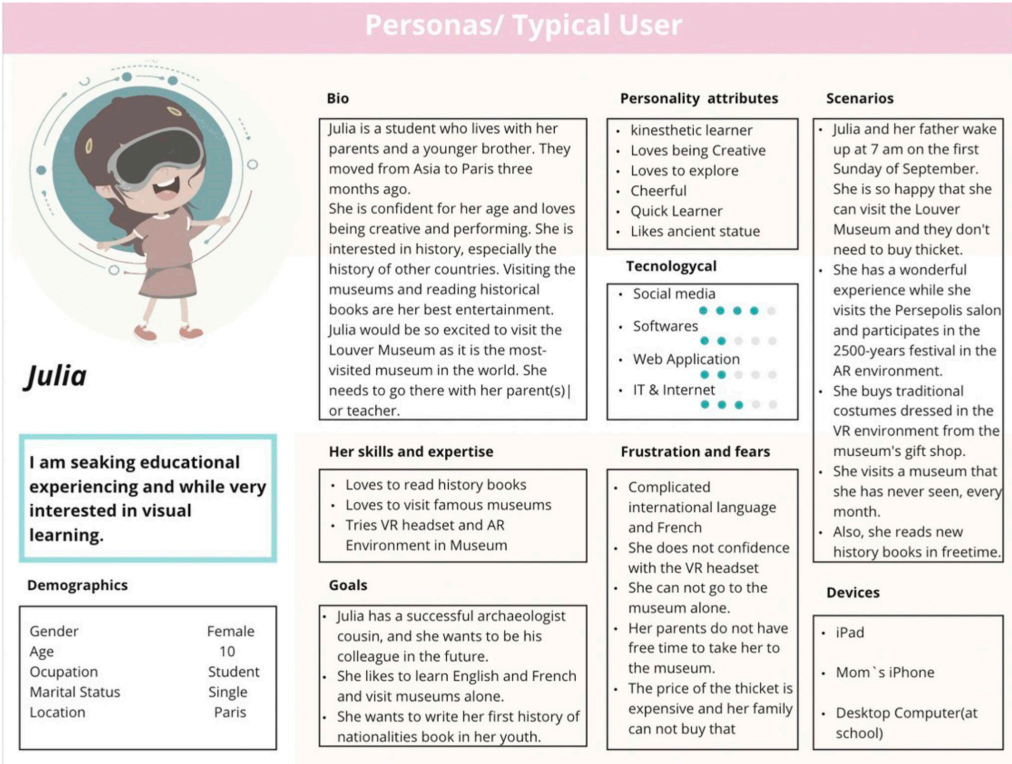
Chilly Mo applied user-centered design principles through the development of detailed persona descriptions representing typical toddler users, aiming to clearly identify their needs and behavioral patterns [36]. This approach provided a precise understanding of the target audience and guided the design to suit their specific developmental context.

This approach supports a shared understanding of user needs and enhances design authenticity. Personas provide detailed visual profiles—including demographics, goals, skills, and usage scenarios—that help tailor solutions to target audiences (see Figure 2).

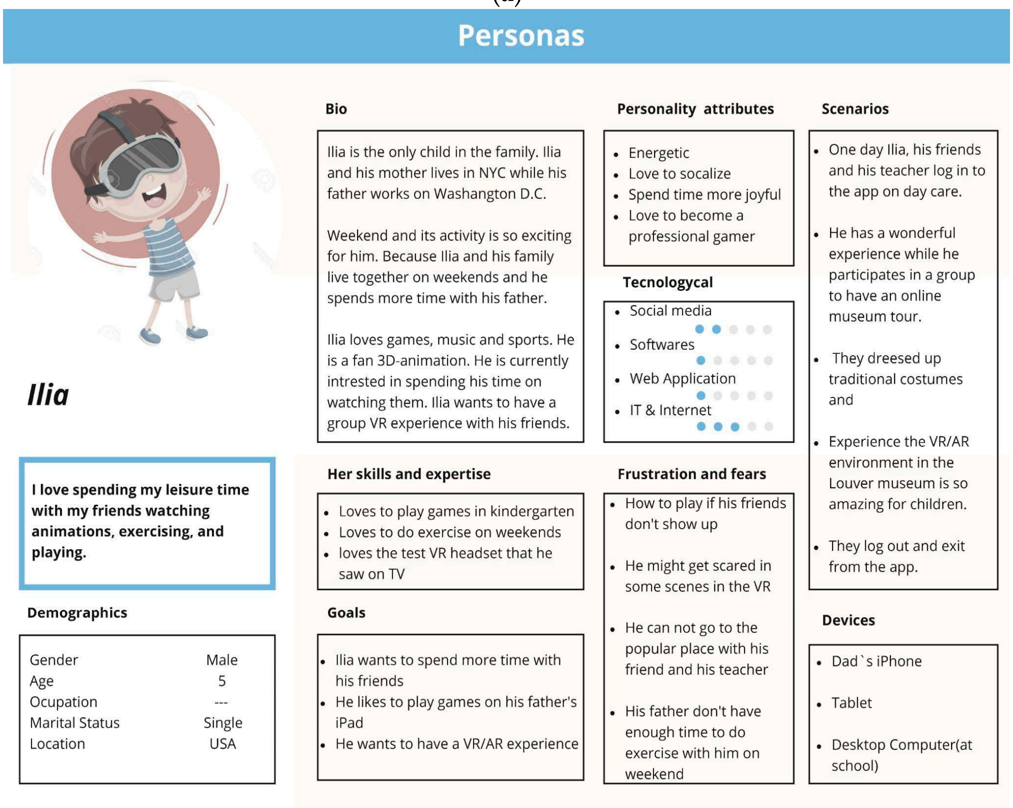
For the example User Task Analysis, see Table 3, representing the Hierarchical Task Analysis (HTA). Users sign up for the app, requiring parental guidance for toddlers.

**Table 3.** The Hierarchical Task Analysis.

| Task Step | User Needs | User Limitations |
|---|---|---|
| Arrive at the Louvre Museum | - Children need their parents or guardian to accompany them | - Children cannot visit the museum alone<br>- The price of a ticket |
| Arrive at Persepolis salon | - Users need the visitor's guide | - Visitor's guide does not work well, especially on busy days in the Louvre Museum<br>- Generally, the Louvre Museum is crowded |
| Connect to an AR environment | - Connect easily and quickly<br>- Shapes and text must be clear | - Some disabled visitors cannot hear or see<br>- Different learning rates of visitors |
| Enter the AR/VR environment | - Set data/pictures with the AR environment<br>- Convey emotional senses from the AR environment<br>- High quality of 3D space and characters | - Different quality levels of 3D space |
| Exit | - Finish the program<br>- Release | - Time over<br>- Tiredness |




(a)

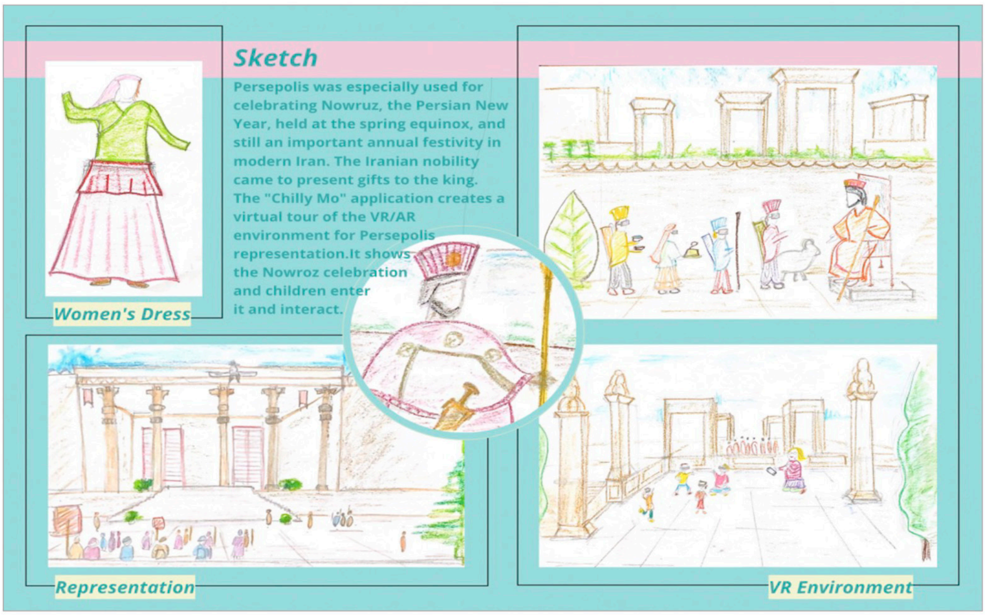



(b)

**Figure 2.** Persona descriptions for the Chilly Mo VR app: (**a**) represents a typical user, and (**b**) an atypical user [6].

For the Chilly Mo VR app demonstrator, it was decided to limit the number of civilizations to be developed to the Nowruz event from Persian culture as a first example. First, a mood board (see Figure 3a) and sketches (see Figure 3b) were created [58].


(**a**)

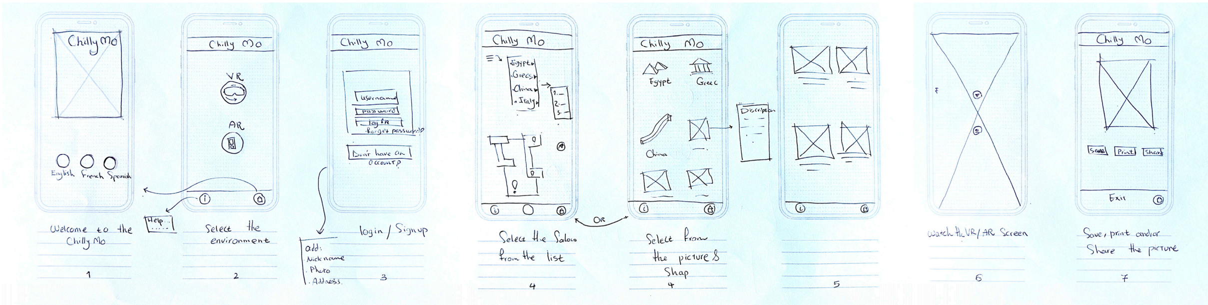



(**b**)

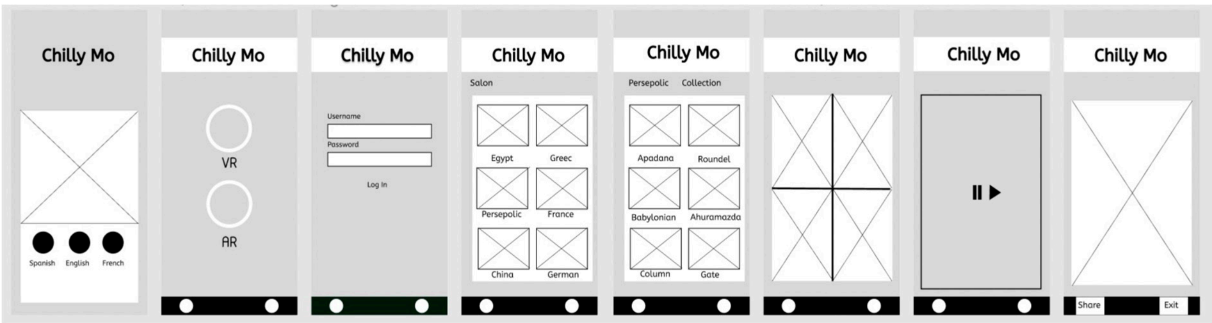
**Figure 3.** The moodboard (**a**) and the sketches (**b**) for the Chilly Mo app design [6].

The initial concept for Chilly Mo features a scene from the Persian Nowruz Festival. Characters in this scene explore the historic "Persepolis Complex" in an interactive VR game. They set up Haft Sin, symbolizing the Persian New Year, while dancing and reading poems with other characters (see Figure 4c).

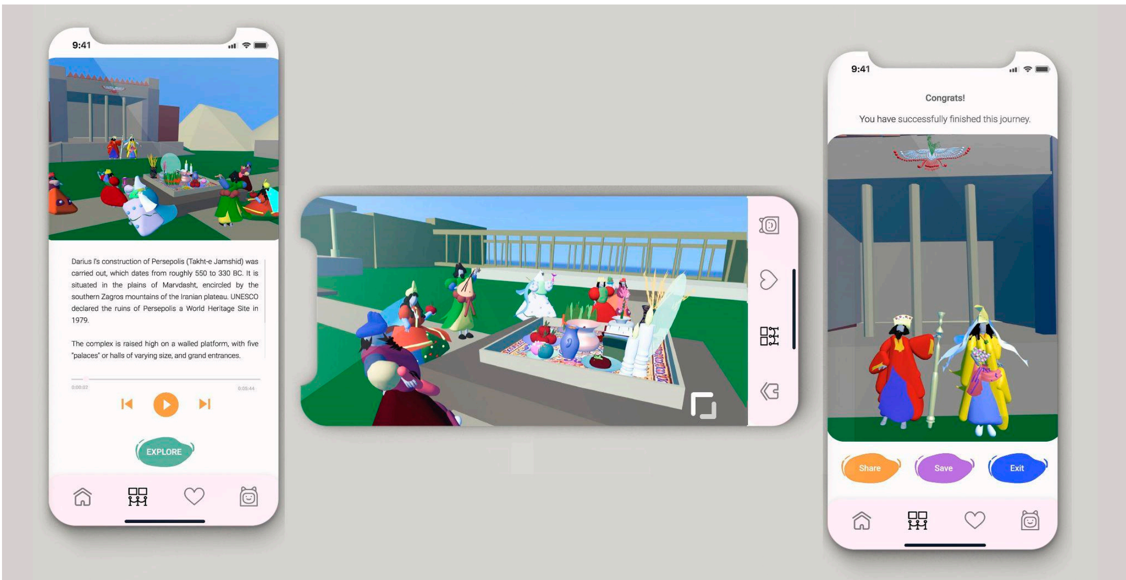
Design tools like Figma, Gravity Sketch, and VR-based 3D modeling were used to create the mockups and the virtual environment [58]. Figure 4 provides an impression of the first prototypes from the different phases of the development process: phase 1: sketches of the UX on paper with a template of the smartphone screen (see Figure 4a); phase 2: digital 'wire-frames' of the UI (see Figure 4b); and phase 3: visualization of the XR scene(s) (see Figure 4c).



(**a**)




(**b**)




(**c**)

**Figure 4.** Prototyping phase 1 (**a**), phase 2 (**b**), and phase 3 (**c**) [23].

Evaluation Method and Results

As the Chilly Mo app was conceived as a proof of concept, validating the proposal with feedback from potential end-users becomes imperative. The aim is to gauge opinions regarding the value of an CH XR edutainment application. This kind of market validation data is important in support of applications for commercial product investment at fundraisers.

The Chilly Mo app was evaluated using interviews with pre-prepared questions and answers. Table 4 presents an example of the interview questions. Employing semi-structured interviews and questionnaires can be instrumental in obtaining comprehensive insights into the app's pros and cons. Insights from users engaged with the prototype in real-world scenarios are collected via direct interviewing and follow-up meetings. The data analysis encompasses both quantitative and qualitative analyses, involving coding and categorizing the collected data according to any observed patterns. This analytical process aims to unveil any challenges faced by users and discern their desires, contributing to a nuanced understanding of the user experience with the application.

**Table 4.** The interview questions for the Chilly Mo app MVP user validation [23].

| Interview Question | Interview Answer |
|---|---|
| What colors do you like the most for museum application? | Green, Pink, Orange, Blue |
| Do you like to travel to the past and see traditional ceremonies movies? | Yes, No |
| Do you like to be a king/queen or a soldier while you can dress up their customs and play their role? | King/queen, Soldiers |
| Which one is your choice? Wearing a headset and participating in a traditional movie or using your tablet and watching the same movie? | Wearing a headset, Using a tablet |
| What is your mother language? | Spanish, French, English, Others |
| Do you like to use the Chilly Mo app in a group in your kindergarten or individually at home? | In a group, Alone |
| Which part is your favorite? Coloring a painting in VR or participating in a new year party in VR | Participating in a party in VR, Coloring a painting in VR |
| How much experience had you before with VR or AR? | One time, 2 or 3 times, More than 10, Several times |
| What do you like to do when you wear a headset? Painting, dancing, parade | Painting, Dancing, Parade |
| What do you feel (what do you want to see) when you walk and visit an ancient stony town with magnificent palaces? | Learning, Fun, Boring |

#### 3.1.2. Case Study 2: "The Cham Culture AR App"

The Cham Culture AR app (demo video available at https://youtu.be/5iuNeLzh8OA (last accessed on 1 July 2025)) was created as a proof of concept to showcase how smartphone AR can showcase ancient Cham cultural dance and artifacts, animating scenes from a Cham temple relief displayed in the Cham Museum, Da Nang, Vietnam. The app includes accurate music, dances, clothing, and coloring [64]. The Cham people, a Southeast-Asian ethnic minority, saw a decline in the 14th century, leading to cultural erosion. The app uses QR codes to trigger animations on smartphones, preserving Cham traditions for young audiences. Mỹ Sơn, a famous Cham site, became a UNESCO world heritage site in 1999.

##### User Interactions

The AR app is driven by QR codes on small paper cards which trigger animations visible on the device's screen when aimed at the QR code. Users can move the QR code cards around to manipulate the scene. The animations include audio tracks with authentic music. An 11th century sandstone relief found at Mỹ Sơn inspired the initial development, depicting musicians and dancers still used by the Cham during rituals and festivals. This AR app helps preserve and share Cham cultural heritage by making it accessible to a young audience through smartphones. Szentirmai and Murano [65]'s seven Universal Design (UD) principles for mobile AR interfaces (see Table 4) were used for the evaluation and an Acceptance and Opinion survey was conducted, using a tailored version of the international SUS. Persona descriptions were created to inform the choices for the best UXUI design solutions.

The Cham culture AR app is aimed at cultural heritage teachers, students, and museum visitors, allowing them to create animated scenes, using QR codes on palm-sized cards. Scanning these QR codes with a smartphone or tablet triggers 3D figures or artifacts and audio. Users can manipulate the on-screen artifacts, derived from Cham stone reliefs in the museum (see Figure 5). The app provides detailed text information and allows zooming and movement of artifacts on the device screen.

(**a**)

(**b**)

**Figure 5.** Cham Culture stone carving (**a**) and Cham Culture AR app (**b**).

Evaluation Method and Results

The user requirements specification was based on a triangulation of user needs data: the SUS, the UD evaluation, and the persona descriptions. The goal of this early stage fully functional prototype was to create a MVP to assess acceptance and opinions of potential end-users and attract investors. Intended end-users include teachers, students, scholars, museum visitors, and tourists of all ages. A persona description was created to clarify typical end-user types, including goals, background, and behaviors.

Szentirmai and Murano [65] identified a lack of guidelines for AR design and evaluation, created seven Universal Design (UD) principles for mobile AR interfaces (Table 5, first column, shows the seven UD heuristics). They tested these new heuristics on educational AR apps, finding them effective in identifying usability flaws, addressing gaps in existing guidelines.

The seven UD principles' heuristics were applied to the ChamAR app, yielding the usability findings and a severity score which can be seen in the final column in Table 5. Using a 1–5 scale (1 being serious, and 5 being cosmetic), the app scored 32/35. This summative score helps prioritize usability issues.

The acceptance and opinions survey was conducted using the SUS. Sixteen participants (nine females and seven males) completed the survey, resulting in an average SUS score of 71/100. An online SUS survey was customized for the app, collecting demographic details and usability feedback from DCH teachers and developers. Invitations were sent via Facebook 3D developers and VR/AR chat groups. The respondents represented diverse end-users like teachers, students, and tourists. The survey collected 16 responses over two weeks. The average SUS score of 71 indicated good usability. Open-ended feedback highlighted the app's interactivity and engagement but noted concerns from older users about adopting new technology. Further research with more diverse age groups is needed to understand these issues in depth. Persona descriptions were created to clarify user types and backgrounds, including goals, behaviors, and needs.

**Table 5.** Universal Design Principles for AR design and evaluation, and their seven heuristics by Szentirmai and Murano, applied to the Cham AR app [65].

| AR Heuristics | User Interaction | Action Result | Issues | Score |
| --- | --- | --- | --- | --- |
| Equitable Use | Multimodal: Visual figures, auditory music. | Inclusive accessibility for diverse users. | None | 5 |
| Flexibility of Use | Supports handheld/table use; adaptable to different scenes. | Adaptable to user needs and environments. | None | 5 |
| Simple and Intuitive Use | QR codes control figures; inbuilt tutorials. | Easy, intuitive interaction; potential for information overload. | Information overload unclear | 3 |
| Perceptible Information | Virtual figures aligned with QR codes; labeled interface. | Clearly perceptible; distinguishable elements. | None | 5 |
| Tolerance for Error | Hand blocking pauses figure; potential for undo. | Self-correction evident; prevention and warnings needed. | Unclear alert and notification system | 4 |
| Low Physical Effort | QR code manipulation with simple gestures. | Controllable without complexity. | None | 5 |
| Size and Space for Approach | QR codes and elements comfortably reachable; scalable for devices | Comfortable reach and manipulation. | None | 5 |

Conclusion of Case Study 2

Three HCI methods were used to be able to collect mutually informative, complementary usability feedback: persona descriptions to understand end-users, heuristic evaluations using UD principles for mobile AR, and SUS surveys for quantitative and qualitative data. The heuristic evaluation and user opinions provided clear insights into usability and desired improvements. The final scores from both methods allowed for easy comparison of usability across design iterations. Early results were published at an international VR conference [66].

#### 3.1.3. Case Study 3: "Memories of Kellie"

Many cultural heritage projects use creative technologies to convey information about artifacts and locations, with varying success [67–70]. Ensuring a robust lifecycle of design and testing is essential [71–73]. "Memories of Kellie" was developed at the Glasgow School of Art to explore using interactive narratives for DCH. It is a 3D application for desktop PCs, digitally representing Kellie Castle and Gardens in Scotland, reflecting its historical evolution from 1150 AD to the 1970s [74].

User Interactions

The project included a literature review on interactive digital technology and narrative for DCH, identifying design principles and audience needs for engaging applications [75–82]. "Memories of Kellie" aimed to deliver emotive, contextualized narratives through a visually appealing interface, engaging users with interaction.

The prototype was built using Unity®, and featured a dynamic interface, audio soundscape, and interactive digital environment (Figure 6). Narrative elements were conveyed through interactive panels, revealing historical information as users explored the environment, aided by prompts and feedback mechanisms.


**Figure 6.** Four screenshots from the Memories of Kellie—desktop VR application [83].

Evaluation Method and Results

The application was tested by 16 users of varying ages and technological confidence. After using the application for about 10 min, participants completed a questionnaire assessing the design themes' goals and their impact on the user experience (see Table 6). Design principles were categorized into four themes: design fundamentals, functionality, storytelling, and atmosphere. Fifteen out of sixteen participants found the application intuitive and appropriately timed, with suitable content levels. Most feedback for improvement focused on the storytelling aspects, such as the information format and animation pace. Overall, "Memories of Kellie" was engaging, with 14 participants expressing a desire to visit the site after using the application.

The open ended final question received some interesting responses:

Q19: Is there anything else you would like to add about your experience of using Memories of Kellie?

> *"No other than to note again that I hadn't heard of Kellie before, and I would now like to visit"*
>
> *"Absolutely loved it! Loved the fairytale/dream feel to it, thought it made it seem more like a memory and less like a history lesson"*
>
> *"Would love to see it evolve into a less linear version with more interaction"*
>
> *"Really enjoyed it and felt I learned something"*
>
> *"Can't wait to visit the actual place in real life!"*
>
> *"Would have loved to see the interior of the Castle to add to the experience"*
>
> *"It said there was a picture inside the castle, I would like to know what else I could see inside"*
>
> *"I would like to see a more accurate garden and the inclusion of greater detail in the information"*
>
> *"It is a good advert for the Castle, and I can't wait to visit again!"*
>
> *"It is a taster for better things to see—a good advert for the castle and grounds"*

**Table 6.** User testing responses to quantitative questions.

| | | | Age | | |
|---|---|---|---|---|---|
| | | Total | 16–25 | 26–50 | Over 51 |
| How do you feel about the length of Memories of Kellie? | Too short | 1 | 1 | - | - |
| | About right | 14 | 3 | 4 | 7 |
| | Too long | 1 | - | 1 | - |
| What did you think about the level of information presented? | Not enough | 3 | 1 | 1 | 1 |
| | About right | 13 | 3 | 4 | 6 |
| | Too much | - | - | - | - |
| Do you think the information was relevant? | Yes | 15 | 3 | 5 | 7 |
| | No | 1 | 1 | - | - |
| Do you feel you learned anything new? | Yes | 15 | 3 | 5 | 7 |
| | No | - | - | - | - |
| | Not sure | 1 | 1 | - | - |
| Did you want to continue through Memories of Kellie until the end? | Yes | 16 | 4 | 5 | 7 |
| | No | - | - | - | - |
| | Not sure | - | - | - | - |
| Did you find it easy to use? | Yes | 15 | 4 | 5 | 6 |
| | No | - | - | - | - |
| | Sometimes | 1 | - | - | 1 |
| Did you understand what you needed to do? | Yes | 15 | 4 | 5 | 6 |
| | No | - | - | - | - |
| | Sometimes | 1 | - | - | 1 |
| How much did you enjoy using Memories of Kellie? | Not much | - | - | - | - |
| | Somewhat | 1 | 1 | - | - |
| | A lot | 15 | 3 | 5 | 7 |
| Would you like to visit Kellie Castle and Gardens after using Memories of Kellie? | Yes | 14 | 4 | 3 | 7 |
| | No | - | - | - | - |
| | Not sure | 2 | - | 2 | - |

Conclusions of Case Study 3

The project successfully communicated historical information and enhanced engagement with the cultural heritage site through a narrative. Feedback indicated areas for future development, such as mobile deployment, AR incorporation, and ongoing content optimization. The full project report is a master's thesis.

### *3.2. In Situ (Museum/On-Location)*

#### 3.2.1. Case Study 4: "The Fort Ontario AR Experience"

Fort Ontario, founded in 1755 in upstate New York, served various military roles and sheltered Jewish refugees during WWII [84]. Now a State Historic Park, visitors explore its history through self-guided tours and iPad displays in the Enlisted Men's Barracks. Recognizing the need to enhance visitor experiences, the project investigated AR technologies to integrate historical photos from the 1860s to recent events, enriching the understanding of the fort's extensive history and allowing the public to view archival photos in context while exploring the site.

User Interactions

The project aimed to enhance the Fort Ontario experience using AR. An AR version of the self-guided tour booklet was created, with high-resolution photos of mapped areas. Developed with Artivive, the AR app allows visitors to point their smartphones at booklet photos to view historical slideshows while exploring the fort grounds (see Figure 7).

**Figure 7.** Using the AR application at Fort Ontario.

Interactive items in the AR app interface provide additional historical information and access to the Fort Ontario website. This enhances the visitor experience by allowing them to view historical information in context on-site. The app functions as a visual extension of traditional audio tours, making history come alive through interactive and immersive AR technology.

Evaluation Method and Results

The self-guided AR tour was evaluated through a cognitive walkthrough (CW). In this case, the CW method was used with real end-users. The CW was focused on the first four points in the guidebook to identify usability issues. Conducted on-site at Fort Ontario, the method assessed each task step and user interface interaction, generating the typical CW's quick, low-cost feedback [85]. The within-subjects design ensured all participants experienced the same AR tour, while still collecting data to compare.

User feedback highlighted problems like difficulties using the app in windy weather and challenges for users with arthritis. Despite 80% of participants being new to AR, they found the instructions easy to understand. All participants liked the app and would use it again. The developer felt that the evaluation provided valuable insights for future improvements.

Conclusions of Case Study 4

The AR application at Fort Ontario enhanced the visitor experience by allowing personalized content access. This flexibility improved engagement and satisfaction, suggesting potential for increased visitor traffic and site revenue [86]. The self-guided AR tour is now live, providing a richer historical exploration. The full development and evaluation report is a master's thesis [87], and the student won a prestigious student prize for their project.

### 3.2.2. Case Study 6: "The Life of a House"

The Weigh House, located in Old Town Tallinn, Estonia, was a key economic building constructed in 1554 and listed as a UNESCO World Heritage site. Severely damaged in 1944, it was demolished in 1946. Archaeological excavations in 2007 revealed fragile foundations, marked in the Town Hall Square pavement [88]. Interest in its history persists. AR can provide immersive experiences, enhancing public awareness by visualizing the site's original state and promoting understanding through interactive narratives [89,90]. Further research is needed to optimize AR for engagement and learning.

User Interactions

The project aimed to create an AR tour-guide app for the Weigh House in Tallinn, enhancing engagement and learning about the city's architectural past [91]. The "Life of a House" app, developed for Android using Unity® and Vuforia®, offers an interactive journey through the Weigh House's history with 3D models and archival images. The app overlays digital reconstructions onto real-time views of the site, encouraging users to explore and connect physical artifacts with the historical context, thereby enhancing their emotional impact and memory retention. Figure 8 shows the digital reconstruction of the Weigh House.

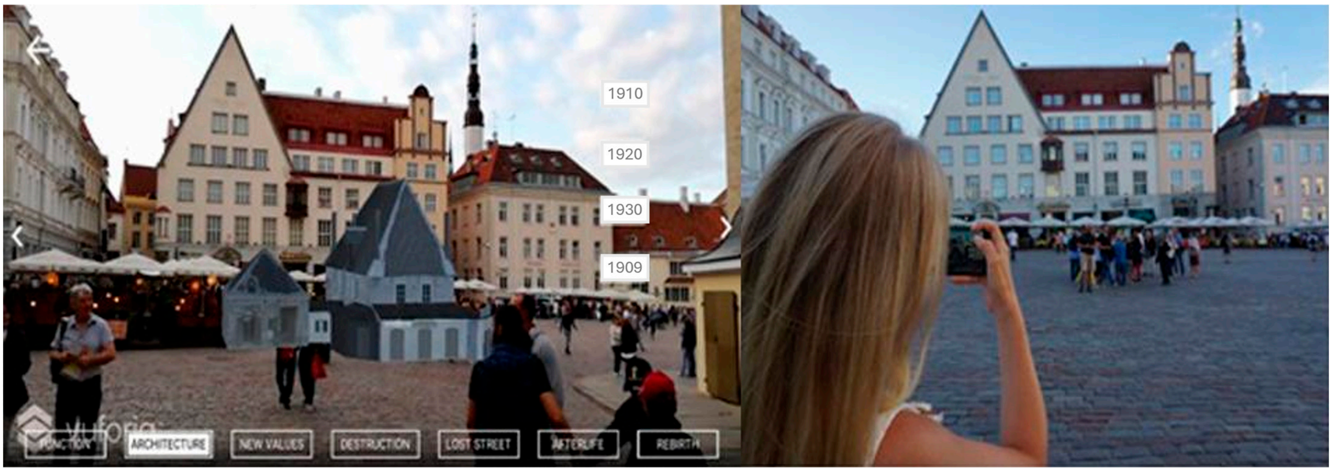



**Figure 8.** Using the "The Life of a House" application on Old Town Tallinn's Town Hall Square.

Evaluation Method and Results

The application was tested in Tallinn's Town Hall Square with ten adult AR novices, including locals and tourists. They used a pre-installed Huawei P20 Lite smartphone for the study, which included three phases: pre-screening, a self-directed trial, and a post-testing interview. Observations during the trial noted the usability and engagement with the app's content. The interview used seven open-ended questions based on Farrell's guidelines and the EMOTIVE Evaluation Framework [92,93]. Theme-based content analysis [94] structured and interpreted the interview data into higher and lower order themes.

Conclusions of Case Study 6

Participants understood the interface but found some indicators confusing, mistaking them for buttons. The AR overlay was well received, though clearer instructions and reduced jittering were needed. Participants appreciated the self-paced exploration and found the AR feature helpful for visualizing the Weigh House's original location and dimensions. They recalled historical facts better than architectural details. All participants suggested that similar AR technology in archaeological sites or museums would aid information retention. The full report can be found in the student's master's thesis [91].

#### 3.2.3. Case Study 7: "Fountain of the Lions"

The Fountain of the Lions is a 3D model of a fountain in the Court of the Lions at Alhambra, a UNESCO World Heritage Site. Developed by computer science and history researchers at the University of Granada, the software uses data from before and after restoration [95–97]. It helps visitors understand the conservation process, allowing them to interact with the model, view inscriptions, and adjust perspectives (Figure 9). The application runs on a PC with a touch-screen monitor and a 3D Power Wall system for immersive interaction [20].


**Figure 9.** Demonstrating the navigation around the Fountain of the Lions.

User Interactions

Users interact with the software by moving the point of view around the virtual artifact space. Wearing motion sensors and geolocation sensors in a VR headset, users control the viewing angle. The Power Wall system also has similar sensors. The interaction includes selecting and turning statues or inscriptions using a mouse or game controller. Zooming adjusts the viewing angle. On a touch screen monitor, users navigate using arrow icons, touch, and drag gestures, and pinch to zoom. Sub-menus and transcription screens allow detailed interaction with the 3D model.

Evaluation Method and Results

The evaluation assessed the user experience of museum visitors using the touch-screen display. Both qualitative and quantitative evaluations were conducted to gather subjective and objective data. Three methods were used: persona descriptions to understand typical users, a 3D cognitive walkthrough (CW) with expert evaluators to identify task flow issues, and a standard heuristic evaluation for benchmarking design principles [98,99]. Seven tasks were assessed with the 3D CW, which allowed for a rich insight into the step-by-step activities of the user interacting with the 3D app: 1. navigating the environment in View Mode; 2. viewing and manipulating an individual lion statue in Detail Mode; 3. selecting the fountain; 4. selecting the engraving; 5. selecting Compare; 6. selecting Other Time;

and 7. selecting About and Home. The evaluation provided the following data for design improvements, presented in the order in which the HCI methods were applied:

1. **User Persona Descriptions:** The application leverages user enthusiasm. A suggested improvement is to introduce a screenshot feature with social media sharing functionality to increase awareness and publicity for the heritage site.
2. **3D Cognitive Walkthrough**: Numerous user errors were identified. Recommendations include implementing more common touch-screen mobile interaction standards, such as two-finger zoom and pan, and single-finger tap-to-select.
3. **3D Heuristic Evaluation**: The software was aesthetically pleasing with a minimalist design and consistent color palette. It provided robust error recovery and a rich feedback system, allowing users to understand and correct mistakes easily.

Conclusions of Case Study 7

The HCI evaluation of the Fountain of the Lions application, developed by University of Granada students and employees, identified areas for improvement and highlighted successful features. Key areas for enhancement include navigation, feedback and visible cues, documentation, and language translation. The usability methods used—persona description, the 3D cognitive walkthrough presented above, and 3D heuristic evaluation—were found to be complementary and suitable for this development stage. The full results on the 3D CW are described in the student's HCI master's project report, and the 3D HE results are published in a relevant journal [100].

### *3.3. Online Platform*

#### 3.3.1. Case Study 5: "The Hanging Gardens of Babylon"

AR companies, traditionally game developers, are exploring its educational uses. History education benefits from AR, making intangible events and locations more interactive. Time Passport Inc. specializes in historic AR applications, allowing users to explore historical sites virtually. Their first release, the Hanging Gardens of Babylon, brings this lost wonder to life, enabling global access (Figure 10). This project aims to demonstrate AR's potential for immersive educational experiences and to pave the way for future apps tied to specific historical locations.


**Figure 10.** Time Passport's The Hanging Gardens of Babylon.

User Interactions

AR and VR technologies enhance information retention through interactive stimuli like sound, sight, and touch, aiding learning, tourism, history, and cultural awareness. AR offers richer interactions than conventional interfaces, expanding the capabilities of devices like smartphones and wearables [101,102]. Unlike VR, AR supplements rather than replaces reality, overlaying digital information onto the real world. This integration helps users better understand and absorb information, making AR a valuable tool for various educational and experiential applications.

Evaluation Method and Results

The evaluation aimed to collect data on the usefulness of the Hanging Gardens of Babylon AR app for learning retention, comparing it to a VR app. The study hypothesized higher retention with AR and VR compared to traditional tools, and higher retention with VR over AR [101–106].

Using an A/B test design, participants were divided into two groups: group A (AR) and group B (VR). Each group completed seven tasks and a comprehension quiz to assess memory retention. This method allowed for a direct comparison of learning retention between the AR and VR conditions.

Conclusions of Case Study 5

The study evaluated historical knowledge retention using the Hanging Gardens of Babylon app developed with Time Passport's AR and VR platforms. The results indicated better retention with AR compared to VR, contradicting prior research that favored VR for education. Both AR and VR showed significant learning retention, highlighting their advantages over traditional methods. AR's effectiveness in educational settings is supported by this and other studies [107]. The full results can be found in the student's HCI master's project report [108].

### 3.3.2. Case Study 8: "The CHISel Platform"

The Cultural Heritage Information System (CHISel) is a multi-user 3D annotation system developed at the University of Granada, Spain [109,110]. It enables cultural heritage researchers to manage the spatial relationships of artifacts and restoration data. CHISel handles non-geo-referenced information, organizing it in layered sets referencing points on the artifact's surface. Users can edit, render, query, compose, and analyze the 3D replicas of artifacts. The system features include organizing and communicating various data types on the model, and adding and editing visible layers, colors, and text to facilitate teamwork and research [111] (see Figure 11).

User Interactions

CHISel users can create and annotate extended information layers on 3D models of archaeological artifacts, linking data to any part of the model's surface. The model can be enlarged or rotated for improved inspection and analysis. Sections can be color-coded and labeled for collaboration and future reference. The software supports the storage and sharing of extensive data, crucial for preserving restoration processes. Multi-user collaboration is facilitated by ensuring consistency and accuracy across all functions, requiring standardization for effective data tracking and manipulation.

Evaluation Method and Results

The evaluation aimed to perform a usability study of the CHISel interface of the first working prototype. The focus was on accuracy, user-friendliness, effectiveness, and efficiency, rather than user attitudes. The software, still in development, was assessed by trained HCI evaluators due to its complexity. Key usability factors included a low learning curve, domain-specific usability, system feature complexity, and multi-user collaboration. A cognitive walkthrough was chosen to evaluate learnability and system functionality. Four representative users tested the system, providing detailed observational and verbal data on user perspectives.

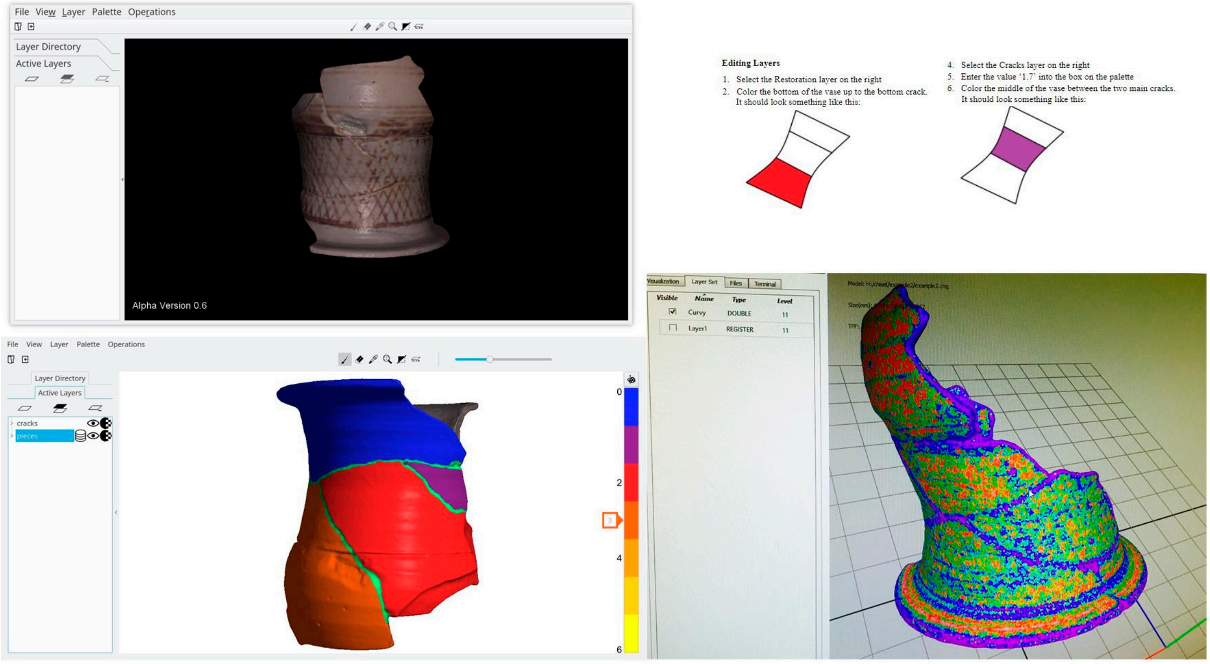



**Figure 11.** Showing the geometry and roughness of an artifact in CHISel.

Conclusions of Case Study 8

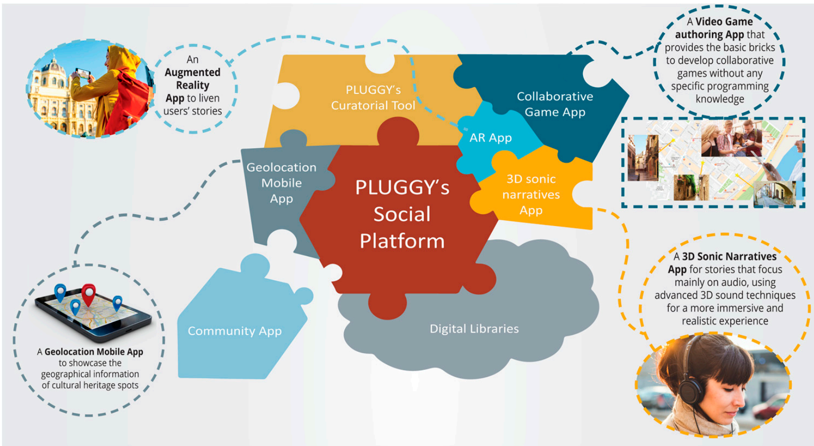
Several usability issues of varying intensities were identified for tasks such as model preparation and layer creation (Table 7). Design improvements were identified from feedback during cognitive walkthroughs. The method provided insightful data on task effectiveness with the application interface. Lessons were learned on preparing for evaluations, running the CW with real participants, and handling the rich information provided. The full description and results can be found in the student's HCI master's project report and the usability findings are published in a relevant journal [112].

**Table 7.** Compilation of usability issues and issue types found, organized by topic.

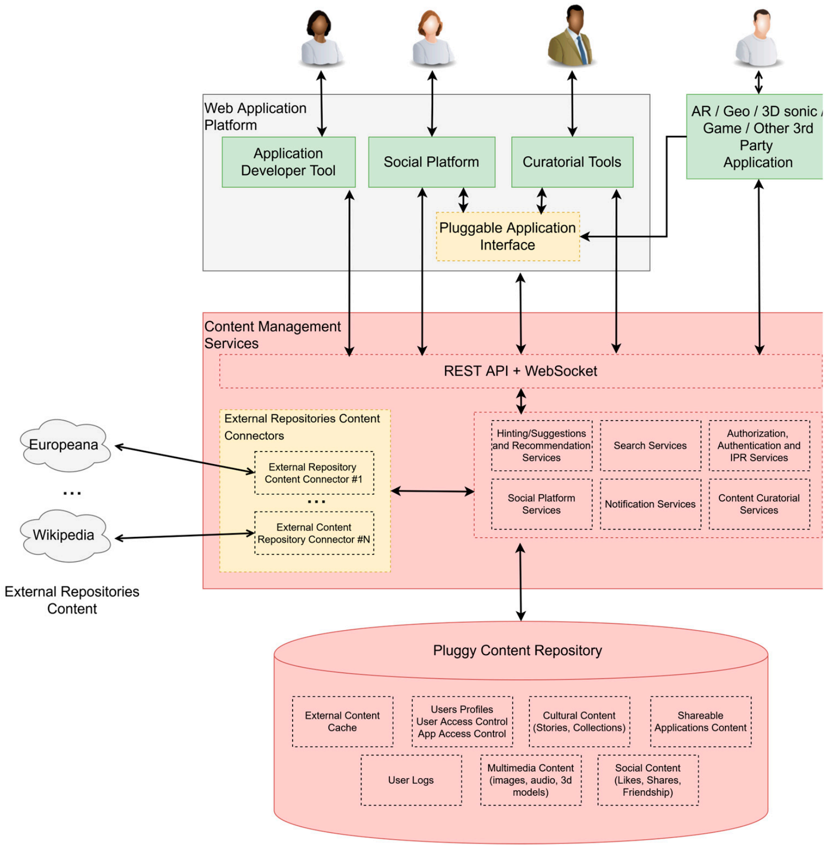
| CW Task | Issues Found | Usability Issue Type |
|---|---|---|
| 1. Model Preparation | - User must use keyboard arrows to adjust resolution<br>- Unnecessary bold text<br>- No difference between "chg" and "achg" file types for saving<br>- Saving to a folder creates extra step<br>- Frequent saving errors<br>- Unnecessary "ok" button<br>- "Loading triangles" message holds no meaning | - Font/visual crowding<br>- Consistency<br>- Navigation<br>- Efficiency<br>- Feedback |
| 2. Creation of Layers | - Many clicks required on "name box"<br>- Uncertainty of saved values<br>- "Size box" name ambiguous<br>- "Ok" should be changed to "save"<br>- Pop-up window disruptive to view of model<br>- Presence of pen tip is assumed for coloring mode and not rotation of model | - Minimal click rule<br>- Feedback<br>- Labeling/meaning<br>- Feedback/error prevention<br>- Pop-up<br>- Feedback/for correct use<br>- Efficiency/training |

### 3.3.3. Case Study 9: "The PLUGGY Platform"

The PLUGGY platform, developed during the EU-funded project [113], aims to revolutionize engagement with cultural heritage by enabling users to be active creators and curators. Unlike other heritage tools, PLUGGY empowers users to share their cultural heritage via virtual exhibitions, virtual museums, and digital collections (Figure 12). Users can upload high-quality images, videos, text, 3D models, and audio through pluggable applications. The Curatorial Tool allows the creation of curated stories that are accessible via mobile interfaces like augmented reality and geolocation. PLUGGY's source code is open source, encouraging third-party development.




(**a**)

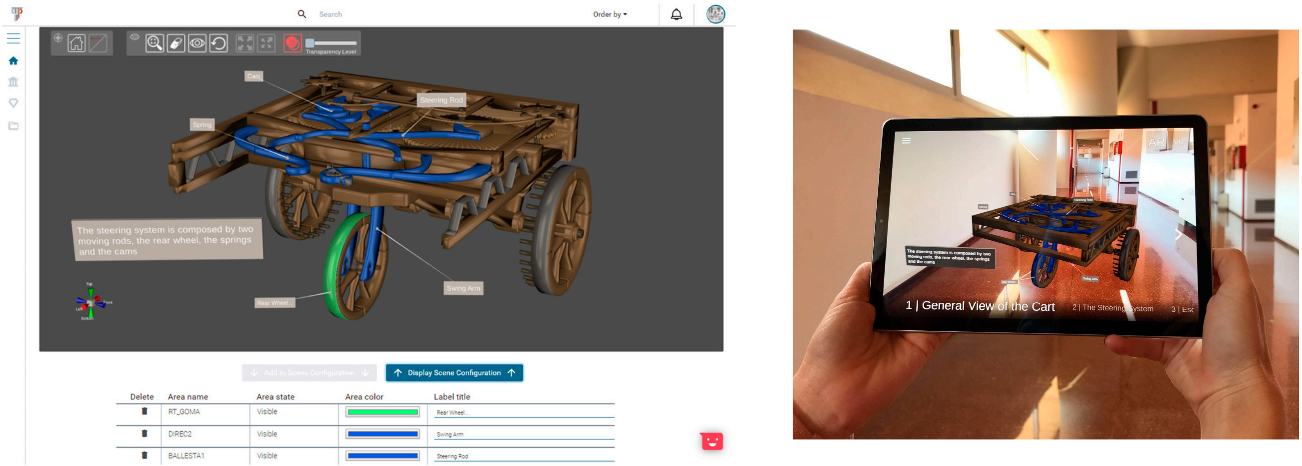



(**b**)

**Figure 12.** (**a**) Storyboard for the PLUGGY platform for social media-curated cultural heritage [114]; (**b**) PLUGGY platform architecture [113].

User Interactions

PLUGGY provides two main entry points, the project webpage and the PLUGGY Social Platform, fostering user engagement with cultural heritage. Users can create immersive experiences through curatorial tools and social networking capabilities, combining their content with knowledge from cultural institutions. The modular PLUGGY architecture supports future application development via an API, managing media assets and curated exhibitions. Users can create various exhibition types, including Media Stories, Timelines, and augmented reality (Figure 13). Social interactions include following, likes, comments, and real-time notifications.




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

**Figure 13.** Screenshots of a wooden cart modeled with the PLUGGY VR (**a**) and AR (**b**) apps.

The collaborative PLUGGY project involved collaboration between nine partners, combining the partners' respective expertise from multiple disciplines. Evaluations included interviews, field studies, and usability testing, ensuring comprehensive feedback and a robust final product.

Evaluation Method and Results

PLUGGY's development included meticulous formative and summative evaluations (see Table 8). The objectives were to establish evaluation protocols, perform iterative formative evaluations, and conduct summative evaluations on heritage awareness and participation [115]. These were grounded in a triangulated methodology, combining qualitative methods, quantitative methods, and infrastructure metrics, to ensure both usability and long-term cultural impact. This multifaceted approach enhanced the credibility and applicability of the results by drawing on complementary data sources and evaluation perspectives.

Conclusions of Case Study 9

In summary, PLUGGY is a pioneering platform that engages users in cultural heritage activities, fostering heritage-centered networks and connecting users with cultural institutions. It emphasizes personalization and community engagement, transforming society's relationship with cultural heritage and exemplifying best practices in user research and development. Persona descriptions guided platform requirements, particularly in helping users choose appropriate licenses for uploaded content. Detailed evaluation results are not provided here, though interested readers can contact Dr. Angelos Amditis for access to the deliverables and reports on the PLUGGY apps, and refer to the summary by Lim et al. [116].

**Table 8.** Formative and summative HCI evaluation methods used during the PLUGGY project.

| Evaluation Type | | Method Used | Objectives/Focus |
|---|---|---|---|
| Formative Evaluation | | Personas<br>Interviews<br>Pilot Field Study<br>Paper Prototype Testing<br>Usability Testing | To iteratively refine concepts through user feedback and improve design decisions in early development. |
| Summative Evaluation | Expert Review<br>For Museum:<br>1. System Usability Scale (SUS)<br>2. EMOTIVE Questionnaire [1]<br>3. Net Promoter Score (NPS) | For Simulated Exhibition:<br>1. Ease of Task<br>2. Observations<br>3. SUS<br>4. NPS<br>5. EMOTIVE Questionnaire [1] | To evaluate final product usability, emotional engagement, and overall satisfaction across different settings. |

[1] The EMOTIVE Questionnaire measures personal resonance, emotional connection, learning, intellectual stimulation, and social connectedness.

### *3.4. Hybrid Pre-/Post-Visit and On-Location*

#### 3.4.1. Case Study 10: "Picasso AR"

VisitAR is a gamified augmented reality (AR) mobile application that brings Málaga's cultural history to life through interactive storytelling, challenges, and rewards. Centered around key landmarks such as the statue of Pablo Picasso in front of his birth house, the app allows users to interact with historical figures like Picasso, explore Málaga through time, and support local businesses. It is designed for tourists, locals, students, and educators, transforming city exploration into an immersive, educational, and entertaining journey. Figure 14 illustrates three screenshots of the Picasso AR application, showcasing different stages of user interaction with the prototype.


**Figure 14.** Screenshots of the Picasso AR prototype showing different interface design.

User Interactions

When users approach a point of interest—like the Picasso statue—they use their smartphone camera to trigger an AR representation of Picasso, who greets them and offers insights into his life and work. Users can ask the AR Picasso questions and receive AI-driven responses. Through the app's interactive map, users discover more locations, complete trivia, solve puzzles, and unlock time-travel overlays that reconstruct how buildings and plazas once looked. Each completed activity earns coins that can be redeemed at local shops and cafés, incentivizing exploration and repeat use. Leaderboards and daily challenges add a layer of friendly competition.

Evaluation Method and Results

Initial evaluation was conducted through pilot tests in Málaga with tourists, educators, and local families. Participants were observed while using the app in real urban settings, providing both behavioral data and feedback via short interviews and SUS questionnaires. Early feedback indicated high satisfaction, particularly for the AR dialogue with Picasso and the historical time-travel overlays. Businesses noted increased visibility from app users seeking rewards, and educators expressed enthusiasm for using the app in school excursions and digital history lessons.

Conclusions of Case Study 10

VisitAR's Picasso experience exemplifies how phygital tourism can elevate local heritage into a memorable, participatory encounter. It leverages XR to support cultural storytelling, boost local economies, and engage younger audiences in historical learning. With scalability across cities and eras, and a strong freemium model with business partnerships, VisitAR represents a promising step forward for Web3-enhanced cultural tourism. The full results can be found in the pitchdeck: https://www.canva.com/design/DAGeOGPD5Fc/PhNaf4n9KZO6ClVHAP5m9A/edit (accessed on 3 July 2025).

## 4. Discussion

An interactive experience not unlike Pokémon GO, such as the Picasso AR use case reviewed above, can be imagined, where visitors embark on an interactive cultural journey that begins at home and continues beyond their trip. Pokémon GO pioneered AR-based gaming on a large scale and demonstrated the potential of blending virtual and physical spaces into hybrid experiences that integrate entertainment, education, and real-world exploration—principles now inspiring CH XR applications.

Before their visit, tourists can explore a metaverse version of the site, completing AR or VR treasure hunts to learn about historical landmarks. By solving puzzles or interacting with virtual guides, they can collect NFTs, which could represent ownership of digital artifacts like ancient coins, statues, or historical documents. The NFTs are stored securely on the blockchain, ensuring proof of unique ownership. Upon arrival at the cultural site, these NFTs could unlock on-location experiences such as exclusive AR quests, live performances, or behind-the-scenes access to museum artifacts. Families can use AR-enabled devices to follow themed trails, where children and parents work together to solve mysteries, meet historical figures in mixed reality, and earn additional points or NFTs that can be redeemed for phygital souvenirs (a physical artifact paired with digital information and animations). Hospitality providers and local shops participate by offering discounts, meals, or custom gifts tied to NFT rewards.

Post-visit, the experience continues with a digital memory book, compiling virtual artifacts, photos, and videos captured during the trip. Enthusiasts can trade, display, or reuse their NFTs in shared XR worlds, contributing to crowdsourced knowledge preservation. Amateur cultural heritage explorers upload their own 360-degree scans or MR recreations of uncovered artifacts, enriching the shared digital archive. This system not only enhances cultural learning and engagement but also creates new economic opportunities for local businesses, tourism providers, and edutainment creators, transforming cultural heritage into a sustainable, interactive ecosystem. Additionally, it can potentially lead visitors off the beaten track to lesser visited areas, thus creating a more distributed visitor experience, a larger area for creating economic opportunities, and a more spread-out eco-footprint.

### 4.1. Stakeholder Analysis for Hybrid CH XR Application Development

A wide range of stakeholders contribute to the development of hybrid online–offline cultural heritage XR applications, each bringing diverse expertise, priorities, and business models. To clarify their distinct roles in content creation, technology, education, and cultural engagement, Table 9 provides an overview of 14 key stakeholder types involved in shaping sustainable and innovative CH XR experiences.

**Table 9.** Stakeholders for the development of hybrid online–offline DCH XR tourism and hospitality experiences.

| Stakeholder | Role in Development | Involvement |
|---|---|---|
| Museum Curators and Cultural Institutions | Preserve and share CH; attract broader audiences | Provide content; validate authenticity; guide XR design |
| Tourism and Hospitality Providers | Enhance visitor experiences; increase tourism | Integrate XR in travel; offer NFT-linked services |
| XR Technology Developers | Create and maintain the technical infrastructure | Develop apps, blockchain, NFT platforms |
| Local Interactive CH Developers | Promote regional heritage and economy | Design interactive experiences; collaborate locally |
| Teachers of CH | Educate about CH | Use XR in classrooms; promote access |
| Students and Homeschoolers | Primary educational users | Engage in XR learning; offer feedback |
| Parents and Homeschoolers | Introduce children to CH in a fun and interactive manner | Promote family use by gamified museum tours and AR-enhanced travel |
| Amateur CH Enthusiasts | Explore and contribute to CH preservation through digital tools | Join XR projects; use NFTs for engagement |
| Local Artisans and Businesses | Promote culture; create revenue | Produce phygital items; NFT artwork |
| Policy Makers and CH Managers | Ensure legal and ethical compliance | Provide preservation guidelines; revenue ethics |
| Environmental Advocates | Promote sustainable tech | Advocate for low-energy XR technologies/sustainable blockchain methods |
| Homeschool Educators | Provide cultural education tools | Use XR in non-traditional curricula |
| Tourists | End-users seeking unique and memorable cultural experiences. | Use XR before/during/after visits |
| Cultural Storytellers and Historians | Narrate cultural stories | Ensure cultural accuracy; co-create narratives |
| NFT Collectors and Blockchain Enthusiasts | Invest and support via NFTs | Trade, fund, and promote CH via tokens |

A systematic framework for development is highly desirable to help manage the multidisciplinary stakeholders. As can be seen from the large number of diverse stakeholders in the ecosystem of hybrid online–offline CH XR tourism and hospitality application and experience providers, there are many different perspectives and many different work styles to take into account.

### 4.2. Frameworks for CH Application Development, Design, and Evaluation

CH XR application development requires a clear framework for planning design and evaluation studies, and careful coordination, ensuring alignment with project and product end goals and the user needs and expectations at all development stages. While the future of XR in CH preservation and sharing is undeniably promising, further investigation and guidelines are necessary to address the unique issues of the four different scenarios of use for CH XR application, such as preventing oversimplification, misrepresentation, misuse, and other security issues. Additionally, the lack of accessibility for all is an important issue for all of these novel technologies and solutions.

Comprehensive methods have been developed for In-Museum scenarios of use, such as the development of the MUSETECH method [117], and the Virtual Museum Transnational Network (https://www.cyi.ac.cy/index.php/starc/research-information/completed-projects/v-must-net-virtual-museum-transnational-network.html, accessed on 3 July 2025) for large scale virtual museum design, also known as V-MUST. Further research is needed to understand best practices for the specific needs of In-Home/School CH XR scenarios of use, online CH XR multi-user platform design, and hybrid pre-visit, on-location, and post-visit CH XR experience development and evaluation. With the rapid advent of Generative AI and the emergence of other new technologies, not only can 3D applications be built much faster, they can also be used to measure human emotional and cognitive responses to make better design decisions, providing objective data to refine the user experience, enhance emotional resonance, and tailor content to create more meaningful DCH applications. For instance, EEG-based affective computing and machine learning introduce new ways of helping design and evaluation by enabling real-time measurement of user emotions and engagement in VR [118].

As mentioned above, the paucity of frameworks available for these types of applications calls for further research and testing of suitable frameworks. A literature review of existing frameworks identified the following important issues:

Kuntjara and Pak (2024) [119] propose a framework that ensures cultural authenticity while integrating digital elements into heritage experiences. This approach emphasizes the complementarity of AR/VR with physical experiences, mitigating the risks of oversimplification or misrepresentation. However, the authors highlight the need for participatory design methods to involve local communities.

De Felice et al. [120] introduced a participatory framework for digital libraries and museums, focusing on accessibility and inclusivity. Their approach integrates phygital tools to bridge gaps in cultural engagement, especially for remote or underserved communities. This framework encourages co-creation with stakeholders to align with diverse user needs. Muangasame and Tan [121] developed a framework to incorporate phygital elements into rural cultural heritage tourism. Their approach, designed for post-pandemic recovery, emphasizes sustainability and resilience in rural areas. The framework highlights the need to balance technological investments with infrastructure limitations in remote regions.

Mele et al. [122] propose a design framework for phygital customer journeys in tourism. This practice-based approach focuses on seamlessly integrating physical and digital interactions, ensuring consistency and emotional engagement across the user experience. Torres [123] explores a framework for integrating intangible cultural heritage into digital platforms. This approach highlights the importance of phygital tools in preserving oral histories, traditions, and rituals while providing innovative opportunities for user interaction and education. Andrade and Dias [124] propose a multisensory AR framework for cultural sites. Their approach integrates tactile, auditory, and visual experiences to enhance immersion and emotional engagement, addressing the challenge of creating sensory depth in digital replicas.

Greco et al. [125] outline a blockchain-integrated framework supporting cultural tourism startups. This framework highlights the economic potential of phygital business models while addressing the high costs and technical complexities associated with blockchain adoption. Ballina et al. (2019) [119] propose a co-design methodology to integrate smart technologies into cultural tourism. Their approach emphasizes the importance of engaging multiple stakeholders in co-creation processes to create phygital experiences that are culturally meaningful and economically viable.

The design and evaluation of XR-based DCH systems, particularly those integrated with metaverse applications and digital twins, require interdisciplinary approaches that connect theoretical principles with practical applications. Several foundational texts provide insights into these methodologies, offering guidance for designing immersive and interactive experiences while linking virtual and physical cultural heritage sites or artifacts.

Bogle's Museum Exhibition Planning and Design (2013) [126] outlines the integration of narrative, spatial, and visual elements in exhibition design, which can be directly applied to XR systems. Her emphasis on storytelling as a tool for visitor engagement aligns well with the immersive possibilities of digital twins and metaverse applications. Similarly, Creating Exhibitions by McKenna-Cress and Kamien (2013) [127] highlights the importance of collaborative and interdisciplinary teamwork in exhibition development. Their case studies demonstrate how innovative experiences can emerge from effective collaboration—a principle vital for complex XR development projects involving diverse stakeholders.

Simon's The Participatory Museum (2010) [128] focuses on visitor engagement through participatory design, emphasizing how institutions can involve users as co-creators of content. This approach is highly relevant for XR systems, where user interaction is critical, but it provides limited technical insights into implementing digital twins or linking virtual and physical environments. MacDonald and Stenger's Digital Heritage: Applying Digital Imaging to Cultural Heritage (2006) [129] fills this gap by delving into digital imaging technologies such as 3D scanning and VR. Their work underscores the technical requirements and potential of digital twins to enhance preservation and virtual accessibility.

Dernie's Exhibition Design (2006) [130] provides practical insights into integrating physical and digital elements in exhibitions, focusing on immersive and interactive design principles. However, its focus on traditional exhibition design leaves room for further exploration of how these principles extend to metaverse-linked XR systems. Finally, Heritage and Globalisation by Labadi and Long (2010) [131] explores the socio-cultural dimensions of heritage management, particularly in a globalized context. While this work emphasizes sustainability and community engagement, it offers less guidance on the technological or interactive design aspects crucial for CH XR systems.

The existing frameworks, reviewed above, offer valuable perspectives for developing development frameworks for XR-based CH systems. The frameworks reviewed above collectively provide valuable strategies for addressing the challenges and opportunities in phygital cultural heritage and tourism, ensuring inclusivity, authenticity, and sustainability. The frameworks emphasize storytelling, collaboration, participatory design, and technical imaging techniques, all of which are essential for linking metaverse digital twins to physical cultural heritage sites or artifacts. A synthesized summary of the frameworks, highlighting how they support HCD, HCI, UXUI evaluation, and XR/phygital cultural heritage application development, can be seen in Table 10.

These frameworks illustrate how much interdisciplinary teamwork is required to implement the development methods with such a wide range of expert stakeholders—spanning HCI, UXUI, museum studies, and tourism innovation experts—whose views must be integrated to develop effective, user-centered CH XR applications. The landscape of CH XR application design is interdisciplinary, phygital, and user-centered. The frameworks described above are recommended to achieve the following:

- Support holistic and inclusive innovation;
- Bridge physical, digital, and emotional experience;
- Ensure co-creation, cultural accuracy, and measurable impact;
- Empower designers, researchers, educators, and tourism entrepreneurs.

**Table 10.** Synthesized summary of the frameworks.

| Type | Primary Focus | Examples |
|---|---|---|
| Scenario-Based Frameworks | Contextual development (museum, home, hybrid, and online) | MUSETECH, V-MUST |
| Participatory and Co-Creation Frameworks | Cultural authenticity, stakeholder inclusion | Kuntjara & Pak [119], De Felice [120], Ballina [132] |
| Tourism and Business Models | Phygital customer journeys, economic models | Mele [122], Muangasame & Tan [121] |
| Sensory and Narrative Experiences | Emotional design, storytelling, spatial and UX design | Andrade & Dias [124], Bogle [126], Simon [128] |
| Technical and Evaluation Frameworks | Emotion sensing, digital twins, usability testing | Torres [123], PLUGGY Eval. |

However, these frameworks still lack specific guidelines for evaluating the user experience within XR systems, and there are still no guidelines for integrating blockchain and NFTs, or gamified CH XR hybrid tourism activities, into these projects. This means there continues to be a paucity of holistic frameworks that include all stakeholders for the development of CH XR applications with their potential innovations. In response to this, a new framework is presented below for the development of CH XR applications for the enhancement of tourism and hospitality. It brings the tasks of all stakeholders together in one workflow. To illustrate the use of the proposed framework, the ten use cases reviewed in this article have been taken as detailed examples, which can be seen in Appendix A.

### *4.3. Framework for Phygital Cultural Heritage Tourism App Development*

The diverse frameworks for the different aspects of XR-based CH experiences are merged into the following eight-stage framework presented below. This framework facilitates multi-stakeholder development of DCH XR online–offline tourism and hospitality applications and experiences. The proposed development process is summarized in Figure 15, which outlines the eight stages of the framework for designing and implementing phygital cultural heritage XR applications. A more detailed description of each stage is provided in Appendix B.

This multi-disciplinary eight-stage framework combines top-level guidelines for all stakeholders in the process, such as DCH domain experts, strategic planning experts, technology integration experts, and iterative development experts. It provides a workflow for all stakeholders to collaborate on creating engaging, sustainable, and culturally enriching phygital CH XR experiences. It aligns with the stakeholders' goals, the visitors' needs, and the technological CH XR advancements, ensuring a transformative approach to cultural heritage and tourism.

The new XR-based CH application development framework proposed was applied to the ten use cases reviewed in this article, as examples of what the framework might look like when applied to an CH XR idea. The results can be found in Appendix A.

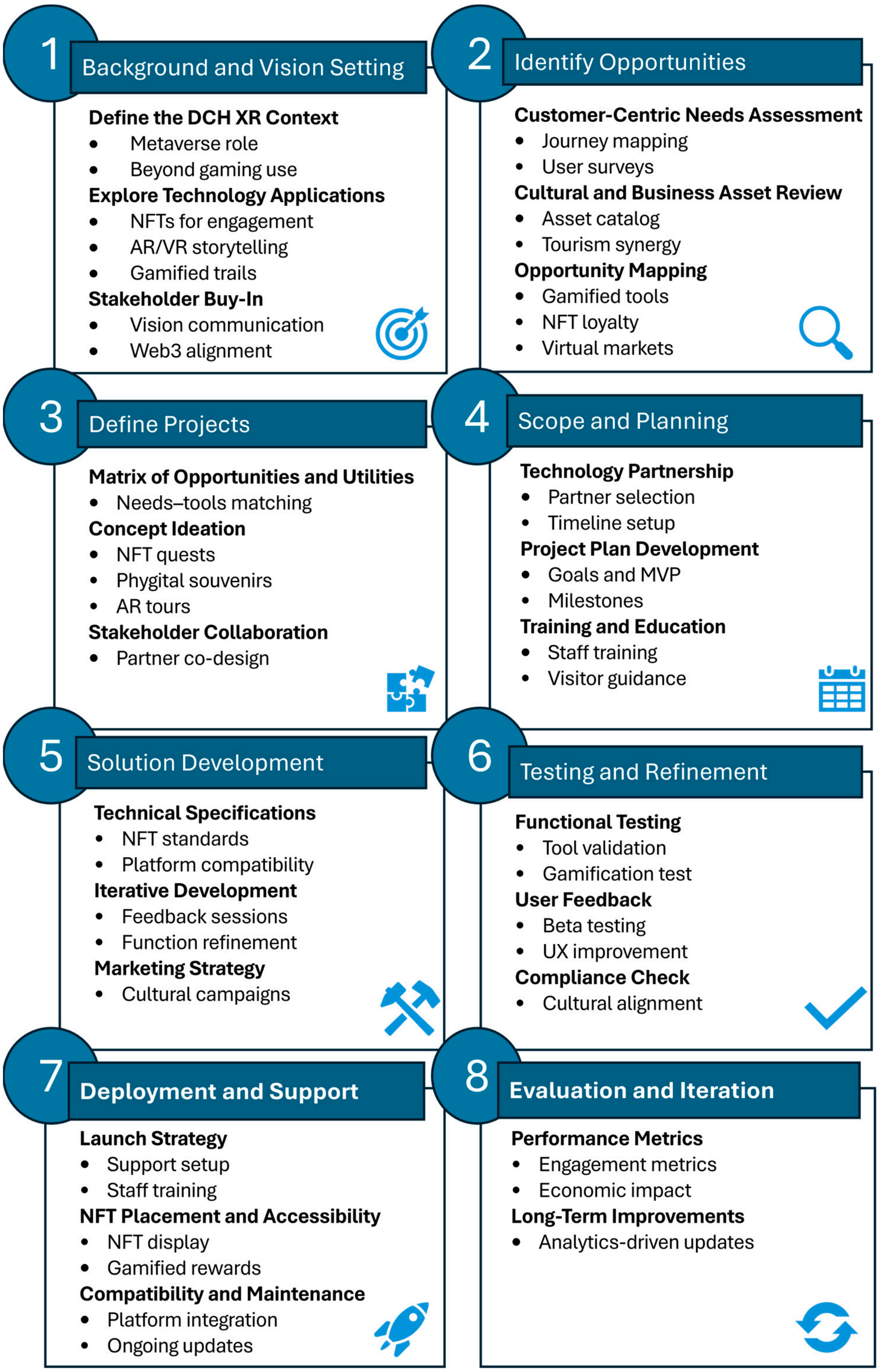



**Figure 15.** Eight-stage framework for phygital cultural heritage XR app development.

### *4.4. Lessons Learned from the Design and Evaluation of Each Application Case Study*

Further research is needed into user-centered design and HCI methods tailored for XR environments, as well as exploration of innovative ways to authenticate and monetize digital cultural heritage using emerging technologies. These are critical for advancing the potential of Web3 metaverse applications in CH and tourism innovation contexts.

The review of the Chilly Mo application use case focused on showing how the overall process of UX Design Thinking is used during the early stages of the development process. It showcased the use of a moodboard, a storyboard, persona descriptions, early stage task diagram visualization, early stage Hierarchical Task Analysis, early stage prototyping using hand-drawn sketches, using computer generated templates with wire-frame UXUI task-flow drawings, mock-ups of the smartphone screen-views of the VR experience, interviews to get early targeted qualitative user feedback, and online surveys to get early quantitative and qualitative feedback on the prototype. It specifically aimed to illustrate the use of persona descriptions to identify representative users, and the respective user needs for typical users, as well as atypical users, early on in the development process. The Chilly Mo study meticulously applied the five stages of Design Thinking (empathize, define, ideate, prototype, and test) and the evaluation methods to validate the prototype's usability and how these were implemented.

The Cham Culture AR case focused on developing a minimum viable prototype to test converting stone reliefs into AR-based educational games. To assess user perception, the widely used SUS questionnaire was applied to measure desirability. The total SUS score is a popular measure, because it provides one data-point about perceived usefulness, for easy comprehension by all stakeholders involved in the decision-making about investing and managing development projects. For example, Hiererra et al. (2022) [133] utilized Design Thinking to create a gamified mobile AR application for cultural tourism, and used the SUS, with an excellent score of 88.5. Similarly, Yanti et al. (2023) [134] employed Design Thinking to develop AR/VR applications for preserving Bali's Lontar Prasi, resulting in an average SUS score of 80, indicating excellent user satisfaction and highlighting the effectiveness of iterative design improvements based on user feedback. The user feedback they collected allowed them to make improvements by making changes to icon display, 3D character information, and UI positioning.

The Cham Culture AR use case review also discussed the paucity of AR evaluation methods and showcased the application of Universal Design principles' heuristic evaluation method that was specifically developed for early AR app testing to address the gap in suitable methods. Dünser et al. (2008) [135] and Georgiou & Kyza (2017) [136] address the long-standing gap in evaluation techniques for AR by reviewing or developing instruments to measure user experiences and immersion. However, neither explicitly covers QR code-based AR mobile phone apps, simply because such technologies were not commonly in use at the time these studies were conducted. This omission can limit the applicability of their methods to newer AR or XR cultural heritage applications, which often rely on mobile-based QR markers or object recognition for location-based interactions. Moreover, while these studies offer significant foundational insights, they do not fully explore the unique challenges of designing for rich cultural heritage contexts—such as integrating multisensory feedback, collaborating in shared AR spaces, or addressing long-duration user engagement. Consequently, evolving AR platforms and domain-specific needs continue to call for more flexible, standardized, and context-aware evaluation frameworks.

This use case study showcased how to use triangulation of HCI methods as a minimum development methodology, to achieve rapid prototyping and user feedback regarding desirability and effectiveness for teaching and learning.

Triangulating design and evaluation methods is key to rapidly producing a viable prototype. By combining persona descriptions, heuristic evaluation, and the SUS, teams establish a swift, minimum quality control pipeline. Persona descriptions anchor design choices in authentic user needs, ensuring that early ideas resonate with real motivations and contexts. Heuristic evaluation then provides a quick, expert-driven scan for major usability flaws, allowing fixes before costly user testing. The SUS questionnaire captures user perceptions of ease-of-use through a concise, standardized format. This synergy of qualitative and quantitative feedback guarantees that each design iteration meets a threshold of functionality and usability. This is vital when time or budget are scarce. As a result, the team can present a lean yet reliable MVP to investors, demonstrating genuine market potential and readiness. It also mitigates risk by preventing deployment of an untested or subpar product. Ultimately, triangulation offers a practical safeguard: persona insights, heuristic checks, and objective usability scores give development teams confidence in their proof-of-concept, all while operating under tight deadlines.

The Memories of Kellie application illustrated the process of HCI-informed research and development, which starts with a thorough literature review to identify any user needs and any potentially useful design solutions other UX developers identified, rather than diving straight into coding. By examining existing knowledge on digital storytelling and cultural heritage, the team can identify foundational design principles, covering functionality, emotional impact, and user needs, to inform their design decisions, before any prototype is built. This ensures that, when development begins, the resulting application aligns with real-world user needs, rather than being based on guesswork.

The Memories of Kellie application exemplifies the design and evaluation methods of human-centered interaction design and evaluation: literature research to inform the design choices, hypothesis development about best design ideas, prototype building according to the literature-informed design ideas, testing of the prototype with representative end-users to assess whether the design ideas work as predicted from the literature research, and writing advice on redesign options derived from the user testing. It demonstrates why creating a tangible model is essential: it allows the researcher to test how the theoretical insights from the literature review translate into practical design solutions. This allows the developers to test their theory that the desired emotional and information goals are met by the design choices of incorporating interactive panels, soundscapes, and visual feedback.

The Fort Ontario use case review focused on the use of combining qualitative and quantitative evaluation methods. For qualitative evaluation, the cognitive walkthrough (CW) was used, which is a step-by-step technique used to spot where new users might struggle when trying out an interface or application. In this project, the student applied it on-site at Fort Ontario, by asking participants to guide themselves through the self-directed AR tour. Each step—such as launching the app, following on screen prompts, and interacting with AR elements—was reviewed for potential confusion or friction. This method generates quick, low-cost feedback since it pinpoints issues as participants walk through the tasks, rather than requiring complex setups or lengthy observation sessions. Traditionally, this method is used by HCI researchers, as it was developed to be used early in the design journey when the application is not sufficiently robust and ready to be evaluated with end-users. However, in this case, it was applied on the prototype by representative end-users, showing that this method has a more versatile use than it was originally designed for.

In addition to qualitative feedback (e.g., participants mentioning that windy weather made the app harder to use, or that arthritis affected tapping accuracy), the team also quantitatively collected data measures to summarize how effectively the walkthrough met user needs. For instance, the finding that 80% of participants had never tried AR before yet still found the instructions easy, is a helpful indicator when interpreting the overall usability score. The project used the statistical within-subjects design—meaning everyone experienced the same tasks—so that any variations in performance or preference scores minimized the effect of individual differences and increased the statistical power of the test. The participants' CW data, combined with the direct observation data, provided a solid overview of what worked well and what required refinement to make the AR experience even more accessible.

Combining quantitative and qualitative methods allows researchers to gain a fuller understanding of user experiences and product performance. Quantitative data—such as completion times, error counts, or SUS questionnaire scores—offers measurable, objective metrics that can be compared, tracked over time, or statistically analyzed. This helps determine whether design changes lead to clear improvements and provides evidence for stakeholders who require numerical results. On the other hand, qualitative feedback—through interviews, open-ended survey responses, or observations—highlights the "why" behind the data. It captures nuanced opinions, emotional responses, and unforeseen usability hurdles that purely numerical measures might overlook. By merging both approaches, teams can validate their hypotheses with hard evidence while also uncovering deeper insights into user motivations and behaviors, leading to more informed, user-centered design decisions. Although not all case studies in this article included quantitative data, future work should explore more consistent numerical evaluation across projects to enable broader comparisons.

The Hanging Gardens of Babylon use case review showcased the usefulness of an A/B test design to compare two versions of a user experience, like in this case, comparing an AR app versus a VR app. This type of test design offers a clear and systematic approach for gauging which option better meets specific goals—in this case, learning retention. By dividing participants into two distinct groups (group A for one design choice, and group B for the alternative design choice), researchers can isolate how each interface impacts performance on the same tasks, ensuring more credible comparisons. Each group then completes identical tasks and takes a comprehension quiz, allowing direct measurement of the user's task performance under both conditions.

This method is particularly valuable for complex choices between different UXUI solutions because it controls for variables like participant differences or fluctuating conditions by making both groups perform comparable actions. The resulting data highlight how effectively each interface supports the intended outcome, whether it is improved recall, faster task completion, or greater user satisfaction. In this case, the surprising finding that AR led to better retention than VR contradicts earlier research, emphasizing the importance of empirical, context-specific evaluations. Ultimately, an A/B test design provides straightforward, quantitative insight into which option excels, guiding teams to refine or adopt the strongest UXUI for their objectives.

The Weigh House Estonia application use case evaluation setup is typically labeled a "field-based, qualitative" user study with a multi-phase design. It includes a self-directed trial in Tallinn's Town Hall Square, during which participants explored the AR application on their own, mirroring how they would naturally use it in a real-world context, giving the test ecological validity. Following that, in-depth, open-ended interviews were conducted to gather detailed user feedback. Theme-based content analysis, a widely used qualitative method, was then used to categorize and interpret the interview data. This involved identifying recurring themes, "higher-order themes", which represent broad, overarching categories of user experiences or issues, and "lower-order themes", which are more specific subcategories that fall under each broader theme. Taken together, these methods not only revealed key usability insights but also captured participants' emotional responses, ultimately guiding designers toward more user-centered improvements.

The Fountain of the Lions application use case builds on the previously mentioned triangulation design explanation, in this case combining personas, heuristic evaluation, and a cognitive walkthrough. However, this study employs a 3D cognitive walkthrough (3DCW) specifically adapted for evaluating three-dimensional user interfaces. It also used a 3D heuristic evaluation (3DHE), which offers a more targeted inspection process for 3D applications. This adaptation is essential in AR/VR assessments because standard walkthroughs do not adequately account for spatial tasks—such as rotating objects, zooming in or out, and navigating through 3D worlds—nor do they address challenges like depth perception or unusual gesture inputs. By examining each step in a 3D workflow, evaluators can pinpoint where users might become confused or stuck, and propose interface improvements and redesigns accordingly. The 3DCW ensures that designers capture issues unique to 3D environments, leading to more robust, user-friendly experiences in AR and VR contexts.

The Picasso AR app use case highlights a lean, entrepreneurial approach to XR product development through Design Thinking/Design Doing and validation of an MVP. It showcases a real-world application of how UXUI prototypes, market research, and user feedback can inform the development of engaging cultural heritage experiences. The Picasso AR app enables users to engage in a virtual conversation with a stylized digital avatar of Pablo Picasso, placed in front of his birth house in Málaga, Spain. On-location, the AR experience allows tourists to activate Picasso through their phones—prompting storytelling, facts, and interactions contextualized to their physical location. Pre-visit and post-visit, users can access the virtual version remotely in VR, continuing the dialogue with Picasso and exploring related artworks and biographical elements.

The special feature of this case study is that it is accompanied by a slide-by-slide MVP pitch deck. Each slide represents a different stage of development:

- Initial UX wire-frames and storyboards based on persona insights;
- Interactive mockup screens designed using prototyping tools like Figma;
- A concise market analysis outlining tourist demand for creative AR experiences at iconic cultural locations;
- User validation results, gathered through early testing with representative end-users, including tourists, local guides, and museum stakeholders.

This MVP validation phase used structured feedback tools and interviews to evaluate desirability, usability, and perceived educational and entertainment value. The direct integration of user feedback into the next design iteration is an example of a lean, agile development pipeline, applied in the context of digital cultural tourism. The Picasso AR use case provides a practical template for cultural entrepreneurs, designers, and educators seeking to bring heritage experiences to life through immersive, phygital applications—grounded in real-world validation, scalable design systems, and user-centered storytelling.

The CHISel application use case exemplifies how to manage the evaluation of a complex UI, while the application is still under development and highly confusing for end-users to understand in its unfinished and potentially unstable state. Trained HCI evaluators were chosen to conduct a thorough CW of specific tasks, focused on accuracy, user-friendliness, effectiveness, and efficiency. Their professional expertise equipped them to methodically explore each task, step by step, revealing subtle design flaws that might otherwise remain hidden. By combining domain familiarity with usability best practices, these experts pinpointed interface complexities, learned about system feature interactions, and assessed multi-user collaboration nuances. Additionally, the experimenter collected observational and verbal data from four CW experts as they went through the CW tasks. Along with the evaluators' own findings, this provided rich, specific feedback on the interface's learnability. As a result, the evaluation not only identified precisely where the UXUI needed improvement but also offered detailed, actionable recommendations for refining the software's design, ensuring a low learning curve and aligning it more closely with the domain-specific goals of the application.

A thorough CW with trained HCI experts produces pinpointed insights for two main reasons. First, these specialists bring extensive knowledge of usability principles and design best practices, allowing them to dissect each interaction step with a clear sense of where problems typically arise and how to address them. They do not simply note that "something's wrong"—they use their expertise to diagnose the underlying cause of the issue, such as unclear feedback or inconsistency in interactive elements, and provide educated suggestions for improvements. Second, the CW process requires evaluators to follow a user's path through the interface task by task, rather than only testing random features. This structured, goal-by-goal approach uncovers specific friction points that might otherwise remain hidden. Because each task is scrutinized against explicit user goals, the resulting recommendations tend to be detailed and actionable, offering clear directions for the designers on how to streamline steps, redesign problematic widgets, or improve feedback mechanisms. Ultimately, this level of methodical analysis ensures that usability improvements directly target the real challenges users face, instead of applying broad, unfocused changes.

The PLUGGY platform application use case review showcased the importance of a development framework employing a complex, triangulated approach, by integrating formative and summative evaluations with diverse methods such as persona descriptions, interviews, pilot field studies, paper prototype testing, usability testing, and expert reviews, collecting both quantitative and qualitative data. This multifaceted strategy is crucial for large-scale, multi-party development teams, as it ensures comprehensive coverage of user needs and system performance. Formative evaluations—including interviews, pilot studies, and prototype testing—are conducted early and iteratively to refine concepts and address usability issues promptly. These methods provide continuous feedback, enabling teams to make informed adjustments that align with user expectations and domain-specific requirements. Summative evaluations—such as expert reviews, the SUS and EMOTIVE questionnaires, and NPS—are performed later to validate the overall effectiveness and user satisfaction of the final product.

Each method was selected to complement the data collected by the other methods: Persona descriptions help in understanding and empathizing with different user segments, ensuring that design decisions are user-centered. Interviews and pilot studies gather qualitative insights, while usability testing and paper prototypes offer practical assessments of interface functionality and user interactions. Expert reviews and standardized questionnaires like SUS and NPS provide quantitative data to benchmark usability and measure user engagement. This holistic approach is essential for coordinating efforts across multiple teams, ensuring that every aspect of the user experience is meticulously evaluated and optimized. By leveraging both qualitative and quantitative data, PLUGGY's framework facilitates robust, evidence-based decision-making, ultimately leading to a more reliable, user-friendly application that meets the diverse needs of its stakeholders and end-users.

The design of the PLUGGY evaluation framework also exemplifies a type of triangulated approach by integrating multiple parallel methods to comprehensively assess the complex user experience in a mutually informative way. Triangulation involves using diverse data sources and evaluation techniques, and collecting multiple perspectives, to thoroughly validate and cross-check the diverse findings and ensure a well-rounded understanding of usability and user engagement. This particular design of the experiments was triangulated in the following way:

1. Diverse Methods: Combining qualitative methods (interviews and pilot studies) with quantitative measures (SUS and NPS) allows for capturing both subjective user insights and objective usability metrics.
2. Formative and Summative Evaluations: Formative methods like usability testing and pilot studies refine the prototype iteratively, while summative evaluations such as expert reviews and standardized questionnaires validate the final design's effectiveness.
3. Multiple Perspectives: Personas ensure the design aligns with varied user needs, expert reviews provide professional usability assessments, and representative end-user feedback from diverse tasks highlights real-world application strengths and weaknesses.

This triangulated design is crucial for large, multi-party development teams with many stakeholders with different professional backgrounds and professional expertise, as it ensures that all aspects of the user experience are meticulously evaluated from different angles. By leveraging both qualitative and quantitative data, teams can make informed, evidence-based decisions that enhance the interface's accuracy, user-friendliness, effectiveness, and efficiency. This comprehensive approach minimizes the risk of overlooking critical usability issues, fosters collaboration across diverse teams, and ultimately leads to a robust, user-centered application that meets both technical and cultural heritage objectives.

## 5. Conclusions

The ten use case studies demonstrated how XR can be applied across diverse contexts for CH and tourism applications: pre-visit planning, on-site exploration, and post-visit engagement for history education, museum visits, cultural heritage site visits, tourist visits, and hospitality perks. Additionally, they explore a diverse application area for scenarios of use, such as in professional and amateur CH research sharing, preservation, analysis, sharing, homeschooling, self-study, and in-school activities. Leveraging phygital design solutions using digital twins, blockchain, NFT technologies, and online–offline gamification, these studies highlight innovative ways to enhance accessibility, collaboration, and learning while transforming the preservation and dissemination of CH. By connecting to the past with cutting-edge technology, this review underscores the potential for XR to reimagine the cultural heritage experience for scholars, enthusiasts, and the general public alike.

For each of the ten use cases reviewed above, the HCD methods that were highlighted in the use case reviews were discussed in detail above. A connection was made to the traditional use of the method and how it was adapted, along with important open issues with regards to using these methods for the design and evaluation of CH XR application development projects and phygital CH tourism and hospitality experiences. It is clear from our use case reviews that phygital CH tourism and hospitality innovations present significant opportunities for enhancing visitor engagement, accessibility, education, and economic growth, while also supporting global sustainability and resource preservation efforts.

While this work has focused on usability aspects during the design and validation phases of the XR experiences, it is equally important to consider their long-term impact in terms of sustained user engagement and knowledge retention. Post-deployment evaluation can provide valuable insights into how user interactions and perceptions evolve over time. Future implementations should incorporate usage analytics (e.g., real-time interaction metrics), follow-up surveys, and iterative testing with returning users. These strategies would not only help ensure the continued effectiveness of the applications but also support their adaptability to evolving user needs.

Although the development of the XR experiences emphasized usability and expert-driven design, the importance of involving end-users, community members, and cultural stakeholders in the creation process is increasingly recognized. Participatory design methods—such as workshops, collaborative storytelling, and iterative prototyping—can enhance authenticity, foster user engagement, and support culturally representative outcomes. While full co-creation was not implemented across all cases, certain applications, such as PLUGGY, did incorporate stakeholder input through the active involvement of curators and cultural experts. Future work should more systematically integrate co-creation practices to promote shared ownership and contextual relevance.

In addition, there are some remaining design and evaluation challenges, such as cultural authenticity, accessibility, technical complexity, and sustainability. These remain areas requiring further exploration. Collaborative research and innovative design practices are essential to maximize the potential of these transformative technologies while addressing their inherent limitations. The anticipated positive effects and challenges of integrating phygital experiences in CH tourism and hospitality are as follows:

- Enhanced Visitor Engagement

Phygital technologies significantly enhance visitor engagement by creating immersive and interactive experiences. For instance, Malvica et al. (2024) [137] demonstrated how digital storytelling in Italy's Naxos Archaeological Park increased visitor immersion and understanding of historical narratives through augmented reality (AR) overlays and gamified exploration. However, the integration of phygital tools poses challenges in maintaining cultural authenticity. Kuntjara and Pak (2024) [119] highlighted how digitization often oversimplifies complex cultural elements, risking the loss of meaningful details in the pursuit of user-friendly experiences. Future research must focus on reconciling authenticity with technological innovation.

- Broader Accessibility

Phygital tourism makes cultural heritage accessible to diverse audiences by eliminating physical and geographical barriers. Custodero (2024) [138] found that virtual tours expanded participation among global visitors and individuals with disabilities, promoting inclusivity and equity in cultural engagement. Accessibility remains incomplete, as many phygital systems rely on high-speed internet and advanced devices, which are not universally available. Marino et al. (2025) [139] called for research into cost-effective solutions and simpler technologies to ensure equitable access across diverse populations, particularly in underserved regions.

- Economic Benefits for Local Communities

Phygital tourism generates economic opportunities for local businesses by connecting virtual economies with physical commerce. Greco et al. (2024) [125] reported that NFTs and blockchain-enabled phygital souvenirs supported artisans and small businesses, creating innovative revenue streams while promoting cultural preservation. Despite the potential for economic growth, Greco et al. also noted technical and logistical challenges in implementing blockchain solutions, such as high development costs and low adoption rates among local businesses. Research should explore scalable and user-friendly blockchain frameworks tailored for small enterprises.

- Preservation and Promotion of Cultural Heritage

Phygital tools facilitate the preservation of cultural heritage by creating digital replicas of artifacts and endangered sites. Marino et al. (2025) [139] emphasized the role of AR and VR in safeguarding and promoting heritage that is otherwise inaccessible or at risk of physical degradation. Giaccardi (2012) [140] observed that, while digital replicas are valuable for preservation, they often lack the emotional and sensory depth of physical artifacts, potentially reducing their cultural impact. Future designs should integrate multisensory technologies to bridge the gap between digital and physical experiences.

- Educational Impact

Gamified phygital experiences have shown remarkable success in promoting educational outcomes. Custodero (2024) [138] demonstrated that embedding quizzes, puzzles, and interactive storytelling into cultural heritage tours engaged younger audiences and enhanced their historical knowledge retention. However, Kuntjara and Pak (2024) [119] noted that designing age-appropriate and culturally sensitive gamified content remains a significant challenge. Content often risks oversimplification or misrepresentation of cultural narratives. Further research is needed to develop frameworks for creating meaningful, accurate, and inclusive educational tools.

- Strengthened Sustainability Efforts

Phygital tourism supports sustainability by reducing the need for physical travel through virtual exploration. Giaccardi (2012) [140] highlighted how virtual-first approaches aligned with SDG 13 (Climate Action) by lowering environmental footprints and promoting awareness of sustainable practices. Sustainability efforts are often undermined by the energy-intensive nature of blockchain and XR technologies. Greco et al. (2024) [141] called for the development of low-energy platforms and green technologies to minimize the environmental costs of phygital implementations.

The exploration of standard and new design methodologies tailored to the unique challenges and opportunities of XR in CH preservation and sharing is crucial for future development. Future research should focus on developing such frameworks further, incorporating user feedback into iterative design processes, and exploring the potential of emerging XR technologies (e.g., haptic feedback and advanced interaction modalities) to further enhance user engagement and accessibility.

The scalability of these methodologies across different cultural heritage sites and user demographics also needs further investigation. The impact of these technologies on accessibility for users with disabilities is another critical area for future research. The lack of standardized UX design frameworks specifically for XR applications in cultural heritage presents a significant hurdle. The rapidly evolving nature of XR technologies also poses a challenge, requiring continuous adaptation and refinement of UX design methodologies. The complexity of developing and deploying XR applications, particularly those involving high-fidelity 3D models and immersive interactions, presents a significant challenge. The cost of development, including hardware and software, as well as expertise in XR development and UX design, can limit scalability. However, the emergence of user-friendly XR development tools and platforms could potentially address this challenge. The adoption of open-source frameworks like 5DMETEORA [142], which automates the dissemination of 3D and 2D content for customized XR experiences, can also contribute to increased scalability and accessibility. Further research into the development of more efficient and cost-effective design processes and the assessment of the newly proposed framework are essential. In this context, future work could explore adapting selected XR applications developed in these case studies to web-based environments using technologies such as WebGL or WebXR, enhancing their accessibility and long-term impact beyond the original academic settings.

Online multi-user virtual worlds, including the Spatial XR, Web3, and Metaverse (https://en.wikipedia.org/wiki/Metaverse, accessed on 3 July 2025) concepts, provide new collaboration opportunities, including for DCH preservation and sharing. Development of these new technologies is still rapidly advancing, and audiences now expect photo-realistic visuals in XR museums and cultural heritage sites. Our culture is influenced by computer-generated images, and understanding their impact requires combining insights from various academic disciplines. Many museums and heritage sites are adopting sophisticated computer-generated visuals, replacing traditional learning materials with 3D, interactive, and multi-user environments. Digitalization is crucial for preserving the rich living heritage of marginalized groups. For instance, Google and UNESCO's collaboration on the Google World Wonders Project makes world heritage more accessible globally. Researchers and practitioners must continuously evaluate the advantages and disadvantages of XR technologies, especially considering the significant development costs for complex scenarios of use such as DCH sharing applications. Real development experience via internships and real-world design teamwork experience are vital for students to gain practical HCD tailoring skills. The CH XR HCD use case reviews showcased how a framework of multiple standard HCI methods in real-world settings can provide informative usability insights. Learning-by-doing helps acquire valuable skills for HCI method tailoring and framework development. Smaller project development experiences are great for building skills and problem-solving awareness for future application design and evaluation and prepare the individuals of the team to bring their expertise to the team and guide larger projects successfully.

While the case studies presented illustrate the application of XR in diverse cultural heritage scenarios, the need for a more structured framework to guide adaptation across different contexts remains evident. To address this, future developments should focus on modular design principles that can be tailored to specific cultural settings while maintaining core usability and interpretative goals. Complementary efforts could include the creation of open-source tools and scalability guidelines to facilitate broader adoption by institutions with varying technical and curatorial resources. Such a framework would support the transferability and sustainability of XR solutions within the cultural heritage sector.

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# Appendix A. Framework for Phygital Cultural Heritage Tourism Application Development

The framework is presented in Section 4.1, in the Discussion, Section 4, of the article. It is applied below to the ten use cases presented in the article in Section 2: Ten Use Case Studies in Extended Realities for Cultural Heritage Preservation. The results of applying the framework to the ten use cases are presented here to demonstrate how it can be used to develop phygital tourism application proposals. The framework consists of eight stages:

- Stage 1: Background and Vision Setting;
- Stage 2: Identify Opportunities;
- Stage 3: Define Projects;
- Stage 4: Scope and Planning;
- Stage 5: Solution Development;
- Stage 6: Testing and Refinement;
- Stage 7: Deployment and Support;
- Stage 8: Evaluation and Iteration.

The framework is intended as a development tool to help guide and facilitate the developers' multi-disciplinary teamwork activities. It provides a step-by-step guideline to describe and specify the project scope and the development, design, and evaluation of these types of applications. It emphasizes the opportunities for gamified tourism, metaverse-enhanced cultural heritage education, and integration of Web3 technologies like NFTs and blockchain into cultural heritage (CH) tourism and hospitality.

## *Appendix A.1. Applying the Framework to the Chilly Mo VR Application*

The Chilly Mo VR application is a compelling example of using XR technology to create immersive educational experiences for toddlers in the realm of digital cultural heritage (DCH).

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The Chilly Mo app connects toddlers to cultural heritage through VR, introducing them to ancient civilizations in an engaging, gamified manner. The role of the metaverse in this context is to bridge the physical and digital realms, enabling interactive storytelling, cultural preservation, and education.

Explore Technology Applications:

- NFTs: Offer collectible digital artifacts (e.g., cultural costumes or traditional items like the Haft Sin from the Persian New Year); these NFTs could serve as rewards for completing tasks or as a means to unlock additional features in the app.
- Interactive Storytelling: Enhance learning with narratives like the Persian Nowruz festival, featuring VR-guided activities such as assembling a Haft Sin table and exploring Persepolis.
- Gamified Trails: To enrich the learning experience, include in-app quests, such as gathering cultural items or solving puzzles related to historical events.

Stakeholder Buy-In:

The app can engage parents, educators, cultural institutions (e.g., the Louvre), and technology developers. The app's alignment with cultural preservation, early childhood education, and economic innovation can be highlighted through phygital offerings.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Provide virtual previews of civilizations and festivals, allowing parents to select experiences tailored to their toddler's interests.
- On-Site Phase: Extend the VR experience to museum visits by connecting app content with physical exhibits (e.g., special QR codes for unlocking in-app features).
- Post-Visit Phase: Enable toddlers to share digital mementos, such as selfies in cultural costumes or NFTs earned during quests, with friends and family.

Cultural and Business Asset Review:

- Catalogue unique cultural elements from each civilization, such as costumes, artifacts, and festivals, and then rank them by educational and engagement potential.
- Partner with local artisans to translate digital items into physical souvenirs that families can purchase.

Opportunity Mapping:

- Explore applications like NFT-based loyalty programs, where completing multiple cultural quests unlocks special rewards.
- Create AR/VR-integrated guided tours within the Louvre, linking the app's digital content to physical exhibits.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use NFTs as digital mementos, enhancing personalization and rewards in the app.
- Develop AR-guided trails in the museum that synchronize with the VR content that toddlers can experience at home.

Concept Ideation:

- Integrate an interactive feature allowing toddlers to customize cultural avatars and receive NFT versions of their creations.
- Expand the gamified activities to include other cultural celebrations, fostering global cultural literacy.

Stakeholder Collaboration:

- Work with cultural experts, art therapists, and educators to ensure the app balances educational value with age-appropriate design.

Stage 4: Scope and Planning

Technology Partnership:

- Identify blockchain and XR development partners to incorporate NFTs and improve VR functionality, ensuring compatibility with smartphones.

Project Plan Development:

- Define milestones, such as completing prototypes for new civilizations (e.g., Egyptian and Indian).
- Establish a Minimum Viable Product (MVP), focusing on a single museum integration with the Nowruz content.

Training and Education:

- Develop resources for parents and educators, enabling them to guide toddlers through the app effectively.

Stage 5: Solution Development

Technical Specifications:

- Use ERC-721, ERC 1155, and EIP 6551 standards for NFTs to ensure compatibility with common digital wallets.

- Design high-resolution digital twins of cultural artifacts and environments, such as Persepolis.

Iterative Development:

- Regularly test prototypes with toddlers and parents, gathering feedback to improve usability and engagement.

Marketing Strategy:

- Promote the app through partnerships with cultural institutions like the Louvre.
- Highlight the educational and gamified aspects in campaigns targeting parents.

Stage 6: Testing and Refinement

Functional Testing:

- Ensure seamless operation of the VR experience across devices, particularly smartphones.
- Test NFT minting, redemption processes, and in-app integrations.

User Feedback:

- Use semi-structured interviews and questionnaires with parents, educators, and toddlers to evaluate engagement and usability.
- Address feedback to refine intuitive navigation and interactive features.

Compliance Check:

- Verify alignment with cultural authenticity, age-appropriate design, and accessibility standards.

Stage 7: Deployment and Support

Launch Strategy:

- Provide live tech support during the app launch to assist users with installation, navigation, and troubleshooting.

NFT Placement and Accessibility:

- Display digital artifacts in-app, with physical representations available at museum gift shops.

Compatibility and Maintenance:

- Regularly update the app to include new civilizations and quests.
- Ensure compatibility with emerging XR devices and blockchain platforms.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Track user engagement through metrics such as VR session durations, completed quests, and NFT redemptions.
- Measure educational outcomes using feedback from parents and educators.

Long-Term Improvements:

- Expand content offerings by incorporating additional civilizations and festivals.
- Explore partnerships with other museums and cultural institutions to scale the application.

By applying the integrated framework, the Chilly Mo app can evolve into a comprehensive DCH XR platform, blending educational value with gamified tourism and phygital offerings. The inclusion of NFTs and blockchain provides new dimensions for personalization and rewards, while the iterative design process ensures the app meets the needs of its young audience. This approach not only enriches the cultural learning experience for toddlers but also creates innovative opportunities for museums and cultural institutions to engage with the next generation.

*Appendix A.2. Applying the Framework to the Cham Culture AR App*

The Cham Culture AR App is a notable example of integrating AR technology to preserve and share endangered cultural traditions. Below, the previously developed framework is applied to guide the design, development, and evaluation of this AR application, emphasizing user-centered design, gamified engagement, and the integration of Web3 technologies to enhance cultural preservation and audience engagement.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The Cham Culture AR app serves as a digital bridge between the ancient Cham traditions and modern audiences. Its primary role is to preserve cultural heritage through interactive AR animations and accurate representations of Cham dances, music, and artifacts. By embedding the AR experience into museum visits and educational settings, the app can extend its reach beyond entertainment to cultural education and preservation.

Explore Technology Applications:

- Interactive Storytelling: Utilize AR to bring Cham temple reliefs to life through music, dance, and narrated cultural stories.
- Gamified Trails: Create interactive challenges, such as identifying Cham cultural elements during museum visits, to increase user engagement.
- NFTs and Blockchain: Offer digital collectibles, such as Cham artifacts or dance sequences, as NFTs; these could serve as educational tools or memorabilia for visitors, ensuring authenticity and uniqueness through blockchain.

Stakeholder Buy-In:

The app can engage museum curators, cultural preservationists, educators, and local Cham communities. The app's role in preserving Cham culture for younger generations can be emphasized, while fostering global appreciation for Southeast Asian heritage.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Provide virtual previews of the AR experience on museum websites or apps to attract visitors.
- On-Site Phase: Use QR codes in museum exhibits to trigger AR animations, allowing users to manipulate artifacts and scenes.
- Post-Visit Phase: Enable users to share their AR experiences on social media and collect NFTs as digital souvenirs of their visit.

Cultural and Business Asset Review:

- Catalog Cham cultural elements, such as traditional instruments, dances, and costumes, to prioritize their inclusion in AR scenes.
- Explore partnerships with local artisans to create physical versions of digital items featured in the app.

Opportunity Mapping:

- Expand the app's functionality to include educational modules, allowing users to learn Cham traditions interactively.
- Introduce a loyalty program using NFTs, rewarding repeat visitors or those who explore multiple Cham-related exhibits.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use NFTs to provide visitors with unique, blockchain-verified digital replicas of Cham artifacts.

- Implement AR-guided museum tours that link the app's digital content to physical exhibits.
- Develop virtual Cham experiences for users unable to visit the museum in person.

Concept Ideation:

- Enhance the app by integrating multiplayer AR interactions, allowing users to collaborate on Cham cultural activities, such as recreating a traditional Cham dance or ritual.
- Introduce gamified elements like trivia questions or puzzles based on Cham history.

Stakeholder Collaboration:

- Work closely with Cham cultural experts, museum curators, and educators to ensure cultural authenticity and pedagogical value.

Stage 4: Scope and Planning

Technology Partnership:

- Identify partners specializing in AR, blockchain, and gamified learning to implement NFT functionalities and improve user engagement.

Project Plan Development:

- Set clear objectives, such as expanding the app to cover additional Cham artifacts and dances.
- Develop a Minimum Viable Product (MVP) focused on a specific Cham cultural element, such as an artifact or a festival dance.

Training and Education:

- Create training materials for museum staff to guide visitors in using the app and understanding its cultural content.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721, etc.) to mint NFTs representing Cham cultural elements.
- Develop AR animations with high fidelity to ensure accurate representation of Cham traditions.

Iterative Development:

- Conduct iterative testing with educators, students, and museum visitors to refine the app's usability and cultural content.

Marketing Strategy:

- Highlight the app's role in cultural preservation and education through partnerships with museums and educational institutions.

Stage 6: Testing and Refinement

Functional Testing:

- Validate the accuracy and responsiveness of QR code triggers and AR animations.
- Test NFT functionalities, ensuring seamless integration with digital wallets.

User Feedback:

- Conduct surveys and interviews with diverse user groups, focusing on teachers, students, and tourists.
- Address feedback from older users about technological adoption concerns by simplifying the app interface.

Compliance Check:

- Ensure that the app adheres to cultural preservation standards and aligns with the goals of the Cham Museum and other stakeholders.

Stage 7: Deployment and Support

Launch Strategy:

- Provide technical support during the app's launch phase, ensuring smooth adoption by museum staff and visitors.
- Train staff to explain the app's features and cultural significance to visitors.

NFT Placement and Accessibility:

- Offer digital collectibles, such as Cham artifacts or dance sequences, as NFTs through the app.
- Ensure these NFTs are accessible to users through integrated wallets and museum kiosks.

Compatibility and Maintenance:

- Regularly update the app to include new features, such as additional Cham dances or artifacts, and maintain compatibility with new AR technologies.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Track app engagement through metrics such as QR code scans, NFT redemptions, and user interaction times.
- Assess educational impact through feedback from teachers and students.

Long-Term Improvements:

- Expand the app's reach by including content from other Cham-related sites or artifacts.
- Use user feedback to refine cultural content and improve usability for diverse age groups.

By applying the integrated framework, the Cham Culture AR app can evolve into a comprehensive cultural preservation tool that bridges digital and physical experiences. The inclusion of NFTs and blockchain ensures authenticity and provides lasting value for users. Gamified elements and interactive storytelling enhance engagement, making the app a model for using AR in the preservation and sharing of endangered cultural traditions. This approach not only preserves the Cham heritage but also fosters global appreciation and sustainable cultural tourism.

### *Appendix A.3. Applying the Framework to the "Memories of Kellie" Case Study*

The "Memories of Kellie" application demonstrates the potential of interactive narratives and 3D environments for engaging users with digital cultural heritage (DCH). Below, the framework is applied to guide future developments of this project, by integrating gamified elements, Web3 features like NFTs, and XR technologies to enhance user engagement and promote site visits.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The application serves as a digital gateway to Kellie Castle, offering users an immersive experience of the site's history. Its focus on interactive storytelling aligns with the role of XR technologies in conveying emotive and contextualized narratives that enhance cultural preservation and user engagement. Expanding this project with AR or mobile deployment can bridge the gap between the virtual experience and the physical site.

Explore Technology Applications:

- Interactive Storytelling: Enhance the current narrative with dynamic choices and branching storylines to deepen engagement.
- NFTs: Offer digital collectibles tied to key historical periods or artifacts within the application, allowing users to own a piece of Kellie Castle's story.
- Gamified Exploration: Introduce quests or challenges, such as solving historical puzzles, to encourage deeper interaction with the digital environment.

Stakeholder Buy-In:

The app can engage local heritage organizations, educational institutions, and community stakeholders. The project's ability to drive tourism, support cultural education, and preserve local history for future generations can be highlighted.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Provide a web-based preview of the application, allowing users to explore Kellie Castle virtually and pique interest in visiting the site.
- On-Site Phase: Incorporate AR features for in-person visitors, such as virtual guides or overlays that reveal how the castle evolved over time.
- Post-Visit Phase: Allow users to share their digital journey through the application, coupled with NFTs representing their visit.

Cultural and Business Asset Review:

- Identify key elements of Kellie Castle's history (e.g., architectural changes and famous events) to prioritize for gamified storytelling or digital collectibles.
- Collaborate with local businesses to offer phygital souvenirs linked to NFTs earned through the application.

Opportunity Mapping:

- Expand the application's reach with AR functionality, allowing on-site visitors to interact with historical overlays of Kellie Castle.
- Create an NFT-based loyalty program, rewarding repeat visits or engagement with new content updates.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use NFTs to offer users ownership of unique digital artifacts, such as a 3D model of Kellie Castle at different points in history.
- Develop interactive, branching storylines that guide users through Kellie Castle's transformation over the centuries.
- Integrate AR overlays for use on-site, synchronized with the application's desktop content.

Concept Ideation:

- Introduce gamified elements, such as a 'time travel' feature where users complete challenges in each historical period to unlock rewards.
- Create phygital souvenirs, blending physical and digital items, such as postcards with QR codes linked to NFTs.

Stakeholder Collaboration:

- Collaborate with historians, local artisans, and educational institutions to ensure cultural authenticity and educational value.

Stage 4: Scope and Planning

Technology Partnership:

- Partner with developers experienced in Unity®, AR platforms, and blockchain to enhance the application with XR and Web3 features.

  Project Plan Development:

- Set milestones, such as incorporating AR overlays and designing NFTs for historical periods.
- Develop a Minimum Viable Product (MVP) with a single timeline of Kellie Castle's history integrated with gamified challenges.

  Training and Education:

- Create guides for educators and site staff to help users navigate the application and connect it to the physical site.

Stage 5: Solution Development

  Technical Specifications:

- Use blockchain standards (e.g., ERC-721, ERC-1155, etc.) to mint NFTs for digital collectibles.
- Develop AR functionality with accurate overlays of Kellie Castle's architectural evolution.

  Iterative Development:

- Test each feature with target users, including educators, tourists, and heritage enthusiasts, to refine usability and engagement.

  Marketing Strategy:

- Promote the application through partnerships with tourism boards and educational platforms, emphasizing its immersive storytelling and cultural preservation goals.

Stage 6: Testing and Refinement

  Functional Testing:

- Validate the performance of AR features and NFT integrations.
- Test the application's interactivity and narrative flow across different user demographics.

  User Feedback:

- Conduct surveys and focus groups to evaluate the app's usability, storytelling effectiveness, and emotional impact.
- Address concerns, such as pacing and information delivery, identified during earlier user testing.

  Compliance Check:
  Ensure alignment with heritage preservation standards and accessibility guidelines.

Stage 7: Deployment and Support

  Launch Strategy:

- Roll out the updated application with AR and Web3 features, ensuring smooth integration with existing systems.
- Train site staff to guide visitors in using the app's on-site AR features.

  NFT Placement and Accessibility:

- Offer digital collectibles through an integrated marketplace within the app.
- Use QR codes in physical locations to link visitors to relevant NFTs or interactive features.

  Compatibility and Maintenance:

- Regularly update the app to include new stories, features, and technical improvements.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Monitor user engagement through metrics such as NFT redemptions, time spent in the app, and feedback on storytelling.
- Assess the app's impact on-site visitation rates and user satisfaction.

Long-Term Improvements:

- Expand the narrative to include additional historical periods or architectural changes.
- Explore partnerships with other historical sites to scale the application for broader use.

Applying the framework to "Memories of Kellie" enhances its potential as an interactive DCH tool, bridging digital and physical heritage experiences. By integrating NFTs, AR features, and gamified storytelling, the application can create lasting connections between users and Kellie Castle's history. These additions not only enrich the user experience but also support cultural preservation and sustainable tourism, ensuring the project's long-term relevance and impact.

*Appendix A.4. Applying the Framework to the Fort Ontario AR Experience*

The Fort Ontario AR Experience illustrates the application of AR technology to enhance historical exploration through immersive storytelling and contextualized visuals. Below, the framework is applied to refine the project, integrating gamified features, XR enhancements, and Web3 elements like NFTs to create a more engaging and sustainable Digital Cultural Heritage (DCH) experience.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The Fort Ontario AR app bridges historical narratives and interactive technology, transforming self-guided tours into immersive experiences. The use of AR provides visitors with contextual access to archival photos and detailed historical narratives, linking physical spaces to significant events from the 1860s to WWII. Expanding the app's functionality with gamified elements and phygital rewards can deepen engagement and attract diverse audiences.

Explore Technology Applications:

- Interactive Storytelling: Add AR-based narratives that immerse visitors in the fort's history, such as reenactments of key events.
- NFTs and Blockchain: Create digital collectibles based on archival photos or historical landmarks at Fort Ontario; these NFTs could be earned through exploration or purchased as memorabilia.
- Gamified Trails: Introduce quests, such as finding historical markers on-site, to encourage active participation and discovery.

Stakeholder Buy-In:

The project can collaborate with historical societies, local tourism boards, and state park authorities to align the app's goals with heritage preservation, visitor education, and revenue generation.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Allow visitors to preview the AR experience through online demos, encouraging on-site visits.
- On-Site Phase: Use AR to enhance the guided tour, with interactive prompts that unlock stories tied to specific fort locations.
- Post-Visit Phase: Enable visitors to purchase or earn NFTs of archival photos or maps, creating a lasting digital connection to their visit.

Cultural and Business Asset Review:

- Identify key historical events, landmarks, and artifacts at Fort Ontario to prioritize for AR content development.
- Develop partnerships with local businesses to offer phygital souvenirs tied to the app's digital content.

Opportunity Mapping:

- Introduce loyalty rewards, such as NFT badges for completing AR-based challenges.
- Expand AR capabilities to include overlays of how the fort changed over time.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use blockchain to authenticate and mint archival photos as collectible NFTs.
- Develop AR-guided challenges that allow users to uncover hidden stories within the fort's history.

Concept Ideation:

- Enhance the app with an interactive timeline, allowing visitors to explore different historical eras of Fort Ontario.
- Create AR scenes that visualize historical events, such as WWII refugees arriving at the fort.

Stakeholder Collaboration:

- Engage historians, local educators, and tourism experts to ensure the app provides accurate, engaging, and educational content.

Stage 4: Scope and Planning

Technology Partnership:

- Partner with AR and blockchain developers to expand the app's functionality and integrate NFTs seamlessly.

Project Plan Development:

- Define milestones, such as creating AR overlays for key fort locations.
- Develop a Minimum Viable Product (MVP) with a single gamified trail and NFT integration.

Training and Education:

- Train park staff to guide visitors in using the app and emphasize its cultural and historical significance.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721) to create unique digital collectibles.
- Develop AR content that seamlessly overlays archival photos and historical animations onto physical locations.

Iterative Development:

- Conduct usability testing with diverse user groups, including tourists, educators, and older adults, to refine content and interface design.

Marketing Strategy:

- Promote the app through social media, local tourism websites, and partnerships with historical organizations.

Stage 6: Testing and Refinement

Functional Testing:

- Validate the AR app's functionality in various weather conditions to address feedback about usability challenges in windy environments.
- Ensure NFT transactions are seamless and intuitive for non-technical users.

User Feedback:

- Collect feedback through on-site surveys and online forms, focusing on engagement, usability, and content appeal.
- Address accessibility issues, such as challenges faced by users with arthritis, by refining the interface design.

Compliance Check:

- Ensure alignment with cultural heritage preservation standards and accessibility guidelines.

Stage 7: Deployment and Support

Launch Strategy:

- Roll out the updated app with AR enhancements and NFT capabilities, ensuring staff support during the initial launch phase.
- Train guides to emphasize the app's unique features during visitor interactions.

NFT Placement and Accessibility:

- Offer NFTs representing key historical events or artifacts, available through the app or physical QR codes at the site.
- Provide visitors with resources to understand and use NFTs effectively.

Compatibility and Maintenance:

- Regularly update the app with new AR content and address technical issues as they arise.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Track user engagement through metrics such as NFT redemptions, AR feature usage, and app session durations.
- Assess the app's impact on visitor satisfaction and site revenue.

Long-Term Improvements:

- Expand AR content to include more historical narratives and interactive elements.
- Explore partnerships with other state parks to replicate the app's success at similar sites.

Applying the framework to the Fort Ontario AR Experience enhances its potential as a tool for cultural preservation and visitor engagement. By integrating gamified elements, NFTs, and XR features, the app can offer richer, more personalized interactions with Fort Ontario's history. These enhancements not only attract diverse audiences but also support sustainable tourism and the fort's long-term preservation efforts.

### *Appendix A.5. Applying the Framework to the Hanging Gardens of Babylon AR Application*

The Hanging Gardens of Babylon AR application showcases AR's potential to revolutionize historical education and cultural heritage experiences by recreating one of the ancient wonders of the world. Below, the framework is applied to enhance the app's educational and cultural impact, incorporating Web3 features, gamified elements, and XR technologies to engage global audiences and promote sustainable cultural heritage.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The Hanging Gardens of Babylon AR app bridges the gap between historical education and modern technology, allowing global audiences to explore a lost wonder. This immersive experience demonstrates the potential of AR for enhancing information retention and cultural awareness. Expanding the app with gamified learning paths and phygital artifacts would further enrich its educational impact and broaden its appeal.

Explore Technology Applications:

- Interactive Storytelling: Develop a guided narrative that immerses users in the history of the Hanging Gardens, highlighting its architectural marvels and cultural significance.
- NFTs and Blockchain: Introduce NFTs tied to key aspects of the gardens, such as collectible digital plants or architectural elements; these could serve as educational tools or digital souvenirs.
- Gamified Exploration: Create tasks such as assembling a virtual replica of the gardens or uncovering hidden historical facts to encourage user engagement.

Stakeholder Buy-In:

The app can collaborate with educators, historians, and cultural institutions to ensure the app aligns with educational goals and historical accuracy. AR and blockchain developers can be engaged to incorporate advanced features.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Offer a preview of the Hanging Gardens' AR experience online, encouraging users to engage with the app and learn about its features.
- On-Site Phase: If tied to physical museum exhibits, enable AR overlays that contextualize the Hanging Gardens' historical setting.
- Post-Visit Phase: Allow users to collect NFTs or share their virtual exploration with peers, fostering continued engagement.

Cultural and Business Asset Review:

- Identify key cultural and architectural elements of the Hanging Gardens for AR features and digital collectibles.
- Partner with museums or educational platforms to expand the app's reach and create revenue opportunities.

Opportunity Mapping:

- Introduce gamified modules, such as quizzes and challenges, to deepen learning engagement.
- Develop an NFT-based loyalty program, rewarding repeat users with unique digital assets.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use NFTs to provide users with ownership of unique digital artifacts, such as rare plants or architectural features from the gardens.
- Develop AR-guided educational modules that provide interactive lessons about Babylonian culture and engineering.

Concept Ideation:

- Expand the app with time-travel elements, allowing users to explore the gardens during different historical periods.

- Integrate phygital souvenirs, such as postcards with QR codes linking to exclusive AR content.

Stakeholder Collaboration:

- Collaborate with educational organizations and tourism boards to integrate the app into school curriculums and cultural campaigns.

Stage 4: Scope and Planning

Technology Partnership:

The app can partner with AR developers and blockchain platforms to implement NFT functionalities and enhance AR features.

Project Plan Development:

- Define milestones, such as developing NFT collectibles and creating interactive storytelling modules.
- Build a Minimum Viable Product (MVP) with a single AR experience tied to a key historical narrative.

Training and Education:

- Provide resources for educators and museums to use the app effectively as a teaching tool.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721) to mint NFTs representing elements of the Hanging Gardens.
- Enhance AR functionality with features like dynamic lighting and 3D animations to bring the gardens to life.

Iterative Development:

- Test the app with diverse user groups, including educators, students, and cultural enthusiasts, to refine usability and content.

Marketing Strategy:

- Promote the app through partnerships with educational platforms and cultural organizations, emphasizing its immersive educational value.

Stage 6: Testing and Refinement

Functional Testing:

- Validate the app's AR features across multiple devices, ensuring a seamless user experience.
- Test NFT integrations and ensure user-friendly accessibility for non-technical users.

User Feedback:

- Conduct surveys and interviews to evaluate the app's effectiveness in enhancing learning retention and engagement.
- Address any usability issues, particularly for older users or those new to AR technology.

Compliance Check:

- Ensure the app meets cultural preservation standards and aligns with educational goals.

Stage 7: Deployment and Support

Launch Strategy:

- Launch the app with introductory campaigns targeting educational institutions and cultural heritage enthusiasts.
- Provide ongoing support to address technical issues and user queries.

NFT Placement and Accessibility:

- Offer NFTs through an integrated marketplace within the app.
- Use QR codes in promotional materials to direct users to exclusive digital collectibles.

Compatibility and Maintenance:

- Regularly update the app with new features, such as additional historical narratives or AR enhancements.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Measure user engagement through metrics such as NFT redemptions, task completions, and time spent in the app.
- Assess the app's impact on learning retention and cultural awareness.

Long-Term Improvements:

- Expand the app to include other ancient wonders, creating a comprehensive AR platform for historical exploration.
- Use analytics and user feedback to refine features and introduce new gamified content.

Applying the framework to the Hanging Gardens of Babylon AR application enhances its potential as an educational and cultural tool. Integrating gamified elements, NFTs, and interactive storytelling ensures a more engaging and sustainable experience for users. This approach not only supports learning retention but also promotes global cultural awareness, demonstrating AR's transformative potential for digital cultural heritage.

### *Appendix A.6. Applying the Framework to "The Life of a House" AR Application*

The "Life of a House" AR app demonstrates the use of immersive technology to bridge the gap between historical education and digital storytelling by visualizing the Weigh House, a lost architectural gem in Tallinn, Estonia. Below, the framework is applied to guide the app's design, development, and evaluation, focusing on enhancing user engagement, integrating gamified features, and employing Web3 elements like NFTs to ensure sustainability and broader appeal.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The app serves as a digital portal to the Weigh House's historical significance, using AR to overlay reconstructions on its original site. This approach aligns with the role of XR in fostering emotional connections to cultural heritage by blending physical artifacts with interactive narratives. Expanding the app with gamified learning paths and digital collectibles would further enrich its educational potential.

Explore Technology Applications:

- Interactive Storytelling: Add narratives that guide users through the Weigh House's history, including significant events from its construction to its destruction and rediscovery.
- NFTs and Blockchain: Introduce collectible NFTs tied to different historical periods or architectural features of the Weigh House; these could serve as digital mementos or educational resources.

- Gamified Exploration: Develop challenges, such as uncovering hidden details of the Weigh House's history, to encourage active participation and learning.

Stakeholder Buy-In:

The project can collaborate with Tallinn's cultural institutions, tourism boards, and UNESCO representatives to ensure the app supports heritage preservation, tourism, and education.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Provide users with an online preview of the app, including an introductory AR experience, to encourage site visits.
- On-Site Phase: Use AR overlays to reconstruct the Weigh House's physical dimensions and architectural details, allowing users to visualize its original grandeur.
- Post-Visit Phase: Enable users to collect NFTs or share their AR experiences on social media, fostering continued engagement.

Cultural and Business Asset Review:

- Identify key architectural elements and historical events related to the Weigh House to prioritize for AR content development.
- Explore partnerships with local artisans to create phygital souvenirs linked to the app's digital assets.

Opportunity Mapping:

- Introduce educational modules that provide in-depth information about the Weigh House's role in Tallinn's economy and architecture.
- Develop an NFT-based loyalty program, rewarding users who complete AR-based challenges or visit related heritage sites.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use blockchain to authenticate and mint NFTs tied to the Weigh House's historical and architectural features.
- Create AR-guided experiences that immerse users in the site's historical context, such as its economic role in the 16th century.

Concept Ideation:

- Expand the app with a timeline feature, allowing users to explore the Weigh House's evolution over centuries.
- Integrate phygital items, such as postcards with QR codes linking to exclusive AR content or NFT collectibles.

Stakeholder Collaboration:

- Collaborate with historians, architects, and AR developers to ensure cultural accuracy and technological excellence.

Stage 4: Scope and Planning

Technology Partnership:

- Partner with AR developers experienced in Unity® and Vuforia®, as well as blockchain platforms, to enhance the app's capabilities.

Project Plan Development:

- Define milestones, such as creating NFT collectibles and developing AR overlays for specific architectural features.

- Build a Minimum Viable Product (MVP) that focuses on a single timeline and a gamified trail.

Training and Education:

- Provide resources for museum staff and tour guides to use the app effectively and communicate its cultural significance.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721, ERC-1155, etc.) to create unique digital collectibles.
- Enhance AR functionality with accurate 3D models and interactive overlays of the Weigh House's reconstruction.

Iterative Development:

- Test the app with diverse representative user groups (including tourists, educators, and local residents) to refine usability and content.

Marketing Strategy:

- Promote the app through partnerships with Tallinn's tourism board and cultural institutions, highlighting its role in heritage preservation.

Stage 6: Testing and Refinement

Functional Testing:

- Validate the app's AR features across different devices to ensure a seamless user experience.
- Address technical issues, such as jittering AR overlays and confusing interface elements.

User Feedback:

- Conduct surveys and interviews to evaluate the app's effectiveness in enhancing learning retention and engagement.
- Incorporate feedback to refine interface design and instructional clarity.

Compliance Check:

- Ensure alignment with UNESCO heritage standards and accessibility guidelines.

Stage 7: Deployment and Support

Launch Strategy:

- Launch the app with targeted campaigns aimed at tourists, educators, and cultural enthusiasts.
- Provide ongoing support to address technical issues and gather user feedback.

NFT Placement and Accessibility:

- Offer NFTs representing architectural features or historical moments of the Weigh House through an integrated marketplace.
- Use QR codes on-site to link visitors to relevant digital collectibles.

Compatibility and Maintenance:

- Regularly update the app with new features, such as additional AR content or gamified challenges.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Monitor user engagement through metrics like task completion rates, NFT redemptions, and time spent in the app.

- Assess the app's impact on learning retention and cultural appreciation.

Long-Term Improvements:

- Expand AR content to include other historical sites in Tallinn, creating a city-wide AR experience.
- Use analytics and user feedback to refine gamified elements and introduce new narratives.

Applying the framework to the "Life of a House" AR application enhances its potential to serve as a tool for cultural preservation and public education. By incorporating gamified elements, NFTs, and immersive storytelling, the app can deepen user engagement and foster a global appreciation for Tallinn's architectural and historical heritage. These enhancements not only enrich the user experience but also promote sustainable tourism and the preservation of cultural landmarks.

*Appendix A.7. Applying the Framework to the Fountain of the Lions Application*

The Fountain of the Lions application demonstrates the effective use of interactive 3D modeling and VR to deepen visitor engagement with cultural heritage. Below, the framework is applied to enhance the app's functionality, integrating gamified features, immersive storytelling, and Web3 technologies to elevate its educational and experiential potential.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

The application serves as an interactive digital representation of the Fountain of the Lions, offering users insights into the artifact's historical significance and restoration process. This aligns with the role of XR technologies in preserving and educating about cultural heritage. Expanding the application with features like gamified narratives and phygital souvenirs would further enrich user engagement and extend its reach.

Explore Technology Applications:

- Interactive Storytelling: Develop narratives tied to the fountain's history and restoration, guiding users through different eras of the artifact's existence.
- NFTs and Blockchain: Introduce collectible NFTs representing specific lions, inscriptions, or restoration milestones; these digital assets could serve as educational tools and/or unique memorabilia.
- Gamified Exploration: Add challenges such as quizzes or puzzles about the artifact's history, encouraging active learning.

Stakeholder Buy-In:

The app can engage the Alhambra's conservation authorities, educational institutions, and tourism boards to align it with its preservation, education, and visitor engagement goals.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: Offer users a preview of the app and its features online, encouraging them to explore the artifact virtually before visiting.
- On-Site Phase: Enhance the app with AR overlays, allowing visitors at the site to interact with the fountain's 3D model and its inscriptions.
- Post-Visit Phase: Enable users to share their screenshots or achievements on social media and collect NFTs tied to their exploration.

Cultural and Business Asset Review:

- Identify key elements of the fountain (e.g., inscriptions, statues, and restoration phases) to prioritize for AR/3D features and NFT development.

- Partner with local businesses to offer phygital souvenirs tied to the app's content.

Opportunity Mapping:

- Expand the app's capabilities with features like language customization and AR overlays that compare historical states of the fountain.
- Introduce a loyalty program that rewards users for completing educational tasks or visiting related heritage sites.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use blockchain to authenticate and mint NFTs tied to specific features of the fountain.
- Create AR and VR experiences that visualize the fountain's changes over time, allowing users to interact with its history dynamically.

Concept Ideation:

- Introduce a feature where users can virtually "rebuild" the fountain, earning points or NFTs for completing sections.
- Develop an AR-based treasure hunt at the Alhambra, encouraging users to explore related artifacts.

Stakeholder Collaboration:

- Collaborate with historians, conservationists, and XR developers to ensure cultural accuracy and technical excellence.

Stage 4: Scope and Planning

Technology Partnership:

- Partner with AR/VR and blockchain developers to integrate advanced features and Web3 elements into the app.

Project Plan Development:

- Define milestones, such as creating NFT collectibles and developing gamified storytelling modules.
- Build a Minimum Viable Product (MVP) focused on a single restoration phase or interactive narrative.

Training and Education:

- Develop resources for museum staff and educators to guide users in navigating the app's features and content.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721) for NFTs representing the fountain's individual statues or historical phases.
- Enhance 3D and AR features with accurate textures, lighting, and motion-capture animations.

Iterative Development:

- Test prototypes with diverse user groups, including tourists, students, and cultural enthusiasts, to refine usability and engagement.

Marketing Strategy:

- Promote the app through social media campaigns and partnerships with educational institutions, emphasizing its cultural and educational value.

Stage 6: Testing and Refinement

Functional Testing:

- Validate the usability of 3D and AR interactions across devices, including touch-screen monitors and VR headsets.
- Test NFT integration, ensuring accessibility and seamless transactions.

User Feedback:

- Conduct surveys and interviews to evaluate user satisfaction and learning outcomes.
- Address feedback, such as simplifying navigation or improving instructional clarity.

Compliance Check:

- Ensure alignment with cultural preservation standards and accessibility guidelines.

Stage 7: Deployment and Support

Launch Strategy:

- Roll out the app with targeted campaigns aimed at tourists, educators, and cultural heritage enthusiasts.
- Provide on-site support to help visitors engage with the app and its features.

NFT Placement and Accessibility:

- Offer NFTs through the app's marketplace or as rewards for completing tasks.
- Use QR codes at the site to link visitors to relevant digital collectibles.

Compatibility and Maintenance:

- Regularly update the app with new features, such as additional restoration phases or AR/VR enhancements.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Monitor engagement through metrics like NFT redemptions, task completion rates, and time spent interacting with the app.
- Assess the app's impact on user satisfaction and cultural understanding.

Long-Term Improvements:

- Expand content to include other sections of the Alhambra or related historical artifacts.
- Use analytics to refine gamified elements and introduce new interactive features.

Applying the framework to the Fountain of the Lions application enhances its potential as a tool for cultural preservation and interactive learning. By integrating gamified storytelling, NFTs, and immersive AR/VR features, the app can offer richer and more personalized experiences for users. These enhancements not only deepen engagement but also support sustainable tourism and the preservation of this UNESCO World Heritage Site.

### *Appendix A.8. Applying the Framework to the CHISel Platform*

The Cultural Heritage Information System (CHISel) platform is a powerful multi-user tool for managing and analyzing 3D replicas of archaeological artifacts. Below, the framework is applied to enhance the platform's usability, multi-user collaboration, and support for cultural heritage research. This includes gamified features and Web3 elements to encourage engagement, streamline data management, and ensure sustainable, secure collaboration.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

CHISel serves as a multi-user 3D annotation and analysis platform, enabling researchers to collaborate on artifact restoration and documentation. The platform's layered data system allows precise spatial referencing, essential for restoration and analysis. Enhancing CHISel with gamified elements and blockchain-enabled features could increase user engagement and ensure data integrity across multi-user environments.

Explore Technology Applications:

- Interactive Annotations: Enable users to engage with 3D models through intuitive interactions, such as guided annotations and collaborative editing tools.
- Blockchain and NFTs: Introduce blockchain for secure tracking of edits and data provenance; NFTs could represent specific artifact layers or key restoration milestones, ensuring authenticity and secure access to sensitive data.
- Gamified Collaboration: Add gamified features like points or badges for completing collaborative tasks or contributing high-quality annotations.

Stakeholder Buy-In:

The project can engage cultural heritage institutions, restoration experts, and software developers to align CHISel's goals with the needs of researchers and museums. The potential for streamlining workflows and improving data security can be highlighted.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Use Phase: Provide an onboarding tutorial and demo to familiarize new users with CHISel's features, reducing the learning curve.
- In-Use Phase: Offer live collaboration tools that track edits, changes, and comments in real time, ensuring seamless teamwork.
- Post-Use Phase: Allow users to generate reports summarizing their annotations and analyses, which can be shared or archived securely.

Cultural and Business Asset Review:

- Identify high-value use cases, such as tracking restoration phases or analyzing spatial relationships in artifacts, to prioritize for feature development.
- Explore partnerships with cultural institutions to expand CHISel's applicability across different artifact types and collections.

Opportunity Mapping:

- Integrate NFT-based certificates for significant restoration milestones or contributions, providing a secure record of data provenance.
- Expand the platform's collaborative tools to include real-time chat and task assignment features.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use blockchain to create a secure audit trail for multi-user edits and annotations.
- Develop gamified workflows that reward users for completing key tasks, such as accurately mapping spatial relationships.

Concept Ideation:

- Introduce interactive guides for new users, helping them navigate complex features like layer creation and spatial annotations.
- Create a leaderboard or achievement system to encourage collaborative contributions.

Stakeholder Collaboration:

- Work with archaeologists, conservators, and technology partners to refine CHISel's features and ensure they meet domain-specific needs.

Stage 4: Scope and Planning

Technology Partnership:

- Collaborate with blockchain developers to integrate secure data management features and implement NFT functionality.

Project Plan Development:

- Define milestones, such as implementing blockchain for edit tracking or developing a gamified tutorial.
- Develop a Minimum Viable Product (MVP) focused on a single artifact type or restoration workflow.

Training and Education:

- Provide workshops and tutorials for researchers and cultural heritage professionals to maximize CHISel's usability and adoption.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721) to authenticate NFT-based artifact annotations.
- Enhance the user interface with intuitive tools for layer creation, editing, and multi-user collaboration.

Iterative Development:

- Test the platform with diverse user groups, including restoration experts, museum staff, and students, to refine usability and collaborative features.

Marketing Strategy:

- Promote CHISel through academic conferences, cultural heritage events, and partnerships with museums and research institutions.

Stage 6: Testing and Refinement

Functional Testing:

- Validate multi-user collaboration features, ensuring real-time consistency and data accuracy.
- Test blockchain integration for secure data tracking and NFT issuance.

User Feedback:

- Gather feedback through structured interviews and surveys to evaluate the platform's usability, efficiency, and collaborative capabilities.
- Address usability concerns, such as confusing interface elements or slow rendering.

Compliance Check:

- Ensure alignment with cultural heritage preservation standards and data security regulations.

Stage 7: Deployment and Support

Launch Strategy:

- Launch CHISel with targeted outreach to cultural heritage organizations, emphasizing its collaborative and secure features.
- Provide live support and documentation to assist users during the onboarding phase.

NFT Placement and Accessibility:

- Offer NFTs representing key restoration phases or unique annotations, available through CHISel's integrated marketplace.
- Ensure NFTs are accessible to all users through intuitive interfaces and wallets.

Compatibility and Maintenance:

- Regularly update the platform with new features and improvements, addressing user feedback and emerging needs.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Track engagement metrics, such as the number of collaborative tasks completed and NFT transactions.
- Assess the platform's impact on restoration workflows and research outcomes.

Long-Term Improvements:

- Expand CHISel's capabilities to support other types of artifacts or collections.
- Use analytics and user feedback to refine gamified elements and improve collaborative tools.

Applying the framework to the CHISel platform enhances its potential as a tool for collaborative cultural heritage research and restoration. By integrating gamified workflows, blockchain for secure data management, and user-friendly collaboration tools, CHISel can streamline complex workflows and improve data accuracy. These enhancements not only foster interdisciplinary teamwork but also promote long-term preservation and accessibility of cultural heritage artifacts.

### *Appendix A.9. Applying the Framework to the PLUGGY Platform*

The PLUGGY platform is a transformative tool for engaging users with cultural heritage, empowering them as creators and curators of cultural content. Below, the framework is applied to enhance PLUGGY's features, integrating gamified elements, blockchain-enabled data management, and additional user-centric tools to deepen engagement and foster sustainable participation.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

PLUGGY revolutionizes engagement with cultural heritage by enabling users to create virtual exhibitions, museums, and collections. It bridges the gap between cultural institutions and individual users, fostering participation and storytelling through a social platform. Integrating gamified features and Web3 technologies can further empower users while ensuring secure data management and increased engagement.

Explore Technology Applications:

- Interactive Storytelling: Expand the curatorial tools with interactive narratives and augmented reality (AR) experiences, allowing users to guide audiences through their collections dynamically.
- Blockchain and NFTs: Introduce NFTs tied to user-created exhibitions or specific media assets, enabling ownership and secure sharing of digital cultural heritage.
- Gamified Participation: Reward users for creating, sharing, and curating cultural content with badges, points, or collectible NFTs.

Stakeholder Buy-In:

The project can engage cultural institutions, educational organizations, and developers to align PLUGGY's tools with diverse needs. The platform's potential to enhance cultural preservation and foster global collaboration can be highlighted.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Engagement Phase: Provide tutorials and walkthroughs to help users navigate PLUGGY's tools and features, lowering the learning curve.
- Engagement Phase: Enhance the user experience with collaborative features, such as co-curation of exhibitions and real-time feedback.
- Post-Engagement Phase: Enable users to share their exhibitions widely, integrating social media sharing and NFT-based ownership of their content.

Cultural and Business Asset Review:

- Identify high-value use cases, such as connecting user-generated stories to institutional collections.
- Explore partnerships with local heritage sites to integrate their collections into PLUGGY's ecosystem.

Opportunity Mapping:

- Introduce tools that allow users to gamify their exhibitions, such as interactive quizzes or AR challenges within curated stories.
- Expand PLUGGY's functionality to include tools for creating phygital souvenirs.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Use blockchain to authenticate user-created content and ensure secure ownership and sharing of cultural data.
- Develop gamified modules that reward users for milestones, such as creating a first exhibition or receiving a specific number of likes.

Concept Ideation:

- Introduce features allowing users to link virtual exhibitions to geolocated AR content, enabling hybrid online–offline experiences.
- Expand community features, such as leaderboards or collaborative exhibition challenges.

Stakeholder Collaboration:

- Work with cultural institutions, technology developers, and community leaders to refine PLUGGY's tools and maximize its cultural impact.

Stage 4: Scope and Planning

Technology Partnership:

- Collaborate with blockchain and AR developers to expand PLUGGY's functionality and enable seamless integration of Web3 technologies.

Project Plan Development:

- Define milestones, such as integrating NFTs for user-generated content and expanding gamified features.
- Build a Minimum Viable Product (MVP) for testing enhanced storytelling and gamified tools.

Training and Education:

Workshops and online resources can be developed to train users, educators, and cultural institutions in using PLUGGY effectively.

Stage 5: Solution Development

Technical Specifications:

- Use blockchain standards (e.g., ERC-721) for NFT-based ownership of curated content.

- Enhance the platform's user interface to support intuitive curation, annotation, and sharing of exhibitions.

Iterative Development:

Prototypes can be tested with diverse user groups, including cultural enthusiasts, educators, and institutional partners, to refine usability and engagement.

Marketing Strategy:

PLUGGY can be promoted through cultural heritage networks, emphasizing its user-centric tools and potential for community-driven storytelling.

Stage 6: Testing and Refinement

Functional Testing:

- Validate features like AR integration and NFT issuance across different devices.
- Ensure user-created exhibitions are easy to navigate and share.

User Feedback:

- Conduct surveys and interviews to evaluate user satisfaction, focusing on accessibility, ease of use, and engagement.
- Address usability concerns, such as clarifying licensing options for uploaded content.

Compliance Check:

It should be ensured that the platform meets data privacy and intellectual property standards for user-generated cultural content.

Stage 7: Deployment and Support

Launch Strategy:

- Roll out enhanced PLUGGY features with targeted campaigns to cultural heritage communities and social media platforms.
- Provide live support to assist users in creating and sharing their exhibitions.

NFT Placement and Accessibility:

- Enable NFTs for digital collections, with intuitive interfaces for managing ownership and sharing.
- Allow users to integrate their NFT content into physical exhibits or AR experiences.

Compatibility and Maintenance:

The platform should be regularly updated with new tools and features based on user feedback and emerging needs.

Stage 8: Evaluation and Iteration

Performance Metrics:

- Track engagement metrics, such as the number of exhibitions created, shared, and viewed.
- Monitor user retention and satisfaction through surveys and analytics.

Long-Term Improvements:

- Expand PLUGGY's API to support third-party applications and broader interoperability.
- Use analytics to refine gamified tools and introduce new ways to engage users.

Applying the framework to the PLUGGY platform enhances its role as a collaborative and user-driven cultural heritage tool. Integrating gamified features, AR storytelling, and blockchain technology ensures broader participation, secure data management, and long-term engagement. These enhancements not only empower individuals as creators and curators but also foster sustainable cultural preservation and a deeper connection to heritage.

*Appendix A.10. Applying the Framework to the Picasso AR App*

The Picasso AR experience, part of the VisitAR platform, transforms Málaga's cultural landscape into an interactive playground where users engage with historical sites and figures like Picasso through augmented reality. This use case highlights lean, design-thinking-driven development, integrating gamified exploration and local business engagement to create a sustainable model for cultural tourism and phygital rewards.

Stage 1: Background and Vision Setting

Define the DCH XR Context:

VisitAR uses AR to connect physical landmarks with interactive digital narratives, letting users meet Picasso virtually and learn about Málaga's heritage. It merges edutainment, tourism, and cultural storytelling in a mobile-first experience.

Explore Technology Applications:

- Interactive Storytelling: Users talk to AR Picasso, explore historical overlays, and complete cultural quests.
- Blockchain and NFTs: In-app coins earned through play can evolve into NFTs redeemable at partner venues.
- Gamified Trails: Points of interest are linked by challenges, trivia, and puzzles that drive exploration and repeat use.

Stakeholder Buy-In:

Local businesses, educators, and tourism boards were involved from the start, validating the app's ability to drive economic and educational value.

Stage 2: Identify Opportunities

Customer-Centric Needs Assessment:

- Pre-Visit Phase: City map and teaser content introduce users to the experience.
- On-site Phase: AR interactions and location-based challenges engage tourists in real time.
- Post-Visit Phase: Users share experiences and redeem points, with plans for NFT-based souvenirs and loyalty rewards.

Cultural and Business Asset Review:

- Cultural touchpoints include Picasso's statue, birth house, and historic plazas. Local businesses benefit from coin-based incentives tied to real purchases.

Opportunity Mapping:

- Future expansions include NFT-based collectibles, souvenir co-branding, and AR overlays for other historical figures or neighborhoods.

Stage 3: Define Projects

Matrix of Opportunities and Utilities:

- Combine AR-triggered storytelling with a digital rewards system redeemable for local perks, and introduce NFTs to memorialize visits.

Concept Ideation:

- Virtual Picasso dialogues, time-travel overlays, and citywide cultural scavenger hunts form the core engagement loops.

Stakeholder Collaboration:

- Ongoing collaboration with tourism authorities, teachers, and partner venues ensures cultural accuracy and economic integration.

Stage 4: Scope and Planning

Technology Partnership:

- Building with Unity® 3D and GPT APIs, and supporting blockchain integration and loyalty program scalability.

Project Plan Development:

- Starting with an MVP focused on Picasso's statue and plaza, the next phases will scale across Málaga.

Training and Education:

- Local staff and businesses need guidance on app features and visitor interaction best practices.

Stage 5: Solution Development

Technical Specifications:

- WebAR and geolocation are used to activate AR scenes; coins are to be tracked via a central database with NFT-readiness.

Iterative Development:

- Pilot testing in Málaga guided interface updates and storytelling refinements based on real user behavior.

Marketing Strategy:

- Positioned as a smart tourism tool in digital campaigns, with cross-promotion from local businesses and the city's tourism board.

Stage 6: Testing and Refinement

Functional Testing:

- Real-world testing confirmed location triggers, AR anchoring, and platform stability across devices.

User Feedback:

- Surveys and interviews showed strong user satisfaction, especially with the interactive AR Picasso and city challenges.

Compliance Check:

- Ensure data protection compliance and cultural content validation through expert consultation.

Stage 7: Deployment and Support

Launch Strategy:

- Deploy in central Málaga with media coverage and on-site promotion via tourism kiosks and café partners.

NFT Placement and Accessibility:

- Planned integration of collectible NFTs for challenge completions and time-based milestones.

Compatibility and Maintenance:

- App should work on both Android and iOS; it is future-proofed for expansion to additional XR features and content.

Stage 8: Evaluation and Iteration

Performance Metrics:

- App usage, coin redemption rates, business conversions, and social shares are tracked to guide growth.

Long-Term Improvements:

- Future iterations can expand to include multiplayer challenges, new historical figures, and NFT-based loyalty tiers.

Applying the framework to the Picasso AR Experience reinforces the value of XR and Web3 integration in smart tourism. By combining playful storytelling, cultural education, and local economic participation, VisitAR creates a scalable, user-centered model for digital cultural heritage.

## Appendix B

Stage 1: Background and Vision Setting

1. Define the DCH XR Context:
    - Articulate the role of the metaverse in connecting physical and digital cultural heritage for tourism, education, and preservation.
    - Highlight opportunities beyond traditional gaming, including gamified storytelling, cultural immersion, and community-building activities.
2. Explore Technology Applications:
    - Blockchain and NFTs: Develop virtual collectibles, membership tokens, and phygital souvenirs to incentivize participation and reward engagement.
    - Interactive Storytelling: Use AR/VR tools to enhance visitor immersion with gamified narratives and quests that deepen cultural understanding.
    - Gamified Trails: Integrate treasure hunts and challenges, linking digital twins of artifacts to on-site locations for an interactive experience.
3. Stakeholder Buy-In:
    - Communicate the vision to cultural institutions, local businesses, and technology partners.
    - Emphasize how the metaverse and Web3 technologies align with cultural preservation, accessibility, and local economic growth.

Stage 2: Identify Opportunities

1. Customer-Centric Needs Assessment:
    - Map the Customer Journey:
      Anticipation Phase: Pre-visit planning through virtual tours, gamified previews, and educational content.
      On-Site Phase: Immersive AR/VR-guided tours, gamified treasure hunts, and NFT-earning activities.
      Post-Visit Phase: Memory sharing, NFT redemption for physical souvenirs, and access to exclusive digital content.
    - Conduct surveys and focus groups to identify user preferences for digital engagement.
2. Cultural and Business Asset Review:
    - Catalog unique local assets, including art, cuisine, and crafts, assigning uniqueness ratings (1–5) to prioritize phygital integration.
    - Explore potential synergies between cultural preservation and tourism.

3. Opportunity Mapping:
   - Evaluate overlapping application areas such as gamified educational tools, NFT-based loyalty programs, and virtual marketplaces for local artisans.

Stage 3: Define Projects

1. Matrix of Opportunities and Utilities:
   - Cross-reference customer needs with available XR and Web3 utilities:
     NFTs for membership or event participation;
     AR-guided trails connecting digital twins to physical artifacts;
     Virtual storefronts for local artisans, accessible through blockchain.
2. Concept Ideation:
   - Develop ideas such as the following:
     NFT-based rewards for completing gamified cultural quests;
     Phygital souvenirs blending digital and physical components;
     AR-enhanced storytelling tours with interactive elements.
3. Stakeholder Collaboration:
   - Engage cultural institutions, local businesses, and technology providers to refine project ideas and align objectives.

Stage 4: Scope and Planning

1. Technology Partnership:
   - Identify partners for developing XR platforms, blockchain infrastructure, and NFT design.
   - Establish timelines, budgets, and resource requirements for phased implementation.
2. Project Plan Development:
   - Define objectives, milestones, and deliverables.
   - Develop a Minimum Viable Product (MVP), such as one gamified AR trail with NFT rewards.
3. Training and Education:
   - Train staff in using XR and Web3 tools and educate them on guiding visitors through gamified experiences.

Stage 5: Solution Development

1. Technical Specifications:
   - Use established NFT standards (e.g., ERC-721 and ERC-1155) and ensure compatibility with digital wallets and platforms.
   - Design high-quality digital assets, such as 3D models, animations, and NFT collectibles.
2. Iterative Development:
   - Conduct regular feedback sessions with stakeholders.
   - Test and refine functionalities, ensuring alignment with user needs and project goals.
3. Marketing Strategy:
   - Collaborate with marketing teams to create campaigns showcasing the educational and cultural value of XR and NFT applications.

Stage 6: Testing and Refinement

1. Functional Testing:

- Validate the functionality of AR/VR tools, NFT transactions, and blockchain infrastructure.
- Test the integration of gamified elements, such as QR codes and AR triggers.

2. User Feedback:
   - Conduct beta testing with diverse user groups (e.g., families and international tourists) to address usability issues and improve accessibility.
3. Compliance Check:
   - Ensure alignment with cultural preservation guidelines and project objectives.

Stage 7: Deployment and Support

1. Launch Strategy:
   - Provide tech support and user guidance during the launch.
   - Train staff to troubleshoot issues and enhance visitor interactions with digital tools.
2. NFT Placement and Accessibility:
   - Display NFTs physically at attractions and digitally on websites.
   - Enable visitors to earn NFTs through gamified activities, redeemable for exclusive perks or souvenirs.
3. Compatibility and Maintenance:
   - Ensure seamless integration with AR platforms and digital wallets.
   - Provide ongoing updates and technical support to maintain functionality.

Stage 8: Evaluation and Iteration

## Appendix C. Overview of HCD Methods for XR Development

An overview of the most popular methods is provided in Table A1 below, organized by when to use them during the XR development process. The columns what, why, and how provide more details on the methods, and the final column of Table A1 provides an estimate of the relative cost (in terms of time and other resources) of applying this method compared to other methods. The actual cost will depend on the size of the project.

**Table A1.** Compilation of HCD methods, organized by when to use them during XR development.

| HCD Method | When to Use | What | Why | How | Cost |
|---|---|---|---|---|---|
| Interviews | Early Prototype Stage<br>Data: Qualitative<br>Type: Formative | Involves one-on-one interactions with individual users to gain in-depth insights into their experiences, behaviors, and motivations. | To understand users' specific needs, challenges, and goals when using the application. | Create questions and follow-up questions for the interview by asking experts. Record and analyze the responses finding patterns in what users say. | Moderate |
| Persona Descriptions | Early Prototype Stage<br>Data: Qualitative<br>Type: Formative | Persona descriptions developed through user research, interviews, surveys, and observational studies. Typically include demographic information, user goals, pain points, behaviors, and motivations. | To understand the diverse needs, behaviors, and goals of different user groups and ensure the application meets these varied requirements by providing the design team with a shared resource. | Compile typical and atypical end-user background information in a summary and format that is suitable to emphasize the representative end-user traits, needs, and expectations. | Low to Moderate |
| Expert Review | Early Conceptual Stage<br>Data: Qualitative<br>Type: Formative | Involves one or more usability experts evaluating the application based on established usability principles and best practices. | To identify potential usability issues early on in the development and provide actionable recommendations for improvement. | Identify the typical usability issues for the application and for the scenario of use of the application. Verify for each how well it meets the requirements, and if not met, describe how to improve. | Low |

**Table A1.** *Cont.*

| HCD Method | When to Use | What | Why | How | Cost |
|---|---|---|---|---|---|
| Focus Groups | Early Conceptual Stage Data: Qualitative Type: Formative | Consists of group discussions with target users to gain qualitative insights into their perceptions, needs, and preferences. | To explore users' attitudes and opinions about the application, gather initial feedback on concepts, and understand user expectations. | Identify the screening questions for selecting the focus group members by asking experts. Organize the activities of the focus group, record and summarize focus group opinions. | Moderate |
| Card Sorting | Early Prototype Stage Data: Qualitative Type: Formative | Involves users to organize application content information into logical categories to understand how the users prefer the information to be grouped and structured. | To gather detailed insights into user behavior, identify usability issues, and receive direct user feedback. | Identify the categories for the cards and create them. Record and analyze how participants order them, and look for any patterns in their choices. | Moderate |
| Prototype Think-Aloud Testing | Mid-Development Stage Data: Qualitative Type: Formative | Requires users to verbalize their thoughts and actions as they interact with increasingly more finished prototypes of the application. | To capture real-time feedback and understand users' decision-making processes, pain points, and areas of confusion. | Observe, record and analyze representative end-users' behaviors as they interact with the UI and verbalize their thinking about the task at hand and their interactions with the UI. | Moderate |
| Remote Prototype Usability Testing (if intended to be used remotely) | Mid-Development Stage Data: Qualitative/ Mixed Type: Formative | Allows computational load testing for multi-user applications, and enables users to participate from their own locations, providing flexibility and convenience. | To evaluate the application's usability and robustness and to gather feedback from a geographically diverse user base. | Observe, record, and analyze the behaviors of representative end-users during specific tasks using the application. Identify areas for improvement and write suggestions. | Moderate |
| In-Person Prototype Usability Testing | Late Development Stage Data: Qualitative/ Mixed Type: Formative/Summative | Involves observing users as they interact with increasingly more finished prototypes of the application in a controlled environment. | To gather detailed insights into user behavior, identify usability issues, and receive direct user feedback. | Observe, record, and analyze the behaviors of end-users during specific tasks using the application. Identify areas for improvement and write suggestions. | High |
| A/B Testing | Late Development Stage Data: Quantitative Type: Summative | Compares two or more design variations to determine which performs better with users. | To make data-driven design decisions and optimize specific elements of the application. | Compare the scores of empirically assigned groups using statistical tests. | Moderate to High |
| Interaction Data Stream Analysis | Post-Launch and Ongoing Improvement Data: Quantitative Type: Summative | Involves automatically tracking user interactions and behaviors within the XR application and collecting the data stream. | To gather quantitative data on how users navigate, engage, and interact with the application. | Decide what behaviors to track and how to record and analyze them, creating datasets and statistical analysis. | Low |
| User Surveys and Questionnaires | Post-Launch and Ongoing Improvement Data: Quantitative/Mixed Type: Summative | Gathers feedback from a large number of users on their overall satisfaction, preferences, and user experience with the application. | To collect quantitative data and assess user opinions on various aspects of the application, helping to identify areas for improvement and measure overall user satisfaction. | Decide what data to collect and how to record and analyze them, creating datasets and statistical analysis. | Low to Moderate |

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