Multi-Stakeholder Perspective on Socio-Technical XR Implementation in Higher Education Curricula

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Abstract

As eXtended Reality (XR) technologies continue to mature, they present significant opportunities to enhance higher education through immersive, experiential, and learner-centered pedagogies. Despite this potential, adoption within higher education institutions remains limited due to complex, interdependent socio-technical barriers that extend beyond the technology itself. This study investigates XR implementation at Virginia Tech, a land-grant R1 institution, through a systems engineering lens, focusing on identifying key stakeholders, characterizing their roles and interdependencies, and examining the barriers and enablers influencing adoption and scalability.

A single-case study design was employed, integrating mixed methods comprising a campus-wide survey (N = 232), educator focus groups (N = 14), and semi-structured interviews with domain experts in information technology, accessibility, and information security (N = 3). The study also documents the development process of a supplemental XR tool, in collaboration with an external team, to examine the real-world development workflows and identify implementation constraints.

Across these data sources, findings indicate that XR adoption is shaped by interdependent socio-technical factors. These include financial constraints, infrastructure limitations, pedagogical misalignment, accessibility concerns, governance requirements, and fragmented institutional coordination. Critical gaps were identified in faculty training, cross-functional collaboration, and governance frameworks for XR-generated behavioral and biometric data. Despite these challenges, XR demonstrates strong potential to enhance engagement and experiential learning when aligned with instructional goals and supported by sustained institutional infrastructure. This study contributes a stakeholder-informed framework and actionable recommendations, namely a Stakeholder Needs Document and an External XR Development Guide, to support scalable and sustainable XR implementation in higher education.

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General Audience Abstract

Universities are under increasing pressure to modernize teaching in a rapidly evolving, technology-driven world. eXtended Reality (XR), which includes virtual, augmented, and mixed reality, offers new ways to create immersive, hands-on learning experiences. However, many universities struggle to adopt these technologies due to cost, technical challenges, and the need for coordination across different institutional groups.

This study explores how XR can be effectively implemented in higher education through a case study at Virginia Tech. Rather than focusing only on the technology itself, the research examines the people and systems involved, including faculty, instructional designers, technical staff, accessibility experts, and administrators. Using surveys, focus groups, and interviews, the study identifies what challenges these groups face and what support they need.

The findings show that while XR has strong potential to improve engagement and real-world skill development, successful adoption depends on addressing broader institutional challenges, including limited funding, lack of faculty training, accessibility barriers, unclear data privacy policies, and poor coordination across departments and colleges, and limited institutional awareness hindering cross-unit collaboration. The study provides practical tools and recommendations to help universities adopt XR more effectively. Ultimately, immersive technology succeeds not because of what it is, but because of how well institutions prepare to support it.

Dedication & Acknowledgements

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CHAPTER 1: Introduction

Higher education is at a critical point as institutions face increasing pressure to evolve traditional pedagogical approaches in response to a rapidly changing, technology-driven world. The emergence of Industry 4.0, characterized by rapid advancements in automation, digitalization, and intelligent systems, is reshaping workforce demands and redefining the skills required for future careers. These transformations have led to a growing recognition that traditional educational models may be insufficient for preparing students to navigate complex, interdisciplinary, and evolving professional environments (Ahmad et al., 2022; Udvaros et al., 2023).

In response, higher education institutions (HEIs) are increasingly expected to provide learning experiences that foster advanced digital competencies, critical thinking, and practical, application-based skills aligned with the "Jobs of Tomorrow." At the same time, the expectations of digitally native Generation Z and Alpha students - who are accustomed to interactive, technology-rich environments - are further driving the need for more immersive, flexible, and student-centered learning approaches (Caratozzolo et al., 2021; Akour & Alenezi, 2022). These converging pressures highlight a growing mismatch between traditional lecture-based instruction and the demands of both modern learners and the evolving workforce, reinforcing the need for active, experiential, and technology-enhanced pedagogies (Almeida & Simões, 2019).

Within this context, eXtended Reality (XR), an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a promising avenue for transforming higher education. XR technologies enable interactive, experiential, and self-regulated learning opportunities that are often absent in traditional instructional methods. These immersive experiences have been shown to enhance learner motivation, engagement, and knowledge retention, particularly in domains requiring spatial understanding, hands-on practice, and/or access to otherwise inaccessible environments (Radianti et al., 2020; Aguayo & Eames, 2023). Additionally, the increasing availability of commercially accessible head-mounted displays (HMDs) has lowered technical barriers, making XR more feasible for classroom integration.

Despite its potential, XR remains underutilized in HEIs. This underutilization is largely attributed to a range of socio-technical barriers that extend beyond the technology itself. HEIs are complex, bureaucratic organizations with distributed decision-making structures, where implementation requires coordination across multiple stakeholders, including faculty, administrators, instructional designers, and technical staff. Challenges such as limited technical expertise, insufficient development resources, lack of pedagogical alignment, and concerns related to cost, scalability, and infrastructure continue to hinder widespread adoption (Obeidallah et al., 2023; Kluge et al., 2022). These barriers are often interdependent and embedded within broader institutional systems, making XR implementation a complex organizational challenge rather than a purely technological one.

Given these challenges, understanding the roles, needs, and relationships of stakeholders involved in XR implementation is critical. Successful integration requires coordinated effort across multiple organizational levels and functional domains, highlighting the importance of examining XR adoption as a socio-technical systems problem. However, existing research has largely focused on learner outcomes or isolated implementation challenges, with limited attention to system-level coordination, stakeholder interdependencies, and institutional processes that influence adoption at scale.

To address these gaps, this case study investigates XR implementation in higher education as a socio-technical systems problem within the context of Virginia Tech (VT), a land-grant R1 institution. Drawing on the XR Community of Practice (XR CoP) initiative (see Section 2.4), the research examines multiple phases of XR adoption, including identifying institutional needs, assessing current implementation practices, and analyzing development workflows. This study is guided by the following research questions:

- **RQ1:** Who are the key stakeholders involved and what are their roles, needs, and relationships in XR implementation within higher education institutions?
- **RQ2:** What socio-technical barriers and enablers influence the adoption and scalability of XR in higher education?
- **RQ3:** How do socio-technical factors shape the external XR development process in higher education?

By adopting a systems engineering (SE) perspective, this study captures stakeholder perspectives through surveys, semi-structured interviews, and focus groups. The research examines both the benefits and barriers associated with XR integration, with particular attention to processes that support the development of modular XR content aligned with curricula, institutional policies, and regulatory requirements.

Ultimately, this work generates evidence-based, actionable recommendations to guide HEIs in modernizing educational practices through XR. By characterizing socio-technical barriers and identifying best practices, the study contributes to the development of a structured framework for scalable, sustainable, and pedagogically aligned XR adoption, advancing the broader discourse on the role of immersive technologies in higher education.

CHAPTER 2: Literature Review

2.1. Technology & Learning Foundations

2.1.1. Drivers of Transformation in Higher Education

HEIs are increasingly under pressure to adapt to a rapidly evolving, technology-driven economy. The emergence of Industry 4.0 (i.e., the integration of automation, digitalization, and advanced technologies) is reshaping labor market demands and redefining the skills required for future work, leading to growing recognition that traditional educational models are insufficient for preparing students for complex, interdisciplinary career pathways (Ahmad et al., 2022; Udvaros et al., 2023; Zárate & Rondero, 2023). Consequently, universities are compelled to emphasize digital competencies, higher-order cognitive skills, and practical, application-based knowledge while continuously adapting curricula to anticipate shifting workforce expectations (Alenezi, 2022; Røe et al., 2022; Bondin & Zammit, 2025).

Traditional lecture-based pedagogies are widely viewed as misaligned with both modern learners and Industry 4.0 environments. Research advocates for active, student-centered, and experiential approaches that promote engagement, collaboration, and problem-solving (Almeida & Simões, 2019), expectations further reinforced by Generation Z and Alpha students, who are characterized as digital natives expecting interactive, flexible, and immersive learning environments (Caratozzolo et al., 2021; Akour & Alenezi, 2022).

Collectively, these trends signal a broader digital transformation in which institutions must reconsider not only how they teach, but also how they organize, design, and resource their educational environments (Bonfield et al., 2020; de Moraes et al., 2024). Within this landscape, technologies such as XR and immersive learning environments have emerged as promising tools to support experiential learning, enhance engagement, and bridge the gap between academic instruction and real-world application (Ilie & Budac, 2025).

2.1.2. State of XR Technology

Although XR technology is still evolving across various domains, HEIs have historically been slow to adopt emerging technologies, especially XR (Aditya et al., 2022). According to Gartner's Hype Cycle, XR currently resides in the "Trough of Disillusionment," a phase characterized by declining initial enthusiasm and unmet return on investment (ROI) expectations (Marks & Thomas, 2022). During this stage, organizations often struggle with the financial and technical burdens of implementation, leading some to abandon XR initiatives altogether. As XR technologies progress toward the "Slope of Enlightenment," their practical benefits become more evident, supported by the emergence of second- and third-generation products (Linden & Fenn, 2003). Strategic adoption decisions vary across institutions, ranging from early risk-taking adoption to cautious, cost-benefit-driven approaches, with some delaying implementation until XR reaches the "Plateau of Productivity," where technologies achieve maturity and widespread adoption (Linden & Fenn, 2003). Currently, many HEIs are in a piloting phase, recognizing XR's potential to enhance student recruitment, engagement, and operational readiness, though significant financial, technological, and socio-technical barriers continue to hinder broader adoption.

2.1.3. XR Usage in Higher Education

XR adoption in higher education is closely tied to its capacity to enhance engagement and learning through interactive experiences. When learners actively interact with XR environments rather than passively observe, engagement and retention increase (Makransky & Petersen, 2021). This interactivity redistributes cognitive resources toward task-relevant perception and problem-solving, creating conditions conducive to experiential learning (Aguayo & Eames, 2020; Ilić et al., 2021; Pregowska et al., 2023). From the perspective of embodied cognition, XR allows learners to navigate, manipulate, and test representations, effectively externalizing abstract concepts into sensorimotor experiences (Wilson, 2002; Johnson-Glenberg, 2018).

Within experiential learning theory, XR aligns particularly well with the "concrete experience" phase of the learning cycle, providing immersive simulations that support subsequent reflection, conceptualization, and experimentation (Kolb, 2014; Aguayo & Eames, 2023; Crogman et al., 2025). These environments enable access to otherwise inaccessible contexts (i.e., laboratories, fieldwork settings, etc.) in a safe and scalable manner (Barteit et al., 2021; Dodds, 2021), and can serve as a cost-effective solution for delivering immersive educational experiences aligned with the goals of HEIs (Dodds, 2021; Gupta, 2024; Kluge et al., 2022; Upadhyay et al., 2024).

Beyond individual learning, XR also creates an ecosystem for collaborative and self-paced learning (Flores-Castañeda et al., 2023), improving both cognitive and practical outcomes. However, immersion alone does not guarantee improved learning outcomes. Learning gains depend on instructional design features such as scaffolding, reflective opportunities, repeated practice, and alignment with assessed competencies (Hamilton et al., 2021; Marks & Thomas, 2022), reinforcing the importance of integrating XR thoughtfully within existing curricula rather than relying solely on its immersive properties.

Despite its promise, XR adoption in HEIs faces persistent challenges. Questions about its reliability in adequately preparing students (Kluge et al., 2022) have made faculty and administrators hesitant about its investment potential (Lee & Takenaka, 2022). Pilot implementations aimed at improving student engagement, recruitment, and applied learning remain limited in scale due to practical constraints. While students often demonstrate enthusiasm toward XR, disparities in technological readiness and confidence result in uneven learning experiences across populations (Kuleto et al., 2021; Kluge et al., 2022). Effective integration requires alignment with curricular goals and instructional practices, supported by careful design, training, and resource allocation to move XR beyond experimental use and toward systematic embedding within higher education (Hamilton et al., 2021). While XR demonstrates strong pedagogical affordances, its realization in practice depends on institutional capacity and coordination across stakeholders responsible for implementation.

2.2. XR Learning Implications for Implementation

2.2.1. Self-Efficacy

Self-efficacy, defined as an individual's belief in their capability to perform tasks successfully, plays a central role in motivation, persistence, and self-regulated learning (Bandura, 1997; Zimmerman, 2000). Rather than reflecting the number of skills possessed, self-efficacy reflects confidence in applying those skills across contexts (Bandura, 1997; Apsari et al., 2023). Higher levels of perceived self-efficacy have been associated with improved academic performance, reduced anxiety, and increased learner satisfaction (Zimmerman, 2000; Kannegiser, 2021), and are consistent with broader career self-efficacy frameworks, which emphasize the role of perceived competence in shaping academic and professional trajectories (Lent & Hackett, 1987).

XR technologies are commonly situated within experiential learning frameworks due to their ability to simulate environments, enable embodied interaction, and cultivate a strong sense of presence (Slater & Wilbur, 1997; Jensen & Konradsen, 2018; Aguayo & Eames, 2023). The phenomenology of presence, defined as the subjective sensation of "being there," plays a critical role in shaping attention, affect, and how learners interpret mediated experiences as meaningful (Makransky & Petersen, 2021). These affordances have demonstrated particular value across several higher education domains, including safety training, conceptual visualization, and experiential learning environments (Radianti et al., 2020). For example, XR enables repeated, consequence-free rehearsal of high-stakes procedures in safety training contexts (Chittaro & Buttussi, 2015; Buttussi & Chittaro, 2017; Kaplan et al., 2020), while spatialized representations support the visualization of abstract concepts that are otherwise difficult to depict (Novick et al., 1999; Zhu et al., 2023). Additionally, XR provides scalable access to simulated field sites, laboratories, and workplace environments otherwise constrained by geography, cost, or safety considerations (Barteit et al., 2021; Dodds, 2021; Gupta, 2024). These experiential and perceptual affordances provide a foundation through which XR can influence learners' self-efficacy beliefs.

Building on these affordances, XR technologies can support self-efficacy development by enabling learners to actively engage with realistic tasks in structured and repeatable ways. Such environments align with key sources of self-efficacy, including mastery experiences through simulation, vicarious learning through modeled interactions, and feedback-driven reinforcement (Heslin & Klehe, 2006; Smith et al., 2015). Additionally, XR-based rehearsal may reduce performance-related anxiety while increasing perceived preparedness (Gupta, 2024).

In higher education contexts, XR may also contribute to identity development, particularly in STEM disciplines where confidence and sense of belonging influence persistence (Lee et al., 2024; Huang et al., 2025). Immersive exposure to disciplinary environments can support learners in visualizing professional roles and pathways (Flores-Castañeda et al., 2023; Barteit et al., 2021). However, these outcomes are contingent upon intentional design and alignment with authentic disciplinary practices rather than immersion alone (Hamilton et al., 2021; Marks & Thomas, 2022).

From an implementation perspective, variability in both student digital readiness and instructor familiarity with XR tools may influence self-efficacy at multiple stakeholder levels. These differences suggest a need for structured onboarding, training, and support systems when integrating XR into institutional contexts.

2.2.2. Cognitive Affordances

XR environments influence learning processes by shaping how attention, perception, and interaction are coordinated. From a cognitive perspective, immersive systems can support perception–action coupling, allowing learners to engage with tasks in ways that more closely resemble real-world contexts (Aguayo & Eames, 2020; Ilić et al., 2021). Embodied cognition further suggests that interacting with virtual objects can support understanding by externalizing abstract concepts into manipulable experiences (Wilson, 2002; Johnson-Glenberg, 2018). These interactive affordances have been associated with increased engagement, improved spatial reasoning, and opportunities for interactive and iterative learning processes (Hamilton et al., 2021; Pregowska et al., 2023). XR environments may also support self-regulated learning by enabling immediate feedback and iterative adjustment within controlled task environments.

However, these benefits are not inherent to the technology. To realize these cognitive benefits, XR environments require instructional design strategies that guide attention, scaffold reflection, and align interaction with learning objectives (Hamilton et al., 2021; Marks & Thomas, 2022). Without such structure, immersive environments may fail to support meaningful knowledge construction.

2.2.3. Cognitive Constraints

Despite its potential, XR introduces several cognitive and experiential challenges that are relevant for implementation. One key concern is cognitive overload, as learners must simultaneously process novel interfaces, navigate virtual environments, and engage with instructional content (Kluge et al., 2022). These competing demands may reduce learning efficiency, particularly for novice users (Hamilton et al., 2021).

Additionally, immersion does not inherently result in improved learning outcomes. Engagement driven by novelty or realism may lead to superficial interaction if not supported by clear pedagogical structure (Obeidallah et al., 2023; Marks & Thomas, 2022). This reflects a broader issue of technological determinism, where XR is assumed to produce positive outcomes without sufficient instructional alignment (Hamilton et al., 2021).

Practical limitations, including simulation sickness (SS) and usability constraints, may further impact learner experience and accessibility (Barteit et al., 2021). These factors highlight the importance of offering flexible implementation models and alternative learning pathways within institutional deployments. From an operational perspective, these cognitive and experiential constraints underscore the need for intentional design standards, user training, and support infrastructure when scaling XR initiatives in higher education. At scale, these challenges extend beyond individual learning contexts and require coordination across institutional systems, stakeholders, and support structures.

2.3. Socio-Technical Barriers to XR Implementation in HEI

While XR demonstrates clear pedagogical potential, its implementation in higher education is fundamentally a socio-technical systems challenge requiring coordination across multiple stakeholders, institutional structures, and technological systems (Radianti et al., 2020; Aditya et al., 2022), encompassing challenges such as financial constraints, hardware and infrastructure limitations, governance and cross-functional alignment challenges, pedagogical and digital literacy gaps, and accessibility concerns.

2.3.1. Financial Constraints

Financial constraints represent one of the most significant barriers to XR adoption in HEIs (Obeidallah et al., 2023; Gupta, 2024). The high initial costs associated with XR hardware (Lee & Takenaka, 2022; Upadhyay et al., 2024), software (Barteit et al., 2021), and supplemental equipment, including VR-ready computers, high-speed internet, and 360-degree cameras (Marks & Thomas, 2022; Pregowska et al., 2023), create substantial entry barriers (Barteit et al., 2021; Kluge et al., 2022; Upadhyay et al., 2024). These costs are further compounded by ongoing expenses such as maintenance, licensing, and software updates, which limit scalability and long-term sustainability (Kluge et al., 2022; Lee & Takenaka, 2022; Upadhyay et al., 2024). For underfunded institutions, particularly public universities in lower-middle-income regions, these financial burdens exacerbate the digital divide and restrict equitable access to advanced educational technologies (Barteit et al., 2021; Ilić et al., 2021; Flores-Castañeda et al., 2023). These financial constraints extend beyond initial procurement, shaping long-term sustainability, scalability, and institutional capacity to support XR initiatives.

2.3.2. Hardware and Infrastructure Limitations

Technological limitations further complicate adoption. Many HEIs lack the infrastructure necessary to support XR integration, including compatibility with existing IT systems and Learning Management Systems (LMS) (Kluge et al., 2022; Goshtasbpour et al., 2023; Upadhyay et al., 2024). Current XR systems also face performance and usability challenges such as lag, tracking inaccuracies, and system-induced discomfort (e.g., SS), which negatively affect usability and learning experiences (Marks & Thomas, 2022; Lie et al., 2023; Pregowska et al., 2023). These limitations highlight the need for systems integration among IT departments, instructional units, and external vendors, requiring integrated infrastructure planning to support compatibility and scalability.

2.3.3. Governance and Coordination Challenges

Additionally, XR systems frequently collect and process sensitive user data, introducing privacy, compliance, and cybersecurity challenges that require additional investment and institutional oversight (Flores-Castañeda et al., 2023; Ilić et al., 2021). Institutional and governance challenges compound these technical barriers. Successful XR adoption requires institutional coordination and governance; yet many institutions face fragmented decision-making, lack of shared vision, and insufficient policy frameworks (Aditya et al., 2022; Goshtasbpour et al., 2023; Obeidallah et al., 2023). Resistance to change among faculty and administrators, often driven by skepticism regarding XR's alignment with learning objectives and concerns about unintended consequences such as reduced face-to-face interaction or increased distraction (Hamilton et al., 2021; Kluge et al., 2022; Upadhyay et al., 2024), further impedes adoption. Stakeholder dynamics add another layer of complexity: active stakeholders such as faculty, students, and instructional designers directly influence XR development and use, while passive stakeholders, including administrators and external partners, shape policy, funding, and long-term sustainability (Ilić et al., 2021; Goshtasbpour et al., 2023). Unlike traditional educational technologies, XR implementation requires simultaneous alignment across pedagogical, technical, and administrative domains, making institutional and governance challenges a primary constraint to the successful implementation.

2.3.4. Pedagogy and Digital Literacy Gaps

Pedagogical and workload-related barriers are equally prominent. Faculty members frequently face increased workloads associated with XR content development, requiring significant instructional alignment and workload integration with course objectives (Lie et al., 2023; Aguayo et al., 2023; Lee & Takenaka, 2022; Obeidallah et al., 2023). Without institutional support, including clear leadership, funding, and established pedagogical frameworks (Ilić et al., 2021; Kluge et al., 2022; Goshtasbpour et al., 2023; Hamilton et al., 2021; Marks & Thomas, 2022), these challenges remain unresolved, and adoption challenges at the faculty level are often influenced by disciplinary differences and institutional culture (Mercader & Gairín, 2020).

In addition to pedagogical and workload constraints, digital literacy gaps further hinder effective adoption. Educators often require substantial professional development to meaningfully integrate XR tools into curricula and apply active learning strategies, while students vary considerably in their readiness and confidence with advanced technologies (Kluge et al., 2022; Kuleto et al., 2021;

Ilić et al., 2021). These disparities can lead to inconsistent learning experiences and uneven implementation outcomes across courses and disciplines. Collectively, these challenges reflect a misalignment between faculty capabilities, institutional support structures, and technological requirements, reinforcing the need for structured professional development and integrated instructional support systems.

2.3.5. Accessibility and Equity Concerns

Accessibility and inclusivity remain critical challenges in XR adoption (Ilić et al., 2021; Flores-Castañeda et al., 2023; Dodds, 2021). XR environments must accommodate diverse learners, including those with disabilities (i.e., auditory, visual, and physical impairments) or sensitivities (i.e., photosensitive epilepsy); however, many institutions lack the integrated policies, technical expertise, and design frameworks necessary to support inclusive XR environments (Lee & Takenaka, 2022; Dodds, 2021; Flores-Castañeda et al., 2023; Pregowska et al., 2023; Upadhyay et al., 2024). From a pedagogical perspective, addressing accessibility further increases complexity, requiring cross-disciplinary collaboration. These limitations contribute to inequitable access and reinforce existing educational disparities.

Collectively, these barriers illustrate that XR implementation is not a singular technological adoption problem, but a complex system-level challenge requiring collaboration across diverse stakeholders. Financial, technical, pedagogical, and accessibility constraints are deeply interconnected, often reinforcing one another when institutional alignment is lacking. As a result, successful XR integration depends not only on technological capability, but on the development of structured implementation frameworks that enable alignment, governance, and sustainable institutional adoption.

2.4. The XR Community of Practice (XR CoP) Initiative at VT

The present study is situated within the XR CoP, an institutionally supported initiative at VT designed to facilitate the systematic and sustainable integration of XR technologies across academic, research, and recruitment domains. Established in response to a recognized gap between the demonstrated potential of XR for teaching and learning and the limited structural support available to stakeholders seeking to adopt it, the XR CoP aims to understand institutional stakeholder needs, identify effective XR use cases, and develop the workflows and resources necessary to support university-wide diffusion of innovation. The initiative has progressed across three phases, each building on prior findings, with data collected across Phases 2 and 3 (i.e., survey responses, focus group discussions, and domain expert interviews) forming the primary dataset analyzed throughout this thesis.

2.4.1. Phase 1

Phase 1 was oriented toward establishing the groundwork for the XR CoP by mapping the current state of XR at VT, identifying the system support architecture required for implementation, and documenting the lifecycle of notable XR projects across the institution.

2.4.2. Phase 2

Building on the Phase 1 findings, a campus-wide survey was developed in collaboration with the research team, TLOS, and Provost representatives and distributed university-wide (see Section 3.4.1). Findings confirmed that most VT stakeholders were situated in the early knowledge or persuasion stages of the diffusion of innovation process, with limited access to centralized resources for XR development and deployment.

2.4.3. Phase 3

Phase 3 was oriented toward establishing a framework for systematic XR adoption and validating XR development in a real institutional context. This phase employed focus groups with educators and semi-structured interviews with domain experts to examine stakeholder perspectives, coordination challenges, and implementation constraints (see Sections 3.4.2 - 3.4.3), and included the development and testing of a supplemental XR training module for VT's Environment, Health, and Safety required training in partnership with an external vendor.

2.5. Research Gap and Contribution

While prior research has established the pedagogical potential of XR and identified key barriers to its adoption, several critical gaps remain in the literature. Existing studies largely focus on learner outcomes, technology affordances, or isolated implementation challenges, with limited attention to the systemic coordination required across stakeholders in higher education institutions (Radianti et al., 2020; Obeidallah et al., 2023; Burke et al., 2025). Although these studies consistently identify barriers such as cost, usability, and pedagogical alignment, they rarely examine how these challenges are interdependent within institutional systems or how they are experienced across different stakeholder groups.

Moreover, current XR implementation studies predominantly center on students and faculty, with comparatively limited empirical work examining the roles, needs, and perspectives of other critical stakeholders such as information technology staff, accessibility specialists, and security or governance personnel (Jin et al., 2022; Wu et al., 2023; Zaman et al., 2024). While emerging studies acknowledge the importance of these roles, they often do so at a conceptual or high-level, lacking detailed, stakeholder-specific investigations that capture system-level requirements and constraints.

Additionally, there is a lack of structured frameworks and practical guidance to support XR implementation at the R1 institutional level. Prior work frequently calls for the development of standardized workflows, institutional strategies, and design guidelines, yet few studies provide empirically grounded models that translate XR from experimental use to scalable, sustainable deployment in higher education (Kluge et al., 2022; Idrees et al., 2022; Burke et al., 2025). This gap is particularly evident in R1 university contexts (Kuleto et al., 2021; Nisiforou & Kosmas, 2024), where complex organizational structures, distributed decision-making, and diverse stakeholder ecosystems further complicate implementation.

Finally, although qualitative and multi-stakeholder approaches are increasingly recommended in XR research (Akhtar & Cochrane, 2025; Antoniou et al., 2024; Hourcade et al., 2024), there remains a lack of studies that systematically investigate stakeholder relationships and needs using a socio-technical or systems engineering perspective, particularly at the scale of U.S. R1 institutions. Existing work provides partial insights through course-level or non-U.S. contexts (Andalib & Monsur, 2024; Meccawy, 2023), but comprehensive, institution-level analyses that integrate multiple stakeholder perspectives remain limited.

Collectively, these gaps indicate that XR implementation is not solely a technological or pedagogical challenge, but a complex socio-technical systems problem requiring coordinated stakeholder engagement, structured processes, and institutional alignment. Addressing these gaps, this study adopts a systems engineering perspective to systematically identify stakeholder needs, model relationships within the XR implementation ecosystem, and generate actionable, institution-level guidelines for scalable deployment. Specifically, this work aims to (1) identify and characterize key stakeholders, (2) examine their roles, relationships, and needs, and (3) develop actionable recommendations and an external XR development guide to support scalable implementation in higher education. Building on this foundation, the following chapter outlines the methodological approach used to investigate XR implementation within a real-world R1 institutional context.

CHAPTER 3: Materials and Methods

3.1 Context

This study investigates XR implementation within a real-world higher education context at VT, a public R1 institution with high research activity. The research builds on the XR CoP initiative, which aimed to explore and support XR adoption across the university. A single-case study approach was adopted, with a primary focus on understanding the socio-technical system of stakeholders involved in XR adoption. This includes examining stakeholder roles, relationships, and needs, as well as the institutional barriers and enablers that influence implementation across academic, technical, and administrative domains. Findings from this component inform the development of a *Stakeholder Needs Documentation* presented in the results.

To serve as a technological use case, the study incorporates the development of an Environmental Health and Safety (EHS) Portable Fire Extinguisher (PFE) XR training module. The PFE module was selected due to its broad applicability across a multidisciplinary university population of students, faculty, and staff, where certification is required prior to participation in university-wide laboratory and maintenance-related activities.

This embedded component enables the examination of an external XR content development process, including collaboration between university stakeholders and a third-party developer. Specifically, this process captures workflows and decision-making structures required to translate instructional needs into a functional XR training tool. Documenting this process provides practical insight into externally driven development constraints, communication limitations, and system-level requirements that influence the scalability and sustainability of XR integration. Findings from this component inform the development of an *External XR Development Guide* presented in the results.

Although single-case studies may limit generalizability, they provide the depth and contextual richness necessary to examine complex socio-technical systems, stakeholder interactions, and real-world implementation challenges. This work represents an exploratory phase within a broader research agenda aimed at understanding XR adoption in HEIs.

All data were securely stored on a password-protected hard drive accessible only to the research team, with personal identifiers removed prior to analysis to ensure participant confidentiality. This study was conducted under two VT Institutional Review Board (IRB) approvals: IRB #23-1042, covering the campus-wide survey administered during Phase 2, and IRB #24-1356, covering the focus groups and semi-structured interviews conducted during Phase 3.

3.2. Study Design

This study approached XR implementation from a systems engineering (SE) perspective and adopted a SE lens for stakeholder identification, a critical step in complex system design and implementation. This perspective enabled a high-level characterization of the higher education ecosystem, including stakeholders involved in planning, developing, deploying, supporting, and sustaining XR technologies. Given the complex, multi-stakeholder nature of XR implementation, this approach supports the examination of interdependencies across technological, organizational, and pedagogical domains.

Prior research on XR implementation and large-scale technology adoption emphasizes the need for structured, system-oriented, and requirements-driven frameworks to guide decision-making, stakeholder coordination, and long-term sustainability (Gong et al., 2021; Jalo et al., 2022; Kluge et al., 2022). These approaches position XR deployment within complex institutional ecosystems requiring alignment across stakeholders, workflows, and processes. Accordingly, stakeholders in this study were categorized into two primary groups: active stakeholders, who are directly engaged in XR use and implementation, and passive stakeholders, who provide indirect institutional, technical, or administrative support.

To capture both breadth and depth, a mixed-methods approach was employed, consisting of a campus-wide survey, focus group discussions, and semi-structured interviews (see Sections 3.4.1 - 3.4.3). The survey was used to characterize the current state of XR usage across the institution, while focus groups and interviews provided deeper insights into stakeholder perspectives, experiences, and perceived barriers. In addition, the study incorporated process-level documentation of the XR development case to capture system-level constraints and development processes (see Section 3.4.4). Findings from these data sources were synthesized to develop a structured stakeholder needs framework (see Section 3.4.5). Full details of the data collection procedures are provided in Section 3.4.

3.3. Participants

Participation was voluntary, and all participants were recruited through university-affiliated listservs, including the XR CoP, Technology-enhanced Learning and Online Strategies (TLOS), and the Center for Human-Computer Interaction (CHCI).

Table 1. Demographic Characteristics of Survey Respondents (N = 232)

Characteristic	n	%
Gender Identity		
Male	125	53.9
Female	93	40.1
Non-binary	2	0.9
Other	11	4.7
Prefer not to disclose	1	0.4
University Affiliation		
Undergraduate student	76	32.8
Graduate student	78	33.6
Faculty	61	26.3
Staff	17	7.3
Total	**232**	**100**

The survey yielded a total of 371 responses, with 232 completed responses (N = 232) included in the analysis. As shown in Table 1, the sample consisted of 125 males, 93 females, 2 individuals identifying as non-binary, 11 identifying as other, and 1 participant who preferred not to disclose. Among these respondents, 76 identified as undergraduate students, 78 as graduate students, 61 as faculty, and 17 as staff. Participants represented multiple colleges across the university, as shown in Table 2; however, the total number of responses for this item (N = 224) is lower due to item-level nonresponse, as not all participants answered every survey question.

Table 2. Department Representation of Survey Respondents (N = 224)

Departments	Count
College of Agriculture and Life Sciences	6
College of Architecture, Arts, and Design	7
Pamplin College of Business	7
College of Engineering	141
College of Liberal Arts and Human Sciences	9
College of Natural Resources and Environment	9
College of Science	14
Medicine (Veterinary & Carillion Medicine)	22
Other (Student Affairs, Construction, University Library, Education)	9
Total	**224**

For qualitative data collection, a total of 17 stakeholders (N = 17) participated, including 14 focus group participants (n = 14) and 3 semi-structured 1-on-1 interview participants (n = 3). Focus group participants represented faculty and staff from 10 departments, selected based on their experience with XR development and implementation. These participants were intentionally selected because they are responsible for designing, selecting, and integrating XR modules into curricula within the university structure. Semi-structured interview participants were recruited to represent key stakeholder roles that are often underrepresented in XR implementation literature (Section 2.5) but are critical to successful XR system operations; participants were drawn from the target population of interest, with individuals selected based on availability and willingness to participate. These included a representative from information technology, accessibility, and information security domains. A detailed breakdown of participant roles and departmental affiliations is provided in Table 3. It should be noted that students were not included in focus groups or interviews, as they are primarily end-users of XR systems within HEIs and typically do not have decision-making authority in curricular integration.

Table 3: Participant Specialties and Roles

Department	Role	Count	Method
Focus group participants			
Veterinary Medicine (Vet Med)	Associate Professor of Practice	1	FG
Interior Design (ITDS)	Assistant Professor	1	FG
	Professor; HCI Deputy Director	1	FG
Computer Science (CS)	Assistant Professor	2	FG
Food Sciences & Technology (FS&T)	Assistant Professor of Practice	1	FG
Sustainable Biomaterials (SBIO)	Assistant Professor	1	FG
Industrial & Systems Engineering (ISE)	Professor	1	FG
General Chemistry (CHEM)	Lab Manager	1	FG
General Engineering (GE)	Director	1	FG
Undergraduate Education (UG)	Assistant Vice Provost	1	FG
Construction Engineering & Management (CEM)	Adjunct Professor; EHS Training Coordinator	1	FG
	Assistant Director, Studios & Innovative Technologies	1	FG
University Library (UL)	Executive Director, ARIES	1	FG
Semi-structured interview participants			
Institute for Creativity, Arts & Technology (ICAT)	Facilities Coordinator; Production Coordinator	1	Interview
School of Performing Arts; College of Architecture, Arts & Design	Assistant Professor of Musicology; Director of Disability Studies	1	Interview
Information Technology Security Office	IT Security Officer	1	Interview
Total		**17**	

3.4. Data Collection Methods and Procedures

A mixed-methods approach consisting of a campus-wide survey, focus groups, and semi-structured interviews was employed to triangulate findings across broad institutional trends and in-depth stakeholder perspectives. This combination of methods was selected to capture both the breadth of XR adoption across the institution and the depth of stakeholder experiences, roles, and system-level challenges associated with implementation.

The survey instrument (see Appendix A) included questions exploring XR usage, resource availability, development practices, and perceived barriers to implementation. It was designed to establish a baseline understanding of institutional readiness and identify patterns to inform subsequent qualitative inquiry. Focus group (Appendix B) and semi-structured interview (Appendix C) protocols were informed by socio-technical systems literature, stakeholder-based implementation frameworks, and initial survey findings. These methods were used to explore participant experiences and perspectives in greater depth, with semi-structured formats allowing flexibility to capture system-level challenges and context-specific insights.

Data collection followed a sequential design. The campus-wide survey was administered during Phase 2 of the XR CoP, followed by focus groups, and subsequently interviews in Phase 3 to further investigate emerging themes and refine understanding of stakeholder dynamics and implementation processes.

3.4.1. Campus-wide Survey

A campus-wide survey was administered online using QuestionPro and distributed through institutional listservs and the Canvas learning platform. The survey consisted of 32 questions, took approximately 8–10 minutes to complete, and recorded responses automatically within the platform. Participants who completed the survey were eligible to enter a raffle, with selected participants receiving a $50 incentive. Conducted as the initial formal phase of data collection for this study (Phase 2), the survey aimed to characterize XR usage patterns and institutional needs across the institution.

The survey was designed to capture data across multiple domains, including demographic information, XR usage and experience, development practices, resource availability, perceived barriers, and interest in XR adoption. Both multiple-choice and open-ended questions were used to collect quantitative and qualitative insights into XR implementation across the university. The full survey instrument is provided in Appendix A.

Not all survey items were mandatory; therefore, response counts vary by item and may not reflect the full sample (N = 232). This approach allowed participants to respond only to relevant questions. Additionally, some items permitted multiple selections, meaning response totals may exceed the number of participants and percentages may not sum to 100%. Accordingly, frequencies and percentages are reported relative to item-level responses.

3.4.2. Focus Group

Two focus group sessions (N = 14) were conducted in a hybrid format. Session 1 included six participants (n = 6), and Session 2 included eight (n = 8), with each session lasting approximately 60–90 minutes. All sessions were video and audio-recorded with participant consent.

A structured Canva slide deck was developed to guide discussions and standardize facilitation across sessions (see Figure 1). The slides included prompts related to XR experiences, perceived implementation barriers, stakeholder roles, and future applications of XR in higher education. Each session began with an introduction and study overview, participant introductions, and guided discussions exploring these topics in depth. The full focus group protocol and questions can be found in Appendix B.

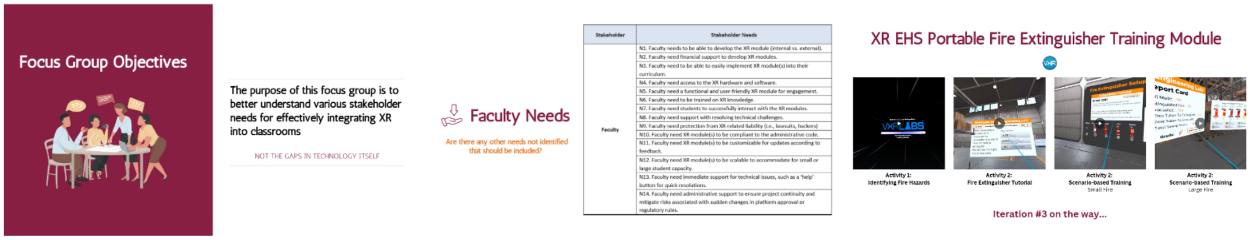

Figure 1: Focus Group Slide Examples

3.4.3. Semi-Structured Interviews

Three semi-structured interviews were conducted with key university stakeholders representing information technology, accessibility, and security roles. Interviews were conducted remotely and lasted approximately 60 minutes. Interview protocols were developed and tailored to each participant's expertise to capture domain-specific insights; while allowing flexibility to probe specific experiences. Participants reflected on their experiences, system-level challenges, and recommendations for XR implementation within a HEI. All sessions were video and audio-recorded with participant consent. The full interview protocols are provided in Appendix C.

3.4.4. External XR Development Process Documentation

In addition to survey, focus group, and interview data collection, this study examined the external collaboration associated with the development of the EHS PFE training module. The module was created in partnership with a third-party developer, VictoryXR (V.XR), providing an opportunity to document a real-world XR development workflow within an industry context.

An iterative design methodology was employed, encompassing stages of requirements gathering, prototype development, testing, feedback collection, and refinement. Development involved collaboration between university stakeholders (e.g., EHS subject matter experts (SMEs), a faculty member, and a Graduate Research Assistant) and an external development team (one representative and a lead developer). Due to the university partnership, budget constraints, and a pro-rated agreement under which the module would be publicly available without institutional ownership by VT, total development costs were reduced to approximately $7,000, including two licenses. A functional prototype was delivered within two weeks. This was followed by two iterative refinement cycles (limited by budget) over an additional two-week period to improve alignment, functionality, and user experience (UX). Following these iterations, the external developer continued to provide ongoing support, including bug fixes.

Observations and documentation were collected throughout development to capture key aspects of collaboration, communication, decision-making, and workflow structure. Particular attention was given to how instructional requirements were translated into XR features, how constraints such as budget and timeline influenced decisions, and how alignment with pedagogical goals and training objectives was maintained.

This component complements stakeholder data by providing process-level insight into XR development in practice. Findings informed the analysis of development constraints, challenges, and system requirements, and contributed to the *External XR Development Guide* presented in Appendix E. Documentation included meeting notes, design iterations, and communication records between university stakeholders and the external development team.

3.4.5. Stakeholder Needs Documentation

A structured stakeholder needs documentation was developed to synthesize findings across data sources. Guided by systems thinking and a systems engineering (SE) perspective, this documentation aimed to identify and organize stakeholder needs, constraints, and functional requirements related to XR implementation in a higher education context.

Stakeholder needs were derived through literature review, and thematic analysis of survey responses, focus group discussions, and interviews. Identified themes were systematically mapped to specific stakeholder groups, including both active stakeholders (e.g., faculty, students, developers) and passive stakeholders (e.g., administrators, IT staff, accessibility, etc.), consistent with systems engineering approaches to stakeholder identification and requirement elicitation.

This process enabled the identification of conditions necessary to support scalable and sustainable XR implementation within an R1 institutional environment. A detailed stakeholder needs document is provided in Appendix D.

3.5. Data Analysis

Qualitative data from focus groups, interviews, and open-ended survey responses were analyzed using an inductive thematic analysis approach. Video and audio recordings were transcribed using Zoom's automated transcription feature and exported to Microsoft Word for initial review and annotation. Key excerpts were then transferred to Microsoft Excel for organization and analysis.

Transcripts were reviewed to identify recurring concepts, which informed the development of an initial set of provisional codes. Codes were iteratively refined and consolidated into higher-level themes. These were continuously compared across data sources (survey responses, focus groups, and interviews) to identify converging patterns and discrepancies.

To enhance the credibility of the analysis, several strategies were employed. Triangulation was used to compare findings across data sources and participant groups. Iterative coding supported consistency and alignment with research objectives. Representative excerpts were reviewed to ensure themes accurately reflected participant perspectives. Together, these strategies support the trustworthiness of the findings.

Quantitative survey data were analyzed descriptively to characterize XR usage patterns, development practices, and perceived barriers across the institution. These data were used to characterize the XR project landscape at VT, including users' experiences, the nature of ongoing or completed projects, and common implementation challenges. The analysis also examined strategies used to address these challenges.

CHAPTER 4: Results

This case study examined XR implementation at VT, an R1 university, through a multi-stakeholder, socio-technical lens. Findings are presented across key themes, integrating quantitative survey data with qualitative insights from focus groups and SME interviews.

Survey results provide a foundational overview of current XR adoption and institutional context, while qualitative findings offer deeper insight into stakeholder perspectives, relationships, and system-level challenges. Results highlight trends in XR adoption, the structure of stakeholder ecosystems, perceived benefits and limitations, and socio-technical barriers influencing implementation.

4.1. Current State of XR Adoption and Stakeholder Needs

Survey responses indicate that immersive technology use in higher education remains relatively low across the sample. Of the 232 completed responses (N = 232), 119 respondents (51.29%) reported no prior use of immersive technology in a higher education setting, 66 (28.45%) reported some level of use, and 47 (20.26%) reported having experience in XR module development.

Educational XR facilitation experience was also low among respondents. Among respondents who answered this item (n = 113), 38 (33.63%) reported prior experience facilitating XR in educational settings, while the majority (n = 75, 66.37%) reported no such experience. Despite limited facilitation exposure, respondents expressed moderate to high interest in adopting immersive technologies. On a 5-point Likert scale (1 = not interested; 5 = very interested), mean interest levels were reported for classroom applications (3.97), research (3.98), recruitment (3.30), enhancing teaching experiences (4.15), and improving student engagement and motivation (4.10).

Motivations for XR adoption were derived from multi-select responses (889 total counts). The most frequently cited motivations were active learning (174, 19.57%) and increased engagement (165, 18.56%), followed by simulating real-world scenarios (145, 16.31%) and research opportunities (130, 14.62%). Additional motivations included competitive advantage (114, 12.82%), accessibility considerations (89, 10.01%), and accommodating large numbers of users (68, 7.65%).

Similarly, perceived barriers to XR adoption were identified from 743 total counts. The most frequently reported barriers were cost (157, 21.13%), lack of equipment (149, 20.05%), and lack of expertise (144, 19.38%), followed by limited content availability (125, 16.82%) and resistance to change (80, 10.77%). Privacy and security concerns were also noted (72, 9.69%). To address these challenges, participants ranked support priorities for immersive technology development. As shown in Figure 2, funding (mean = 4.14), hardware access (mean = 4.16), and UX testing (mean = 4.93) were identified as the most critical needs.

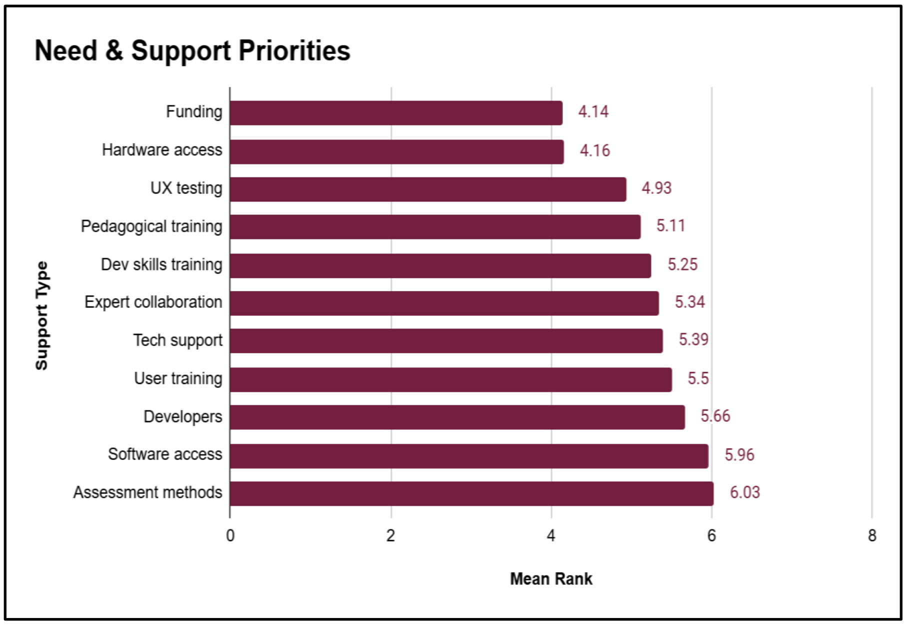

Figure 2. Survey respondents' needs and support priorities ranked by importance.

Qualitative responses (25 total counts) further highlighted needs such as technical skill development pathways (4 counts), centralized institutional coordination (3 counts), motivation and awareness education (3 counts), and content development support (3 counts). Additional themes were also mentioned (2 counts each) and illustrated in Figure 3.

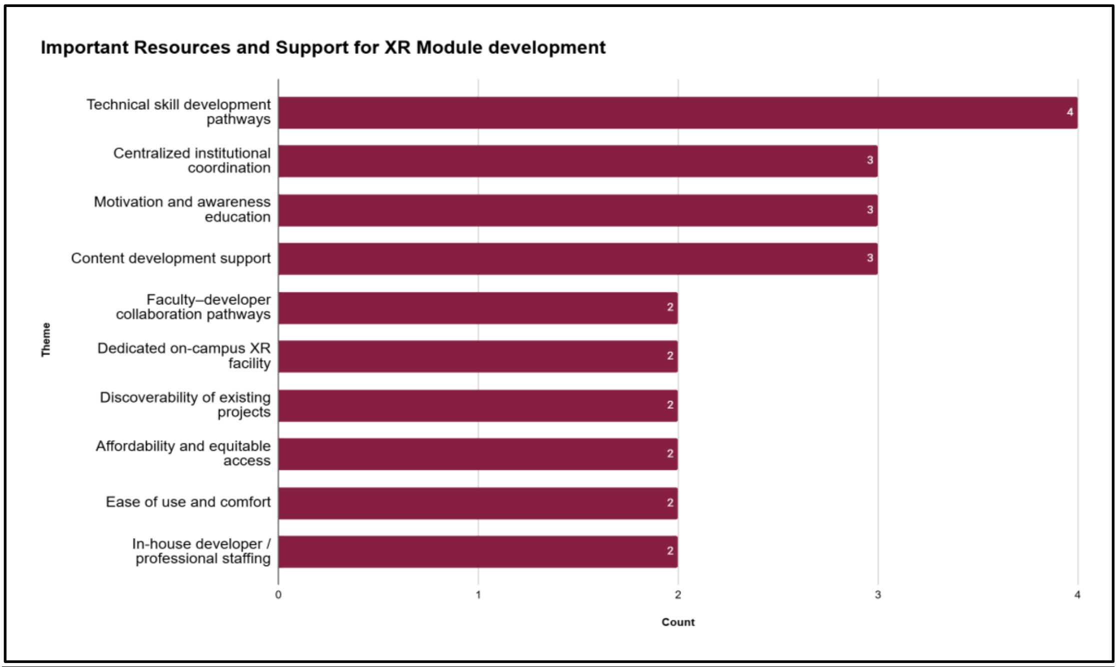

Figure 3. Qualitatively identified resource and support needs for XR development

4.1.1. Previous Facilitation Experiences

Among reported hardware exposure (205 total counts), VR headsets were the most commonly used devices (95), followed by AR glasses (34) and mixed reality headsets (20). Additional platforms included dedicated XR computers (14), AR smartphones (13), and external tracking systems (12), with smaller counts reported for other devices. These findings indicate that XR exposure is primarily concentrated in VR-based systems, suggesting uneven adoption across XR modalities.

Among respondents who reported access to XR resources (n = 136), access was most commonly facilitated through temporary borrowing (65, 47.79%), followed by personal or laboratory equipment (49, 36.03%) and long-term loans (22, 16.18%).

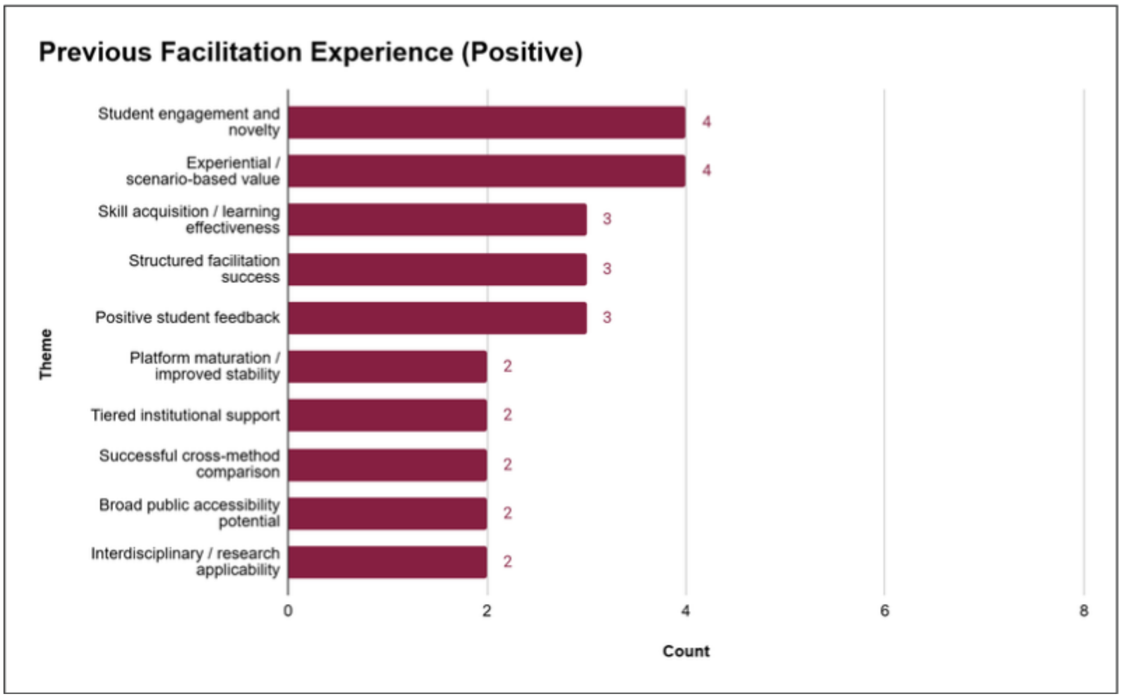

Figure 4. Survey respondents' prior XR facilitation experiences (positive)

As shown in Figure 4, positive experiences (27 total counts) most frequently emphasized student engagement and novelty (4 counts) and experiential or scenario-based learning value (4 counts). Participants described XR as enhancing engagement through interactive experiences, with one participant noting that "novice students enjoyed the novel technology and the interactive nature of the study." Similarly, experiential learning benefits were reflected in comments such as "the experiment showed quicker acquisition of land navigation skills than standard methods." Less frequently cited themes included skill acquisition (3 counts), structured facilitation success (3 counts), and positive student feedback (3 counts). Structured facilitation was often associated with instructional support, as one participant noted that "students didn't have much of an issue because there was a supervisor in the lab helping them." Less frequently reported benefits included platform stability improvements and mobile XR accessibility (2 counts each).

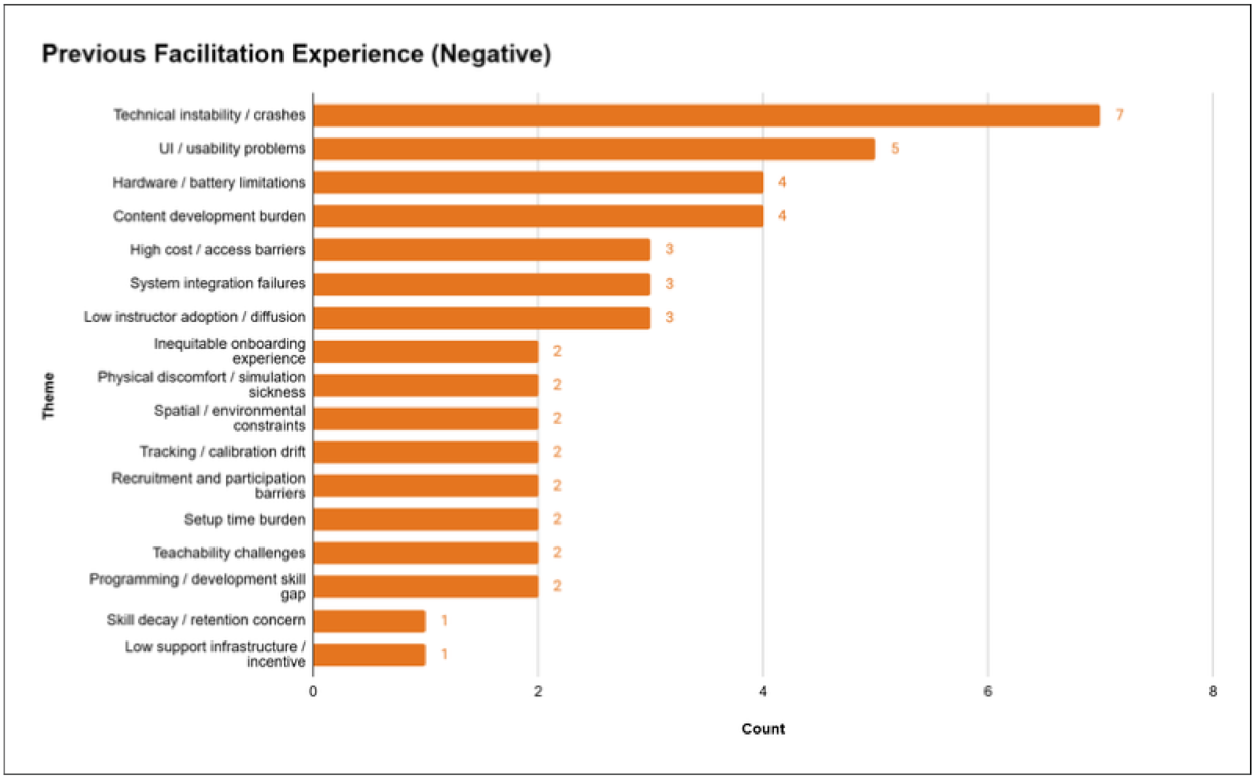

Figure 5. Survey respondents' prior XR facilitation experiences (negative)

In contrast, Figure 5 highlights negative facilitation experiences (47 total counts), which were more frequently reported and centered on technical instability or system crashes (7 counts), with participants noting that systems were "more apt to crash and reduce immersion and productivity for the user." UI and usability issues (5 counts) were also common, with one respondent stating that "they didn't understand how to interact with the UI." Hardware and battery limitations (4 counts) constrained activity completion, as reflected in comments such as "the battery capacity of the AR headset was limited for only 1 student to complete the entire activity." Content development burden (4 counts) was another recurring challenge, particularly in managing development environments and tools (e.g., "dealing with development environments (Unity) and versioning problems"). Additional challenges included cost, access, and system integration issues (3 counts each). SS and physical discomfort were reported less frequently (2 counts), with one participant describing experiencing "vertigo" after prolonged headset use.

4.1.2. Development Experience

As illustrated in Figure 6, among respondents reporting prior exposure to immersive technology or involvement in development (93 total counts), the most common use case was research (39, 41.9%), followed by classroom or educational activities (31, 33.3%).

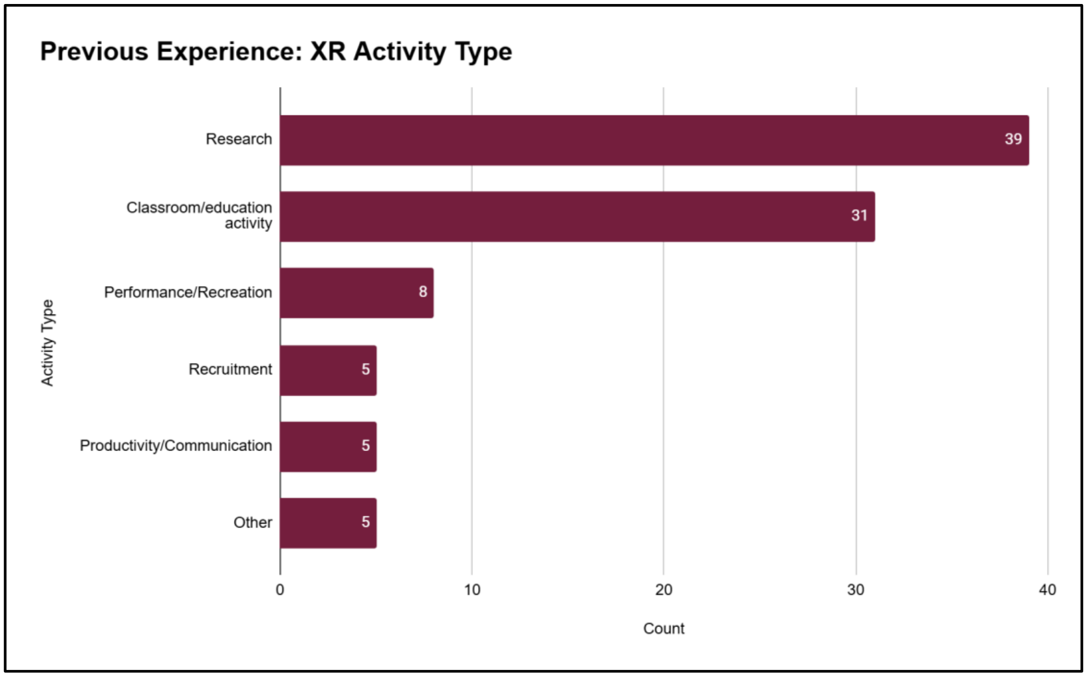

Figure 6. Survey respondents' prior XR activity type exposure.

In contrast, Figure 7 presents XR development timelines. Among respondents with experience developing XR modules (67 total counts), the most common timeline was 6–12 months (20), with 16 projects reported as ongoing beyond 12 months. Overall, the majority of XR development efforts (48, 71.6%) required at least 3–6 months or longer.

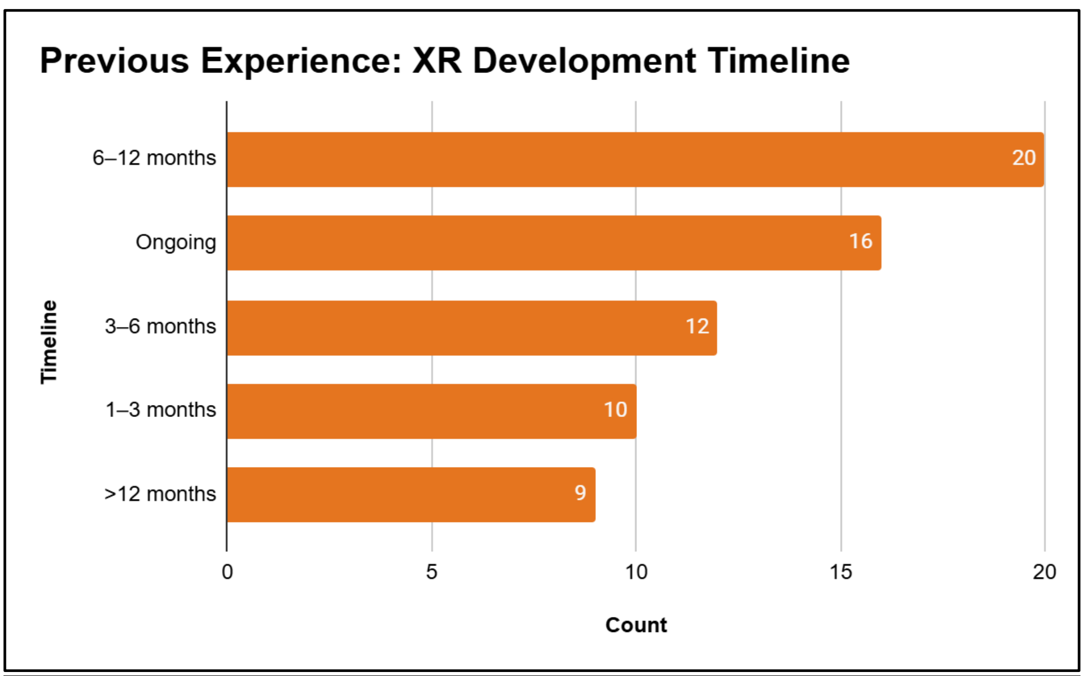

Figure 7. Survey respondents' prior XR development timelines.

Development practices further highlight institutional trends. Among reported development resources (66 total counts), student workers were the most commonly utilized (29, 43.94%), followed by other resources (13, 19.7%), ARIES (8, 12.12%), and departmental teams (8, 12.12%). Third-party developers and VT Library support were less frequently cited (4, 6.06% each).

Challenges encountered during XR development (124 total counts) were most frequently associated with usability/UX issues and technical challenges (21, 16.94% each). Additional challenges included evaluating effectiveness (16), user adoption (14), integration with existing activities (14), and limited hardware availability (13). Less frequently reported challenges included maintenance and physical accessibility (9 each), as well as other concerns (2 counts) related to technical support, training, software access, and developer availability.

4.2. Stakeholder Ecosystem and Relationships

Findings indicate that XR implementation involves a multi-level stakeholder ecosystem spanning academic, technical, and administrative domains, extending beyond faculty, staff, and students (Figure 8).

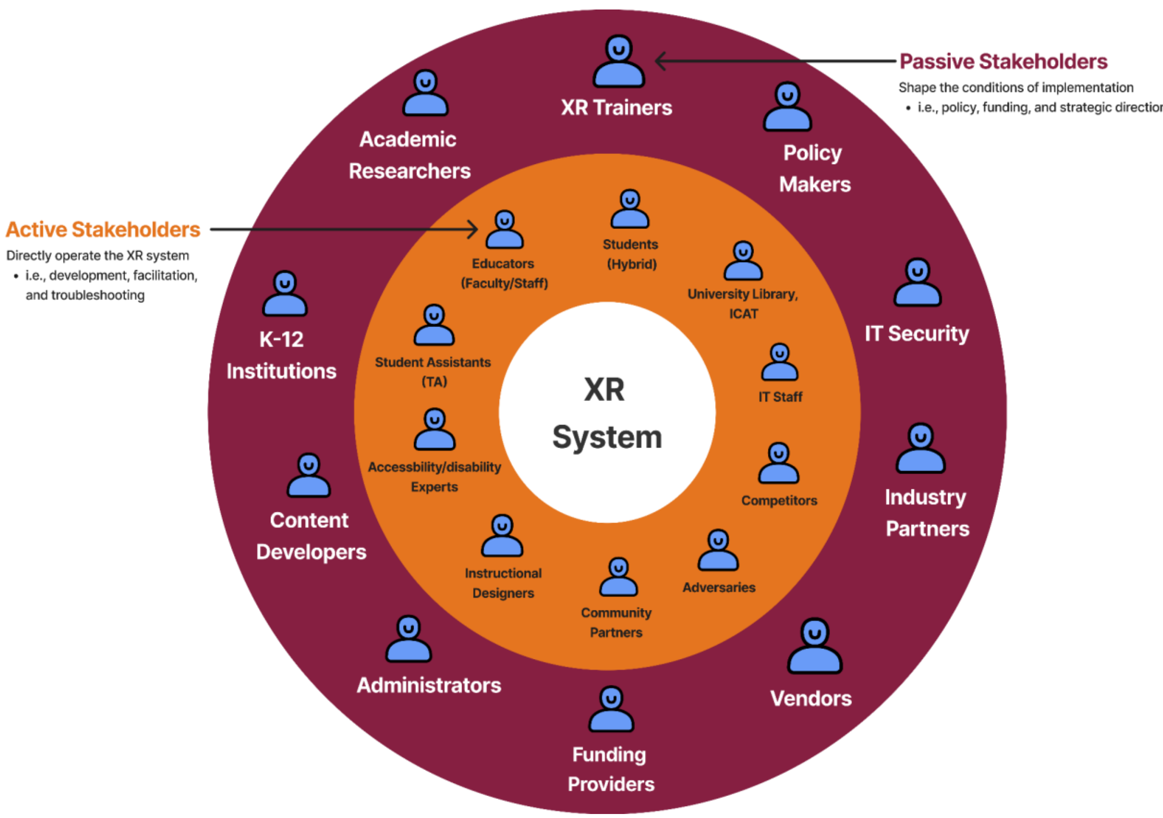

Figure 8. Stakeholder ecosystem involved in XR implementation, illustrating active and passive roles across academic, technical, and institutional domains.

As outlined in Section 2.3.3, stakeholders are classified as either active or passive based on their level of engagement in XR implementation. Active stakeholders are directly involved in day-to-day operation and use of XR systems, shaping instructional practices and UX. Passive stakeholders influence implementation indirectly through governance, policy, funding, or strategic decision-making. This classification is specific to XR implementation in higher education and emphasizes operational involvement and continuity rather than general expertise. It highlights that effective XR integration depends on both direct participation and broader institutional support.

Academic researchers, while intellectually engaged with XR, typically study implementation from outside operational workflows. Although they may access XR systems for data collection, they do not directly facilitate or maintain XR activities. Similarly, content developers contribute to XR implementation through project-based development, producing deliverables that are later deployed by active stakeholders.

IT security officers primarily operate in governance and audit roles during implementation, establishing security protocols and standards. However, they may become operationally engaged when addressing system-level risks, which supports their classification as active stakeholders alongside IT support staff who provide continuous infrastructure support. Adversarial stakeholders are classified as passive due to their lack of direct operational involvement, though they exert disruptive influence on system integrity and stakeholder trust. Community partners are considered active when engaged, given their role in co-development and pilot activities, although their involvement is not consistent across implementations.

Across qualitative data sources (n = 199 coded instances), stakeholder-related themes were commonly associated with institutional coordination and support structures, including institutional siloing (n = 14) and faculty training and support deficits (n = 13), though higher-frequency themes were observed in resource-related and technical barriers.

Participants reported across multiple data sources that stakeholders contribute to distinct phases of XR implementation, including ideation, development, deployment, maintenance, and governance. These phases were described as interconnected rather than linear, requiring coordination across pedagogical, technical, and institutional domains. Differences in stakeholder identification were observed across data sources. Focus group participants primarily referenced instructional roles including faculty, students, and instructional support roles. Interview participants highlighted additional system-level and governance roles including IT, accessibility, and compliance roles. These stakeholders were less frequently identified in focus groups but were described as critical to implementation processes.

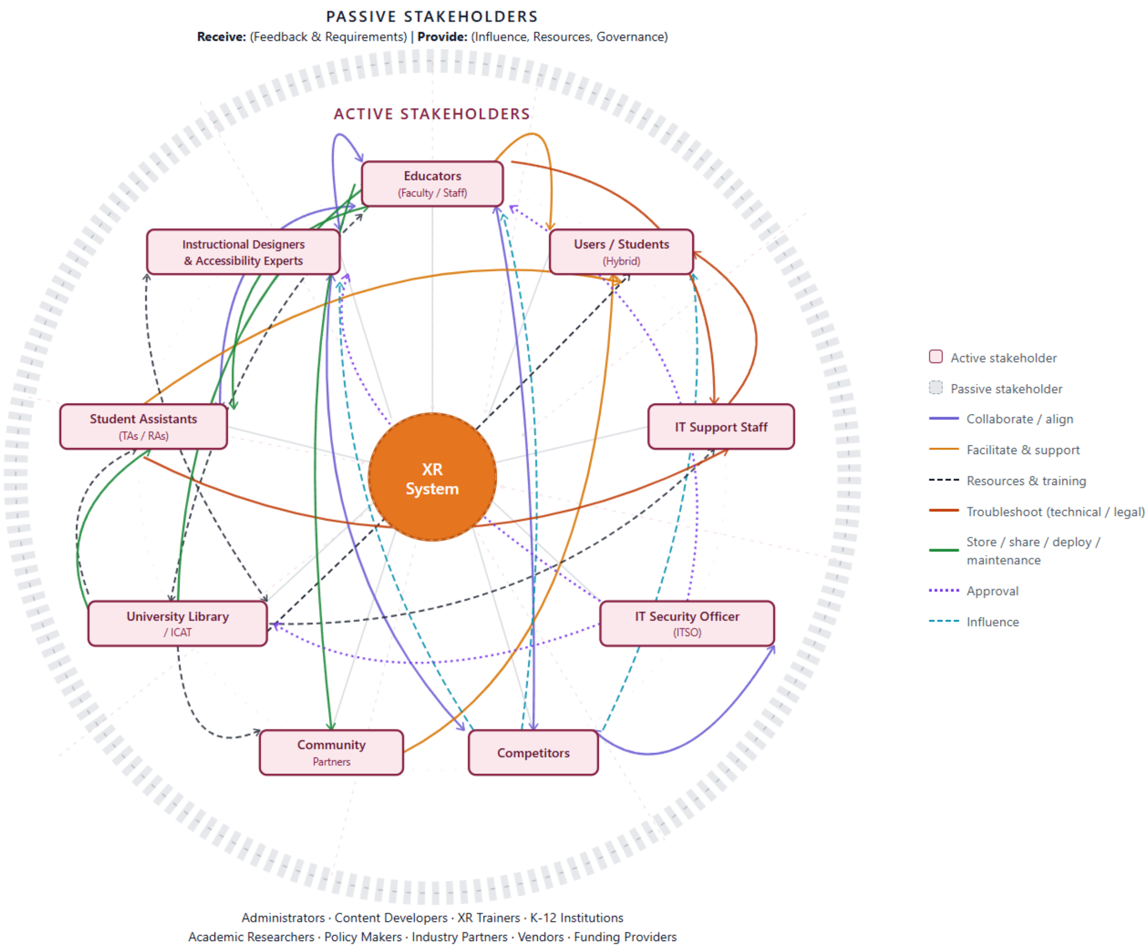

Figure 9. Visual representation of an R1 university stakeholder relationship mapping illustrating coordination pathways and inter-dependencies across XR implementation roles. **Note.** Arrows indicate 'Receiver.'

Stakeholder relationships and interdependencies are illustrated in Figure 9, which highlights coordination pathways and system-level interactions across roles. These findings indicate variation in stakeholder visibility, with instructional stakeholders more frequently identified in focus groups and system-level stakeholders more prominently represented in interview data. These findings were synthesized into a structured *Stakeholder Needs Documentation*, which maps stakeholder roles, interdependencies, and system-level needs to support XR implementation in higher education (Appendix D).

4.3. Stakeholder Perspectives on XR Implementation

4.3.1. Perceived Benefits of XR in HEIs

Participants identified experiential learning as the most frequently cited benefit (n = 14), followed by increased learner engagement, motivation, and supplemental training enhancement (n = 8 each), and immersive conceptual visualization (n = 7), as shown in Figure 10. Participants described XR as enabling engagement with environments and situations that are dangerous, rare, or otherwise inaccessible in real-world contexts, particularly in domains such as safety training and high-risk simulations.

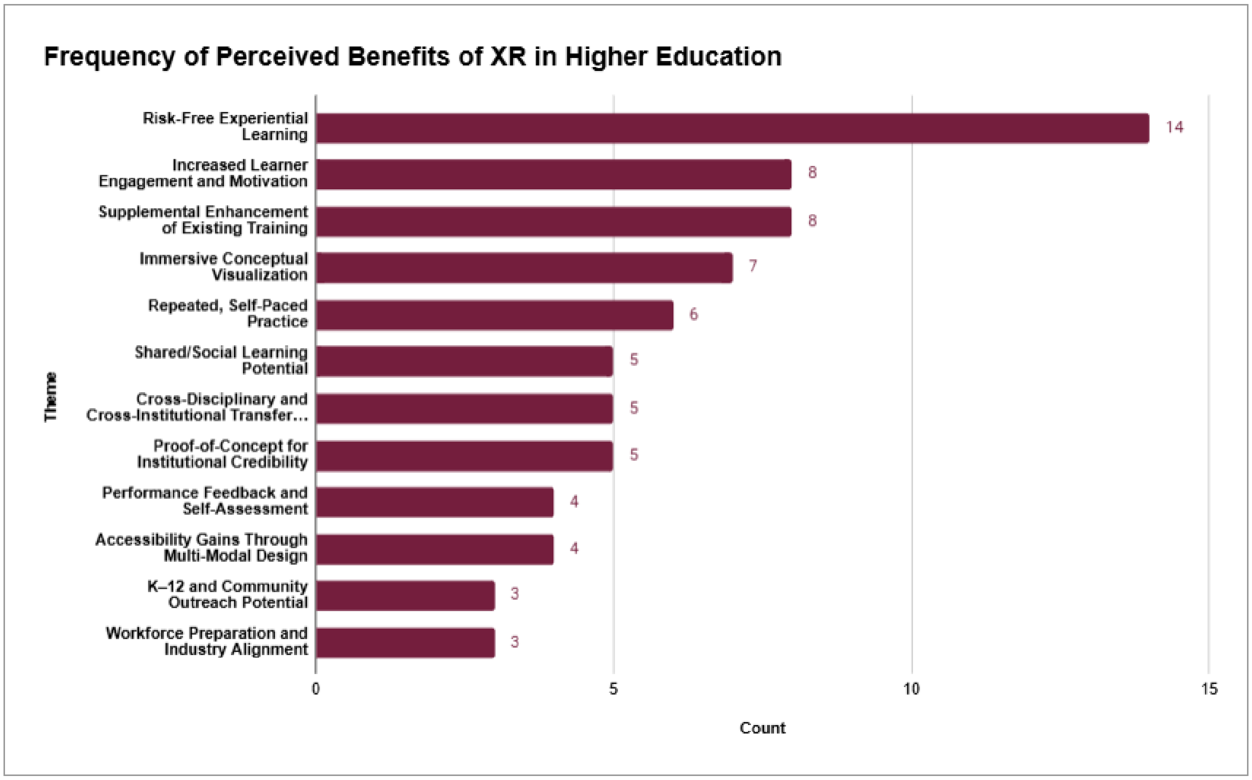

Figure 10. Frequently mentioned perceived benefits of XR in higher education across qualitative data sources

A recurring and closely related theme was the ability of XR to support active, embodied learning. Across both focus groups and interviews, participants described XR as facilitating a shift away from passive instructional formats toward scenario-based and interactive learning experiences. This pattern was evident across stakeholder groups and frequently co-occurred with discussions of engagement and learner motivation. Participants also commonly highlighted XR's role in supporting conceptual understanding. Spatial visualization and embodied interaction were described as enabling learners to engage with abstract or complex concepts in ways that are difficult to achieve through traditional instructional methods. This theme was moderately frequent across sources and often discussed alongside experiential learning benefits.

Additional benefits included increased learner engagement, intrinsic motivation, and opportunities for repeated practice. Participants noted that XR allows learners to revisit scenarios multiple times, enabling self-paced learning and skill reinforcement without additional resource constraints. These themes were frequently mentioned but occurred less often than experiential learning.

Collaborative learning emerged as a secondary benefit, particularly in configurations involving shared or room-scale XR environments. While mentioned across multiple sources, this theme was observed less frequently than individual experiential learning benefits. Less frequently, participants described benefits related to workforce preparation, transferability of skills, and cross-institutional collaboration. These themes were present across the dataset but occurred with lower frequency compared to core experiential and engagement-related benefits.

4.3.2. Perceived Limitations of XR in HEIs

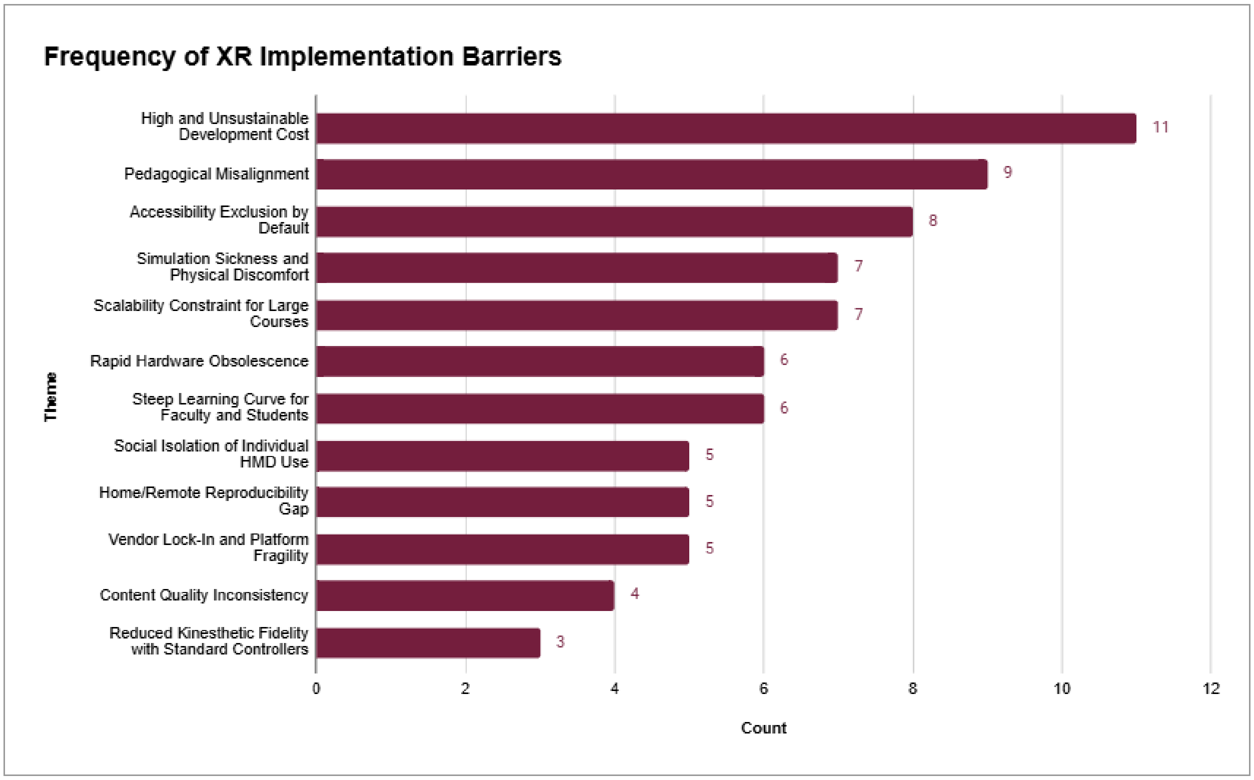

Figure 11. Frequently mentioned perceived limitations of XR in higher education based on qualitative findings

Participants identified several limitations associated with XR implementation across qualitative data sources. High and unsustainable development cost was the most frequently reported limitation (n = 11). This was followed by pedagogical misalignment (n = 9), accessibility exclusion by default (n = 8), scalability constraints (n = 7), and concerns related to SS and physical discomfort (Figure 11).

Focus group participants frequently noted that XR systems are difficult to deploy at scale due to both financial and logistical constraints. Another recurring limitation across all sources was pedagogical misalignment. Participants frequently expressed concern that XR is often implemented without appropriate instructional design, resulting in experiences that replicate traditional lecture-based formats rather than leveraging the affordances of immersive technologies.

Technical limitations were also widely reported. Participants described issues related to SS, physical discomfort, and usability challenges associated with XR hardware. These concerns were raised across both focus groups and interviews, indicating broad agreement among stakeholder groups. Notably, one participant characterized SS not as a minor inconvenience but as an unresolved issue with poorly understood causes and no clear solution. This reframes SS from a manageable limitation to a substantive barrier to classroom deployment.

4.3.3. Future Outlook and Stakeholder Recommendations

When asked "How do you envision XR enhancing education and classrooms in the next five years?" Participants expressed cautious optimism alongside critical concerns, highlighting both transformative potential and persistent structural concerns.

On the positive side, one faculty participant envisioned XR as a means to enhance team-based collaboration and simulation-based learning, building on its affordances for immersive, scenario-driven engagement. Two participants described XR's potential to support virtual "field trip" experiences, enabling students to engage with environments that would otherwise be inaccessible due to geographic, financial, or safety constraints. Another participant identified promise in combining XR with artificial intelligence to foster active learning, though they emphasized that XR and AI each carry distinct cost-benefit considerations that institutions must evaluate independently before integration.

Despite these possibilities, participants also raised substantive concerns about the near-term feasibility of XR adoption. Three participants specifically flagged cost and scalability as barriers, particularly in large lecture-based settings where hardware requirements make widespread deployment logistically and financially unsustainable. Two participants questioned the incentive structure for adoption, drawing comparisons to earlier technology integrations. For example, tools such as Zoom demonstrated limited measurable impact on learning outcomes despite widespread adoption, raising questions about whether XR would follow a similar trajectory. Additional concerns centered on over-reliance on HMDs, which participants noted can cause motion sickness and create accessibility limitations for certain users. To mitigate these constraints, one participant recommended that XR experiences should be offered across diverse modalities, including tablet-based formats, to improve usability and broaden accessibility and inclusion.

Participants were also asked, "Are there any other stakeholders essential in enhancing the XR implementation process?" In response, several participants emphasized the need to expand the stakeholder group beyond faculty and students to include instructional designers, IT staff, administrators, curriculum planners, and cross-departmental partners. Two participants noted that XR adoption should align with subject-specific instructional needs and account for individual learning differences, as certain disciplines or student populations may not benefit equally from immersive technology. A participant stressed the importance of robust cross-departmental collaboration to address the systemic challenges of XR implementation. Several participants also noted that without pedagogical creativity and sustained institutional support, XR risks being underutilized or reduced to replicating traditional teacher-centered instructional models in an immersive format.

In discussing prior experiences and ongoing concerns, participants identified several additional barriers to effective implementation. Two participants highlighted logistical difficulties associated with managing and sanitizing equipment across large classes, as well as inequities arising from uneven student access to the required devices. Another participant expressed concern about the long-term sustainability of XR platforms, citing the rapid evolution of hardware and software and the unreliability of vendors as factors that undermine institutional investment. One participant emphasized the importance of designing XR experiences that are accessible to students with disabilities and adaptable to diverse learning styles, cautioning that poorly designed implementations risk deepening rather than bridging the digital divide.

Participants converged on the view that XR should not be adopted superficially as a visual novelty. Two participants stressed that meaningful integration requires clearly defined learning objectives, structured curricular planning, and robust instructional design as foundational prerequisites. A participant drew on a past XR deployment experience in which insufficient preparation and a lack of faculty training contributed to student discomfort and SS, underscoring that successful implementation demands weeks of deliberate planning, clearly articulated goals, and broad faculty buy-in prior to deployment. Participants further emphasized the need for centralized institutional support structures to coordinate XR initiatives across units and ensure consistency in implementation. Several also noted that cost-benefit analyses are essential to justify XR adoption relative to traditional instructional methods, particularly given the resource intensity of development and the current limitations in scaling XR experiences to large or diverse student populations. In this regard, one participant emphasized that broad adoption requires more than institutional enthusiasm; educators require a compelling, measurable proof of concept that demonstrates XR's effectiveness rather than merely its novelty. Demonstrating that students taught through XR perform demonstrably better on targeted learning outcomes was identified as a prerequisite for moving beyond early adopters to university-wide uptake.

4.4. Socio-Technical Barriers to XR Implementation

Resource-related barriers (n = 34) represented the highest-frequency category, followed by technical (n = 30) and organizational (n = 30) barriers. Pedagogical (n = 28), user-related (n = 19), and security/compliance (n = 15) categories were also identified. These findings show that XR implementation challenges are distributed across multiple system dimensions rather than concentrated within a single domain.

The frequency of identified barrier themes across qualitative data sources is shown in Figure 12. Across qualitative data sources (n = 199 coded instances), funding and sustainability concerns and hardware/infrastructure barriers were the most frequently reported prohibitive factors in XR development and facilitation (n = 19 each). These were followed by experiential learning value (n

= 16), as well as stakeholder-related challenges including institutional siloing (n = 14), faculty training deficits (n = 13), cybersecurity and data privacy concerns (n = 13), FERPA and compliance constraints (n = 11), and lack of community of practice and collaboration (n = 11).

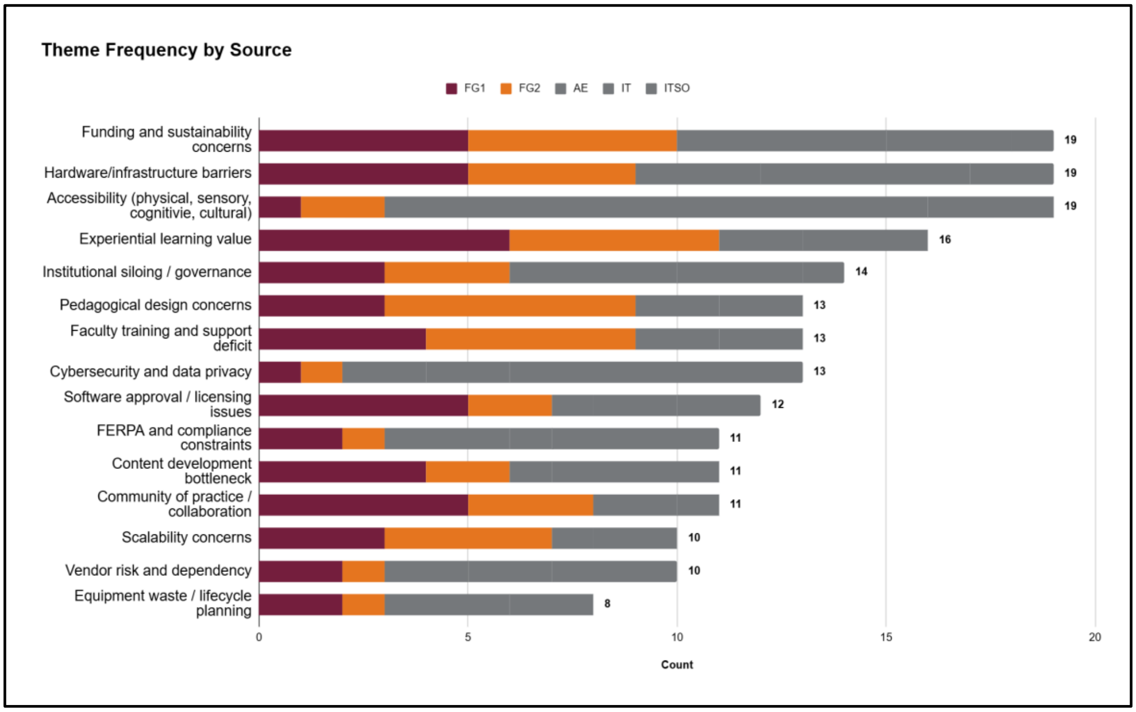

Figure 12. XR implementation prohibitive factors tally analysis showing frequency of identified themes across data sources (i.e., focus groups, and SME interviews).

4.4.1. Technical & Infrastructure Barriers

Technical and infrastructure barriers were among the most frequently cited categories across data sources, with hardware/infrastructure barriers (n = 19) and software approval and licensing issues (n = 12) frequently reported. Participants frequently reported insufficient development computer GPU capacity, lack of centralized XR infrastructure, and limited availability of suitable HMD hardware. Specific technical issues included software approval bottlenecks (n = 7), insufficient computing hardware (n = 6), and unresolved SS challenges (n = 5).

A recurring constraint was the content development bottleneck (n = 11), reflecting the limited availability of skilled developers and the complexity of XR development platforms such as Unity and Unreal Engine. Scalability challenges (n = 10) were also prominent, particularly for large-enrollment courses where hardware access, system setup, and logistical coordination were described as limiting factors. These barriers were often discussed alongside resource and organizational constraints, indicating interdependencies across system components.

4.4.2. Pedagogical & Institutional Barriers

Pedagogical barriers were identified with moderate-to-high frequency (n = 28), with design concerns (n = 13) and faculty training deficits (n = 13) as the most prominent themes. Participants frequently expressed concern that XR is adopted without sufficient grounding in instructional design principles, resulting in experiences that replicate passive, lecture-based formats rather than leveraging the interactive and immersive affordances of the technology. This pattern of pedagogical misalignment was described as a persistent risk, particularly when XR implementation is driven by technological novelty rather than clearly defined learning objectives. Participants emphasized that meaningful XR integration requires structured curricular planning, scenario-based design, and explicit alignment between immersive experiences and intended learning outcomes.

Faculty training deficits were closely linked to pedagogical concerns. Participants described limited institutional preparation, noting that insufficient training leads to inconsistent implementation quality and, in some cases, student discomfort and SS. One participant drew on a prior deployment experience to illustrate how inadequate faculty preparation directly undermined the learning experience, underscoring that successful XR integration demands deliberate onboarding and sustained instructional support rather than one-time orientation.

Institutional siloing (n = 14) was also frequently identified as an organizational barrier. Fragmented coordination across departments, support units, and administrative offices was described as a recurring barrier to coherent XR implementation. The absence of centralized support structures and standardized workflows was associated with inconsistent practices across units and reduced capacity for cross-departmental knowledge sharing. Participants emphasized that without robust institutional coordination, XR initiatives risk remaining isolated, under-resourced, and difficult to scale. A lack of community of practice and collaboration (n = 11) was identified as a related concern, with participants noting that the absence of shared knowledge infrastructure limits the transferability of successful XR projects and inhibits cumulative institutional learning.

The structural dimension of this siloing was identified at the university level. Audio-visual (AV) services and IT support currently operate in separate institutional silos, despite increasing overlap as XR systems depend on both network infrastructure and display technologies. XR implementation will likely require either the development of hybrid roles spanning both domains and the integration of these functions. This convergence is already occurring incrementally, as IT staff increasingly troubleshoot display connectivity issues and AV systems become more deeply network-dependent. Without proactive institutional recognition of this trend, XR deployment risks falling into a support gap where neither community possesses the full skill set required for effective maintenance and troubleshooting.

4.4.3. Accessibility & Equity Barriers

Accessibility and equity barriers were identified across data sources, with physical and sensory concerns reported more frequently (n = 13) than cognitive and cultural concerns (n = 6). A key distinction emerged between accommodation and accessibility. Accommodation is the reactive provision of workarounds for individual disabled users, which was characterized as insufficient and at times counter-productive, as it frequently results in a qualitatively different and socially isolating experience rather than one that is equivalently engaging and inclusive. Accessibility, by contrast, was framed as a proactive and inclusive design orientation aimed at broadening the range of users who can engage meaningfully with a system from the outset. Rather than offering alternatives for disabled users, the goal is to allow all users the same quality and rich experiences as their peers. Designing for multiple modes of engagement from the ideation phase was identified as a more equitable and legally defensible approach, as it eliminates the need for disclosure while broadening access for all users.

Participants described a range of physical and sensory barriers that extend considerably beyond commonly cited concerns such as SS. XR-specific accessibility constraints included the physical weight and pressure of HMDs and sensory overwhelm associated with layered multi-sensory input, which can affect autistic users and create seizure risk among individuals with lower sensory thresholds (i.e., those with autism, epilepsy, etc.), compounded by posture and mobility requirements. These barriers represent known hardware-level design constraints that current XR devices have not resolved and collectively suggest that a significant portion of any university population may be unable to engage with headset-dependent XR modalities without meaningful alternatives. Participants consistently emphasized that no single interface, controller, or modality will serve all users, and that the design goal should therefore be providing optionality (i.e., allowing users to choose among multiple means of engagement) rather than a universal solution applied uniformly.

To realize this goal, participants argued that disabled users and accessibility consultants must be incorporated as compensated members of XR development teams from the earliest stages of the process, not engaged reactively once design decisions have already been made. Retrofitting accessibility after significant development investment was described as both financially costly and often structurally insufficient. Participants framed this as a cautionary institutional precedent: building first and retrofitting later is not a viable accessibility strategy, and XR systems must be designed with accessibility requirements including FERPA and ADA Title II requirements.

Physical space accessibility was identified as a prerequisite that precedes any consideration of XR technology itself. Participants noted that high-technology spaces on campus are sometimes physically inaccessible due to unreliable elevator access, unclear reservation systems, and loan periods that are too short to allow meaningful learning before equipment must be returned. These infrastructural barriers can exclude disabled users before any interaction with XR content occurs, underscoring the need for facility-level accessibility review as part of any XR implementation planning.

Cognitive accessibility was also flagged, particularly in relation to faculty and staff who will facilitate XR experiences. Participants recommended that documentation and training materials be designed for users with no prior knowledge of either the technology or accessibility practices, rather than calibrated to the expertise of developers or early adopters. This design posture, assuming minimal familiarity, was framed as essential to reducing friction at the point of use and ensuring that accessibility features are understood and applied in practice.

4.4.4. Governance & Security Barriers

Governance and security concerns were identified across data sources. Cybersecurity and data privacy concerns (n = 13) and FERPA and compliance constraints (n = 11) were more frequently discussed in interview data than in focus group data. Participants highlighted compliance requirements, including FERPA regulations, as influencing software adoption and implementation practices.

Cybersecurity concerns were associated with XR systems' collection of behavioral and biometric data, as well as networked and cloud-based dependencies. One participant framed these risks using the Confidentiality, Integrity, and Availability (CIA) triad, noting that each dimension presents distinct vulnerabilities in XR contexts. Beyond unauthorized data access, participants raised the possibility that XR-generated content itself could be corrupted or manipulated (e.g., an actor hijacking an immersive educational environment to display harmful or false information), representing an attack vector that is particularly consequential given the heightened sensory engagement of XR systems.

Data ownership and storage were described as areas of significant uncertainty. One participant drew an analogy to legal disputes between John Deere and farmers over proprietary software, using it to illustrate how XR vendors may assert control over data generated through student interactions (i.e., movement patterns, behavioral inputs, and biometric signals) even when that data is produced within a university context. This raises governance questions that existing FERPA frameworks may not fully address, particularly in sensor-rich XR environments. Participants also cautioned that free or freemium XR tools introduce additional risk, as licensing agreements in such models may implicitly authorize vendors to collect and monetize user data, potentially exposing sensitive student health or behavioral information to third parties such as insurers or advertisers.

Vendor dependency and software approval processes were also identified as barriers, with participants noting variability in approval timelines and institutional processes. Vendor risk assessments were described as averaging 10–12 days but extending to nearly a year in some cases, depending on vendor responsiveness and data sensitivity. This variability has direct implications for project planning, particularly when combined with the development bottlenecks described elsewhere in this study, compounding overall implementation timelines.

Infrastructure readiness was identified as a relative strength, with VT's 400 Gbps campus backbone and a planned expansion of its external internet connection providing a foundation capable of supporting bandwidth-intensive XR applications. However, participants cautioned that video-heavy XR traffic will still place meaningful demands on network capacity, suggesting that infrastructure advantages must be paired with careful capacity planning rather than being treated as sufficient on their own.

Participants identified accountability gaps in shared-device environments, where security logs capture machine-level activity rather than individual users. This creates challenges for incident response and data protection. To address vendor-side vulnerabilities, participants recommended ongoing penetration testing of XR applications by institutional security teams, emphasizing that security evaluation should be continuous rather than a one-time process.

4.5. External XR Development Process

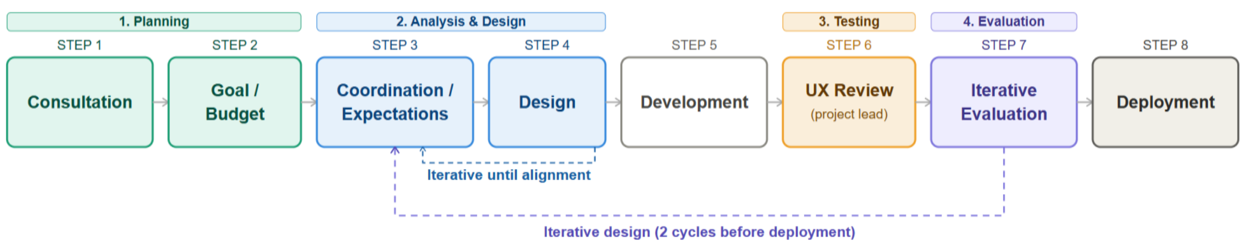

Figure 13. External XR EHS PFE Module development workflow illustrating the sequence of activities from instructional need identification to deployment and evaluation.

Findings indicate that XR development follows a multi-stage, collaborative workflow involving faculty, institutional support units, and external partners (Figure 13). This workflow spans instructional need identification, design, development, and deployment.

4.5.1. Development Workflow & Collaboration

The XR development workflow was faculty-initiated and support-driven. Faculty typically begins with an instructional need, often related to experiential or simulation-based learning, which is then translated into XR applications through consultation with technical staff and support units.

Institutional stakeholders, including educators, instructional designers, accessibility experts, IT staff, and IT security officers played a facilitative role. These stakeholders support feasibility assessment, platform selection, and design translation, bridging the gap between instructional intent and technical implementation. Workflows were iterative and non-linear, involving cycles of prototyping, testing, and refinement. Collaboration was necessary but variable, with some projects involving close coordination while others were more fragmented. External developers and vendors were involved in XR development for projects requiring specialized expertise. External developers enabled specialized development but introduced additional dependencies.

4.5.2. Constraints & Development Challenges

Development constraints closely aligned with high-frequency barrier themes identified across data sources. Content development bottlenecks (n = 11), funding constraints (n = 19), and vendor dependency (n = 10) were among the most frequently reported challenges.

Participants described XR development as constrained by limited access to skilled developers and reliance on small teams, often operating within short timelines. One participant described XR fidelity as analogous to image resolution: high-quality outputs require large teams and extended timelines, whereas small teams operating within academic constraints can produce only moderate-fidelity results. This framing is particularly relevant in contexts where graduate assistants serve as primary developers, making expectation management a critical component of project planning. These constraints were associated with limited iteration cycles and reduced development refinement. Funding limitations were frequently linked to sustainability challenges, with participants reporting that XR projects are often supported by short-term grants that do not extend to long-term maintenance or scaling.

Vendor dependency introduced constraints related to communication, system compatibility, and long-term platform control, while also contributing to coordination challenges and integration difficulties within institutional systems. Participants identified structured collaboration across stakeholders to align instructional goals with technical implementation from early project stages as essential to mitigating these coordination failures. These constraints were frequently described as interconnected.

The consequences of unsustainable funding models were illustrated through a recurring pattern described by participants: equipment acquired through short-term grants and used briefly for a single research project was often abandoned, with no maintenance plan, no institutional memory, and no strategy for continued use. One participant described encountering a room containing more than 50 VR HMDs that had not been used for years following the conclusion of the project. This pattern of equipment obsolescence and institutional siloing represents a direct and preventable cost and argues for sustainable workflow design and lifecycle planning (i.e., the ability to maintain, adapt, and reuse XR applications beyond initial deployment) as prerequisites for any XR investment rather than concerns to be addressed after procurement. Participants also emphasized the importance of early integration of accessibility and security considerations, noting that addressing these factors after initial development introduces significant additional constraints, both financial and structural.

Alternative funding sources, including corporate sponsorships, were noted as a potential supplement to grant-based models. However, participants cautioned against governance risks associated with corporate sponsors bringing their own agendas, timelines, and performance expectations that may not align with institutional, pedagogical, or accessibility goals.

Participants recommended a pilot-first approach as a more institutionally controlled model: beginning with a scoped, well-designed pilot project that demonstrates effectiveness and generates evidence of community-aligned value, rather than replicating existing XR implementations or scaling prematurely. This approach was framed as more likely to produce sustainable outcomes than grant-driven deployments that lack a long-term trajectory beyond the initial funding period. Additional development challenges and corresponding impacts are shown in Table 5. These findings were synthesized into an *External XR Development Guide* outlining key workflows, constraints, and requirements for XR development in higher education (Appendix E).

Table 5. Summary of XR development challenges, associated descriptions, and impacts on implementation outcomes across data sources

Development Challenges		
Theme	**Description**	**Impact**
Learning curve of development platforms	Unity and Unreal Engine require substantial time to learn; even experienced teams take months for moderate-quality outputs	Slows development timelines; discourages faculty from initiating projects
Mismatch between small-team capacity and quality expectations	Small teams of 1–2 GAs working for a few months cannot produce AAA-quality content; expectation management is a persistent friction point	Risk of under-delivered products that undermine faculty and student confidence in XR
Fidelity ceiling under budget constraints	Budget limitations constrain scenario richness, randomization depth, and kinesthetic realism	Reduces instructional effectiveness; limits transfer to real-world performance
Workflow challenge in previewing digital twin at scale	Creators designing for large immersive spaces (e.g., the Cube) cannot accurately evaluate the experience on a standard desktop monitor	Misalignment between intended and actual immersive experience; requires costly iteration
Randomization and replayability under budget	Generating sufficient scenario variation to prevent memorization requires additional development resources most projects cannot afford	Compromises integrity of formative or summative assessments using XR
Iterative development with limited resources	Projects are typically only able to reach 2–3 iterations before funding or personnel runs out; necessary refinement cycles are truncated	Modules are released before reaching sufficient quality or accessibility compliance
Communicating requirements to external vendors	Faculty without technical XR backgrounds struggle to write precise design requirement documents; miscommunication leads to costly revisions	Inefficient use of contracted development budget; outputs may not match pedagogical intent
Transitioning content across platforms	Content developed in one XR environment (e.g., Mozilla Hubs) may not transfer when that platform is discontinued, updated, or de-hosted	Loss of completed work; sunk development costs not recoverable
Hiring and retaining development expertise	VT and similar institutions lack in-house XR development depth; Graduate Assistants provide the primary development resource but rotate out	Institutional knowledge is non-cumulative; each project effectively re-starts from scratch
Accessibility integration cost	Designing for multi-modal access, cognitive scaffolding, and disability inclusion adds significant development overhead that most budgets do not accommodate	Accessibility is deferred or omitted entirely, creating compliance risk and exclusion
Device management at classroom scale	Sanitizing, charging, configuring, and managing multiple headsets per class session adds logistical burden on instructors and support staff	Reduces class time available for learning; discourages repeated or spontaneous use
Content ownership and licensing ambiguity post-development	It is unclear who owns XR modules co-developed with external vendors, Graduate Assistants, or through grant funding	Inhibits sharing, reuse, and scaling of successful modules across the institution

CHAPTER 5: Discussion

5.1. Overview of the Chapter

This study investigated the implementation of eXtended Reality (XR) technologies within a higher education institution (HEI) through a multi-stakeholder, socio-technical systems perspective. Guided by three research questions examining stakeholders, system dynamics, and socio-technical factors influencing XR implementation, the findings offer a system-level analysis that extends beyond purely technological or pedagogical considerations. Overall, XR implementation is best understood as a complex systems challenge requiring coordination across multiple institutional domains.

By incorporating perspectives from non-faculty stakeholders, including IT staff, accessibility and disability experts, and IT security, this study expands XR research beyond its traditional focus on students and faculty. The findings provide empirically grounded insights into XR development workflows, constraints, and implementation requirements, highlighting interdependencies across technical, pedagogical, organizational, and governance dimensions. Together, these contributions frame XR implementation around three core questions: who is involved, how roles and relationships operate, and what socio-technical factors shape development, adoption, and scalability.

5.2. RQ1: Who are the key stakeholders involved and what are their roles, needs, and relationships in XR implementation within higher education institutions?

The findings identify an interconnected stakeholder ecosystem extending beyond traditional instructional roles. While educators and students are central actors, effective XR implementation relies heavily on instructional designers, IT support, accessibility/disability experts, and governance stakeholders (e.g., administrators, IT security). These results empirically expand on prior literature, which has largely focused on students and faculty, by demonstrating the critical enabling role of non-faculty stakeholders in system-level XR implementation.

Stakeholder roles are distributed across interconnected phases of XR implementation: ideation, development, deployment, and governance. Successful implementation requires high interdependence among stakeholders, creating a highly interdependent system requiring coordination across instructional, technical, and administrative domains. Stakeholders' needs extend beyond technical functionality to include workflow integration, communication structures, and institutional support mechanisms, reinforcing the importance of systems-level alignment.

A theoretically significant finding concerns the classification of stakeholders based not only on role identity, but on the continuity and nature of their operational engagement. Active stakeholders demonstrate continuous, hands-on involvement that shapes day-to-day XR practices, while passive stakeholders exert episodic, governance-level influence without directly operating the system. For example, IT Security Officers primarily operate in governance roles during initial implementation but become directly engaged when security incidents arise. This capacity for high-stakes intervention supports their classification as active stakeholders. Similarly, Community Partners occupy a conditionally active role, contributing during co-development phases but without consistent involvement across implementations. These findings suggest that effective XR governance requires clear institutional agreements regarding when and how episodic stakeholders are engaged, rather than assuming participation will emerge organically.

A notable asymmetry in stakeholder visibility was observed across data sources. Focus group participants, primarily educators, identified stakeholders concentrated in the instructional layer (i.e., faculty, students, and instructional support roles). Interview participants, comprising domain experts in IT, accessibility, and security, identified a substantially broader range of stakeholders operating at system and governance levels. This divergence itself is significant — the educators had limited visibility into the institutional infrastructure their work depends on, while system-level stakeholders recognized the interconnected demands of cross-functional coordination. Without deliberate mechanisms to bridge this gap (e.g., cross-functional onboarding or shared planning forums), institutions risk creating invisible dependencies and unrecognized bottlenecks.

This dynamic is evident in the relationship between AV services and IT support, two functions that have traditionally operated separately despite increasing overlap. Broader technological trends are already driving convergence between these functions, as IT staff increasingly take on display connectivity troubleshooting and AV systems become more deeply network-dependent. The adoption of XR is expected to accelerate this convergence further, yet both functions continue to operate in separate institutional silos. To minimize implementation risk, effective XR deployment will necessitate bridging this support gap, either through the full convergence of these functions or the establishment of a dedicated XR systems support entity staffed by technicians possessing the complete skill set required for effective maintenance and troubleshooting. Without proactive institutional recognition of this shift (e.g., hybrid roles or coordinated structures), integration will occur reactively rather than strategically, increasing implementation risk at the operational level.

5.2.1. The Role of Instructional Design and Pedagogical Alignment

Instructional design emerges as the primary mechanism through which XR's potential is either realized or constrained. Participants frequently described implementations that lacked clear learning objectives, resulting in technology-driven use cases that prioritized novelty over pedagogical value and rendered XR a single-use tool rather than a sustainable instructional resource. As participants emphasized, effective XR integration requires focusing on the pedagogical "why" rather than the technological "wow," as novelty-driven implementations consistently fail to produce meaningful learning outcomes. This challenge extends beyond individual instructor practice and reflects broader institutional gaps in faculty training (n = 13), limited access to instructional design expertise, and the absence of standardized educational content development processes.

Central to addressing this misalignment is the meaningful involvement of instructional designers, who are critical stakeholders in ensuring that XR tools are developed with clear pedagogical intent. Despite this, instructional designers are frequently excluded from development phases, including ideation and planning, creating misalignment in expectations across teams and limiting the extent to which XR's potential can be fully realized. Early involvement is therefore critical, as expertise in learning objectives and pedagogical alignment cannot be easily retrofitted once development begins. More broadly, improving XR effectiveness requires shifting from ad hoc experimentation toward systematic integration, aligning XR activities with learning objectives, embedding assessment systems, and supporting iterative refinement. This aligns with prior research emphasizing scaffolding, alignment, and cognitive load management in XR environments, as immersive contexts can introduce cognitive overload when instructional structure is insufficient, reinforcing that XR effectiveness depends on guided interaction rather than immersion alone. In this sense, instructional design represents not only a pedagogical concern, but a core institutional capacity required for sustainable XR integration.

5.2.2. Accessibility, Equity, and Inclusion

Accessibility and equity represent critical yet underrepresented dimensions of XR implementation. Participants identified a range of barriers, such as physical and sensory limitations ($n = 13$) and cognitive or cultural accessibility considerations ($n = 6$). Specific concerns included SS and incompatibility with assistive technologies, highlighting the exclusionary potential of XR when accessibility is not proactively addressed.

The dominance of VR-centric approaches introduces further structural inequities. VR HMDs are associated with SS, and physical interaction demands that limit accessibility for some users, and their reliance on handheld controllers further constrains equitable participation for those with motor or physical disabilities.

Alternative modalities such as AR, MR, mobile, and desktop offer lower barriers to access, reduced physical discomfort, and greater compatibility with existing institutional infrastructure. These modalities reduce physical barriers, improve compatibility with existing infrastructure, and support broader participation. Thus, expanding adoption to incorporate optional and multimodal approaches represents a pathway toward more inclusive and scalable XR implementation, ensuring that access is not contingent on a single modality or hardware ecosystem.

Infrastructure was also flagged as an accessibility barrier. If the physical space (e.g., XR labs) does not accommodate those with disabilities or maintain accessibility support systems (e.g., elevators), it creates compounding barriers to participation. The broader implication is that accessibility is not merely a design consideration but a structural determinant of who can participate in XR-enabled learning. Failure to address accessibility risks FERPA and ADA Title II violations.

5.3. RQ2: What socio-technical barriers and enablers influence the adoption and scalability of XR in higher education?

The findings identify a network of interrelated socio-technical barriers: i) resource constraints; ii) pedagogical misalignment; iii) organizational siloing; and iv) governance challenges. These barriers do not operate independently; they are interconnected. Failing to resolve one barrier can create or worsen others, amplifying the overall impact on implementation outcomes. The primary constraint on XR adoption is not technological capability but institutional coordination. XR fails not because it cannot be implemented, but because the systems required to support it are insufficiently integrated. Enablers such as modular design, cross-functional collaboration, and institutional support structures highlight pathways for scalable adoption. These findings reinforce that XR implementation is fundamentally a socio-technical systems challenge.

Across data sources, XR was consistently positioned as a powerful enabler of experiential learning, particularly in contexts involving simulation, interaction, and otherwise inaccessible environments. Survey data indicated strong interest in XR adoption for enhancing teaching (mean = 4.15) and improving student engagement and motivation (mean = 4.10). Active learning opportunity was identified as the strongest motivation for XR adoption, followed by increased learner engagement and immersive conceptual visualization. Participants described XR as enabling interaction with environments that are dangerous, rare, or otherwise inaccessible, particularly in safety training and simulation-based contexts. These findings align with prior research emphasizing XR's capacity to support experiential learning through simulation and presence (Makransky & Petersen, 2021; Aguayo & Eames, 2023). The observed benefits related to spatial visualization and embodied interaction further reinforce alignment with embodied cognition frameworks, which suggest that learning is enhanced when abstract concepts are externalized into interactive, sensorimotor experiences (Wilson, 2002; Johnson-Glenberg, 2018).

Although XR enables the conditions for experiential learning, it does not ensure its realization. While engagement and motivation were frequently reported, these outcomes did not consistently translate into meaningful or well-aligned learning experiences. Consistent with findings discussed in Section 5.2.1, pedagogical misalignment (n = 9) persisted as a system-level barrier, with its effects observable not only in individual implementations but across stakeholder types and institutional contexts. XR should thus be understood as a contingent affordance whose impact depends on how it is pedagogically structured and institutionally supported, a reframing that challenges prevailing assumptions equating immersion with effectiveness and reinforces prior research findings that immersion alone does not guarantee learning gains (Hamilton et al., 2021; Marks & Thomas, 2022).

The structural gap between interest and actual adoption further underscores the importance of the full stakeholder ecosystem. Over half of survey respondents (51.29%) reported no prior use of immersive technologies, while only 28.45% reported any level of use. Many educators reported having no prior experience facilitating XR in educational settings, and only 20.3% had any development involvement. This discrepancy suggests that XR adoption is constrained not by individual willingness, but by system-level readiness, reinforcing that sustainable XR adoption depends as much on institutional infrastructure and coordination as it does on instructor willingness or individual initiative.

These findings suggest that XR is best positioned as a supplemental learning tool that offers targeted experiential learning opportunities, particularly in high-value contexts such as safety training and conceptual visualization, rather than as a replacement for traditional instruction. Participants emphasized that scenario-based XR applications offer greater feasibility and impact compared to large-scale, fully immersive deployments, with an emphasis on concrete experience as a foundation for learning (Kolb, 2014).

5.3.1. Facilitation Experience as a Driver of Adoption

When educators' XR facilitation experiences were examined, negative experiences (47 total counts) nearly doubled positive experiences (27 total counts), with technical instability, usability issues, and hardware limitations representing the most frequently reported challenges. This imbalance is significant not only as a reflection of XR readiness, but as a potential driver of adoption hesitancy. Research on technology adoption suggests that negative initial experiences shape future engagement; repeated exposure to technical failures and usability challenges may discourage faculty from continued XR use even when pedagogical value is recognized.

This finding reframes the adoption gap between interest and actual use. Rather than reflecting only resource or awareness limitations, the adoption gap may also be shaped by accumulated negative experiences among early adopters. Addressing this dynamic requires not only improving system reliability but also providing structured facilitation support, particularly during initial implementation phases, to ensure more positive and sustainable engagement.

5.3.2. Resource and Infrastructure Constraints

Resource constraints are not simply barriers to entry but structural issues that impact the entire XR ecosystem. Participants consistently identified funding, hardware access, and infrastructure as limiting factors affecting not only adoption but also scalability and sustainability. The limited availability of pre-built XR educational content necessitates custom development, increasing both cost and time investment. As a result, institutions face a compounding challenge: limited resources constrain development, while limited development capacity restricts scalable solutions. Addressing these issues will require coordinated institutional investment.

Temporary access fundamentally constrains iterative pedagogical refinement. Among respondents reporting access to XR resources, temporary borrowing was the most common access pathway (47.79%), with long-term loans representing only 16.18% of reported arrangements. Temporary access fundamentally constrains the iterative pedagogical refinement that effective XR integration requires; faculty cannot meaningfully pilot, evaluate, and redesign XR experiences when hardware availability is periodic rather than sustained. From a systems perspective, access conditions are misaligned with the timelines required for effective XR integration. Institutions that rely predominantly on the rental system may inadvertently limit XR use to one-off demonstrations rather than supporting the deeper curricular integration that participants identified as essential. Moving beyond ad hoc hardware distribution toward structured, long-term access models is necessary to support sustained pedagogical experimentation.

Hardware obsolescence introduces a further environmental and financial burden. Participants frequently raised concerns about equipment waste and lifecycle planning, reflecting the pace at which XR hardware quickly becomes outdated and creates an institutional burden of managing and replacing aging devices.

In higher education, where procurement processes are slow and budgets are constrained, long-term investments may not align with the pace of technological change. The consequences of this misalignment, and strategies for addressing it through sustainable development practices and industry partnerships, are discussed further in Section 5.4.1.

5.3.3. Governance, Privacy, and Data Security

XR introduces governance challenges that extend beyond traditional educational technologies. XR systems collect behavioral and biometric data (e.g., gaze tracking, movement, physiological responses) that exceed the data profiles of conventional tools. This raises regulatory and ethical questions that existing institutional frameworks were not designed to address.

A central concern is the uncertain application of FERPA to XR-generated data. FERPA governs the privacy of student educational records, but its application to biometric and behavioral data collected within XR environments remains an area of significant legal ambiguity. Findings indicate that data ownership and storage represent unresolved institutional concerns, suggesting that current governance structures lack adequate frameworks for managing XR-generated data. This gap has direct implications for informed consent, data minimization practices, and institutional liability: students may be unaware of the extent of data being collected, and institutions may lack the technical or policy infrastructure to manage or audit such data appropriately.

The complexity of data ownership in XR environments was further illustrated by the SME through an analogy: the ongoing legal disputes between John Deere and farmers over proprietary tractor software. In the same way that manufacturers have asserted control over operational data generated by farmers using their equipment, XR vendors may assert ownership over data generated through student interactions (i.e., movement patterns, behavioral inputs, and biometric signals) even when that data is produced entirely within a university context. This analogy captures the institutional risk — existing FERPA frameworks were not designed with sensor-rich, immersive environments in mind, and current interpretations may be insufficient to protect students or clarify institutional liability. It was also cautioned that free or freemium XR tools compound this risk, as licensing agreements in such models may implicitly authorize vendors to collect and monetize user data, potentially exposing sensitive student health or behavioral information to third parties (e.g., insurers or advertisers), an outcome with serious ethical and legal implications that institutions may be poorly equipped to anticipate before adoption.

Compounding these concerns is the tendency for governance to be addressed late in the implementation process. When data governance is deferred until deployment, institutions face significant compliance risks and may be required to make costly retroactive modifications to both technical systems and institutional policies. Governance must therefore be treated as a foundational component of XR implementation. This requires early engagement among IT security, legal counsel, instructional designers, and developers during platform selection and content development.

5.4. RQ3: How do socio-technical factors shape the external XR development process in higher education?

5.4.1. Institutional Readiness and the Sustainability of XR Development

XR workflows are characterized as multi-stage, iterative, and highly dependent on cross-stakeholder collaboration. Current workflows are often fragmented and lack standardization, with content development bottlenecks (n = 11), limited access to skilled developers, and reliance on external vendors (n = 10) identified as major limitations. The most common development timeline was 6–12 months. Overall, 71.6% of projects required at least 3–6 months, with 16 projects extending beyond 12 months. The scale of required resources and effort can discourage educators from initiating XR projects without clear long-term sustainability.

The composition of the development workforce compounds these vulnerabilities. Student workers represent the most utilized XR development resource (43.94%). While they provide a cost-effective and technically skilled labor pool, their transient nature introduces critical challenges related to knowledge continuity, quality control, and sustainability. As students graduate or rotate out of positions, expertise must be rebuilt, increasing inefficiency and limiting scalability. This pattern reflects a broader structural gap: the absence of dedicated, professional, internal XR development capacity within higher education settings. One participant described XR fidelity as analogous to image resolution: high-quality outputs require large teams and extended timelines, while small academic teams operating under constraints can produce only low-to-moderate fidelity results. In contexts where graduate assistants serve as primary developers, expectation management becomes a critical component of project planning.

From the external development perspective, while vendor partnerships offer fast-paced, high-fidelity module development, vendor dependency (n = 10) and platform fragility represent sustainability risks. Participants raised concerns about platform discontinuation, updates, or de-hosting, citing the Mozilla Hubs shutdown as a cautionary example. Institutions must therefore approach vendor selection with explicit attention to long-term platform viability, content portability, and data ownership. Agreements should clearly define content ownership and transition support in the event of platform discontinuation.

The consequences of unsustainable development and funding models were illustrated concretely by participants. Participants described a recurring pattern in which equipment acquired through short-term grants was used briefly and then abandoned, with no maintenance plan or strategy for continued use. One participant described encountering a room containing more than 50 VR HMDs that had not been used for years following the conclusion of the funding project. This pattern represents a direct and preventable cost. It underscores the need for sustainable workflow design and lifecycle planning (i.e., the capacity to maintain, adapt, and reuse XR applications beyond initial deployment) as a prerequisite for any institutional XR investment rather than an afterthought to be addressed after procurement. Alternative funding sources, including corporate sponsorships, were identified as potential supplements to grant-based models. However, participants cautioned that sponsors may introduce competing agendas, timelines, and performance expectations misaligned with institutional or pedagogical goals.

In response to these structural limitations, participants identified several practical approaches. Modular, supplemental design approaches emerged as key enablers, emphasizing discipline-specific, scenario-based applications aligned with course objectives rather than large-scale digital twin deployments. Reusable modular content libraries and templates were also recommended as strategies for reducing development burden and improving scalability. Additionally, participants strongly advocated for a pilot-first approach, beginning with a scoped, well-designed project as it is more likely to produce sustainable outcomes than grant-driven initiatives that lack a long-term trajectory beyond the initial funding period. This approach was also seen as a more credible path for building institutional proof of concept and long-term plan before broader adoption.

5.5. Implications

5.5.1. Theoretical Implications for VT

The findings contribute to the evolving theoretical understanding of XR by reframing implementation as a socio-technical systems challenge rather than a purely pedagogical or technological issue. While prior research emphasizes XR's role in enhancing engagement, experiential learning, and conceptual understanding (Makransky & Petersen, 2021; Aguayo & Eames, 2023), the results show that these outcomes depend on coordinated alignment across instructional, technical, governance, and organizational dimensions.

This study extends existing frameworks by empirically demonstrating the interdependence between social and technical components of XR implementation. The identification of interconnected barriers (i.e., resource constraints, pedagogical misalignment, organizational siloing, and governance requirements) supports socio-technical systems theory and advances XR research beyond fragmented, single-variable analyses toward a more holistic, systems-oriented perspective. By demonstrating how these interdependencies manifest within an R1 institutional context, this study contributes a richer empirical foundation to this theoretical tradition.

The findings challenge technology-centric assumptions that immersion and interactivity inherently produce improved learning outcomes. Instead, XR functions as an enabling condition for experiential learning rather than a deterministic driver of effectiveness. This distinction contributes to a growing body of literature critiquing technological determinism in educational innovation and underscores the importance of integrating XR within broader pedagogical and institutional frameworks.

5.5.2. Practical Implications for HEIs

From a practical standpoint, the findings highlight several key considerations for institutions seeking to implement XR at scale. First, the multi-stakeholder nature of XR requires centralized structures to support cross-functional collaboration. Without coordinated governance and shared processes, initiatives are likely to remain fragmented and difficult to scale. Institutions should develop deliberate mechanisms to include instructional designers alongside technical and governance stakeholders from the earliest phases of planning, rather than engaging them only during deployment. Early involvement of instructional designers is critical, as expertise in learning objectives and pedagogical alignment cannot be easily retrofitted once development begins.

Second, institutions must invest in faculty training and instructional design support. The gap between high interest and limited facilitation experience — only 33.6% of respondents reported prior XR facilitation, and just 20.3% had participated in development—indicates that educators require structured development opportunities to effectively integrate XR into their curricula. Early adopters, in particular, can play a key role in advancing institutional capacity by refining and sharing effective XR development and implementation practices, serving as catalysts for broader adoption.

Third, resource allocation remains a central determinant of success. Institutions must plan for sustained investment in infrastructure, technical support, and content development, rather than relying on short-term or ad hoc solutions. This includes establishing long-term hardware access models that support iterative faculty experimentation and developing lifecycle planning frameworks to address hardware obsolescence in a financially and environmentally responsible manner. Institutions may also benefit from cross-institutional partnerships and collaborations, which can help distribute costs, share expertise, and reduce common socio-technical barriers to XR implementation.

Fourth, institutions should prioritize supplemental XR applications over full-scale instructional replacement. By focusing on targeted, high-impact pilot use cases—such as safety training and conceptual visualization—HEIs can balance cost, accessibility, and pedagogical effectiveness while building capacity for broader adoption. Reusable modular content libraries, shared development templates, and standardized workflows can further reduce reliance on transient student labor and external vendors, improving long-term sustainability. Findings and frameworks from this study may also be adapted by other institutions to diagnose their own barriers and tailor implementation strategies to their specific contexts.

Finally, accessibility and governance must be treated as foundational requirements rather than post-hoc considerations. Institutions should ensure that XR labs and delivery modalities accommodate students with disabilities, incorporate privacy-by-design principles into platform selection, and establish clear data governance policies—including informed consent procedures and data ownership agreements—prior to deployment. To support these efforts, institutions should develop formal policies and strategic frameworks that explicitly guide XR adoption, ensuring alignment with accessibility standards, regulatory requirements, and long-term institutional goals.

5.5.3. Practical Implications and Recommendations for Vendors and Industry

The findings carry important implications for XR vendors and industry partners. Platform sustainability and transparency are non-negotiable institutional concerns. The discontinuation of platforms such as Mozilla Hubs has sensitized higher education stakeholders to the risks of vendor dependency. Vendors seeking to build durable relationships with HEIs should prioritize clear communication around platform roadmaps, content portability standards, and data ownership terms. Contractual frameworks that explicitly address transition support in the event of platform discontinuation will reduce institutional hesitation and build long-term trust.

Second, hardware access models should evolve beyond transactional sales. The prevalence of temporary borrowing arrangements (47.79% of reported access pathways) within institutions reflects a mismatch between current hardware distribution models and the iterative, sustained engagement that effective XR pedagogy demands. Vendors and industry partners should develop long-term loan programs, institutional licensing structures, and flexible hardware refresh pathways that enable HEIs to build sustained access without prohibitive upfront costs. Additionally, hardware lifecycle and sustainability considerations must be addressed proactively. Participants raised concerns about the pace of obsolescence and the burden of managing outdated equipment. Vendors should develop refurbishment programs, trade-in pathways, and sustainability certifications that allow institutions to responsibly manage device lifecycles. Industry partnerships that provide institutions with early access to hardware updates, rather than requiring full procurement cycles, can meaningfully reduce both financial strain and e-waste generation.

UX should be treated as a core design priority rather than a secondary consideration. Poorly designed interfaces, steep learning curves, and cognitively overwhelming interaction models represent meaningful barriers to adoption among both facilitators and end users. Vendors should therefore focus on designing onboarding workflows that minimize setup time, reducing cognitive load during initial interactions, and ensuring interfaces are intuitive enough to support independent use without requiring dedicated technical assistance.

Input modality flexibility and accessible multi-modal delivery should be treated as standard design requirements rather than optional features. Controller-based interaction, while common in VR environments, presents accessibility barriers for users with motor or physical disabilities and introduces additional complexity in shared or time-limited instructional settings. More broadly, the documented barriers associated with HMDs, including SS and incompatibility with assistive technologies, reinforce the need for cross-platform delivery that broadens participation across diverse student populations. Vendors should develop optional and alternative input modalities, including gaze-based, voice-activated, and touch-based controls alongside traditional controllers, to ensure equitable participation. This principle should extend consistently across AR, MR, and WebXR platforms, where interaction design varies considerably, and accessibility considerations are often inconsistently addressed. WebXR platforms are particularly valuable, as they enable access across multiple devices without requiring dedicated hardware, reducing both cost and access barriers at the institutional level.

Content co-development and modular design are preferred by institutional stakeholders. The findings indicate that large-scale, fully immersive deployments present feasibility barriers, while targeted, scenario-based, and modular XR applications are more readily adopted. Vendors should invest in co-development models that engage instructional designers and faculty early in the design process, and offer content libraries, reusable templates, and adaptable modules that reduce the development burden on institutions with limited internal capacity. Equally important is transparency in content ownership and editorial access. While vendors have legitimate interests in protecting platform integrity and version control, institutional stakeholders require a meaningful degree of freedom to adapt, modify, and contextualize XR environments to meet their specific pedagogical and operational needs. Vendors should therefore establish clear, mutually agreed-upon frameworks that define the scope and boundaries of institutional editing rights, ensuring that content remains adaptable without compromising platform stability or proprietary design constraints.

Data governance, privacy, and security must be embedded into platform architecture from the outset. XR systems collect sensitive biometric and behavioral data, requiring transparency in data use, institutional control over data settings, and alignment with regulatory frameworks such as FERPA and ADA Title II. XR platforms are capable of collecting sensitive biometric, behavioral, and geographical data, the misuse or mishandling of which can cause meaningful harm to users. Vendors should adopt privacy-by-design principles, provide transparent data use policies, offer institutions meaningful control over data collection and retention settings, and ensure that platforms are configurable to meet institutional compliance requirements. Treating these standards as baseline design requirements, rather than post-release obligations, is essential for building trusted institutional partnerships.

5.6. Limitations

While this case study provides a comprehensive, multi-stakeholder analysis of XR implementation within a higher education context, several limitations should be acknowledged when interpreting the findings.

First, this study was conducted at a single R1 institution, VT, and findings are therefore context-specific. Institutional characteristics such as size, research intensity, available infrastructure, and geographic location may influence XR adoption and implementation dynamics. As a result, stakeholder relationships, resource availability, and implementation challenges observed in this study may differ across institution types, including community colleges, private universities, teaching-focused institutions, or institutions in different regional or international contexts. While the findings offer valuable insight into complex institutional environments, caution should be exercised when generalizing results across diverse higher education settings.

Second, the study relied on a combination of survey responses (n = 232), focus groups (n = 14), and a limited number of domain expert interviews (n = 3). Although this mixed-methods approach enables triangulation, the small number of interview participants, particularly within specialized domains such as accessibility, IT, and security (n = 1 each) limits the breadth of perspectives captured. Additionally, participants were recruited based on availability and willingness to participate, introducing potential self-selection bias, as individuals with prior interest or experience in XR may have been more likely to engage.

Third, the findings are based in part on self-reported perceptions of XR use, benefits, and challenges. While these perceptions provide important insight into stakeholder experiences, they may not fully reflect actual learning outcomes, system performance, or implementation effectiveness. Furthermore, the quantitative component of this study was limited to descriptive statistics, focusing on patterns of adoption, use, and perceived barriers. Inferential analysis, particularly in relation to performance outcomes associated with the EHS PFE XR module across stakeholder groups, is planned as part of future research. As such, causal claims regarding XR's impact on learning and performance remain beyond the scope of this study.

Fourth, the study reflects a snapshot of XR implementation within a rapidly evolving technological landscape. XR hardware, software platforms, and development tools continue to advance at a rapid pace, and associated costs, usability, and accessibility barriers may shift over time. As technologies mature and become more widely adopted, some of the constraints identified in this study may diminish, while new challenges may emerge.

Finally, while this study adopts a socio-technical systems perspective, it does not formally model system interactions using quantitative systems engineering methods (e.g., system dynamics modeling or network analysis). Instead, the analysis relies on qualitative synthesis and descriptive integration of stakeholder perspectives and barrier categories. Future work could extend this research by developing formal system models to simulate and quantify XR implementation dynamics across institutional contexts.

Despite these limitations, the study provides a robust, empirically grounded foundation for understanding XR implementation as a complex, multi-stakeholder, and system-level challenge within higher education.

5.7. Future Research

Future research should examine the integration of XR with emerging technologies such as artificial intelligence (AI) and adaptive learning systems. AI-enhanced XR environments have the potential to support personalized learning, real-time feedback, and process-based assessment, enabling more adaptive and responsive educational experiences. However, the long-term effectiveness, scalability, and cost-benefit implications of such integrations remain underexplored.

Building on the current study, future research should also incorporate inferential and experimental methods to evaluate learning outcomes and performance impacts associated with XR applications. Planned evaluation of the EHS PFE XR training module across stakeholder groups will enable more rigorous assessment of XR's effectiveness in improving performance, self-efficacy, and knowledge retention.

While this study focused on higher education contexts, participants identified K–12 education and community outreach as promising areas for expansion ($n = 3$). Future research should explore how HEIs can leverage existing XR development capacity and content libraries to support K–12 partnerships, workforce development, and community-based learning initiatives. These cross-sector applications may enhance the broader impact and sustainability of institutional XR investments.

Longitudinal research is also needed to examine the long-term outcomes of XR adoption, including return on investment (ROI), sustained learning gains, and institutional scalability. Studies tracking XR initiatives over time would provide valuable insight into how implementation strategies evolve, which models are sustainable, and how socio-technical barriers change as institutions mature in their XR adoption.

Additionally, future work should investigate lifecycle planning frameworks for XR hardware and infrastructure, including strategies for extending device longevity, establishing institutional refurbishment programs, and developing procurement policies aligned with sustainability goals. Addressing these considerations proactively will be essential for institutions seeking to move beyond siloed, short-term deployments toward scalable, long-term XR programs.

Taken together, these directions reinforce that XR implementation remains a complex socio-technical challenge requiring continued interdisciplinary research, institutional coordination, and iterative refinement over time.

CHAPTER 6: Conclusion

Higher education institutions face mounting pressure to modernize pedagogical practices in response to the demands of an increasingly technology-driven economy. XR has emerged as a promising approach for transforming teaching and learning through immersive and experiential environments, yet it remains underutilized in HEIs. Adoption is constrained not only by technological limitations, but by a complex web of socio-technical factors spanning institutional, pedagogical, organizational, and governance dimensions. This study was motivated by the need to understand XR implementation as a systems-level challenge and to generate actionable, empirically grounded guidance for institutions seeking to adopt XR at scale.

Conducted within Virginia Tech's XR Community of Practice, this case study examined XR implementation across multiple stakeholder groups and institutional domains using a mixed-methods approach encompassing a campus-wide survey, focus groups, and semi-structured domain expert interviews. By incorporating perspectives from non-faculty stakeholders, including IT staff, accessibility and disability experts, and information security personnel, this study expanded the scope of XR research beyond its traditional focus on students and faculty, providing a more comprehensive view of the institutional ecosystem in which XR adoption occurs.

The findings reveal that effective XR implementation depends on coordinated alignment across a broad and interconnected stakeholder ecosystem. Stakeholders contribute to distinct yet interdependent phases of XR implementation. Their roles are best understood not only by identity, but by the continuity and nature of their operational engagement. Instructional design emerged as a central mechanism through which XR's potential is either realized or constrained, with pedagogical misalignment identified as a persistent, structurally embedded barrier rather than a result of individual instructor practice. Accessibility and equity were similarly identified as foundational requirements that must be integrated from the earliest stages of design and planning rather than addressed retroactively. Resource constraints, institutional siloing, governance uncertainty, and unsustainable development models collectively represent the primary barriers to scalable adoption and reflect system-level unreadiness rather than a lack of individual interest.

Taken together, these findings position XR as a complex socio-technical systems challenge that demands deliberate, cross-functional coordination across pedagogical, technical, and administrative domains. Institutions that approach XR adoption as a systemic endeavor — investing in structured stakeholder engagement, standardized workflows, and sustainable development models — will be better positioned to realize its potential. This study provides an empirically grounded foundation for that effort, offering actionable guidance for institutions, vendors, and researchers working toward scalable, inclusive, and pedagogically meaningful XR integration.

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Appendix A: Campus-wide Survey

This research seeks to engage with faculty, staff, and students at Virginia Tech (VT) to understand the needs for the development, application, and integration of extended reality at all levels. Extended reality (XR) is an overarching term that refers to any technology that adds technological or digital elements to an interaction. VR creates an immersive digital environment for users, while AR overlays digital information onto the physical, surrounding environment. You may stop the survey at any time.

If you complete the survey, you can choose to be included in a drawing for $50. The odds of receiving $50 are one in forty. If you agree to take part in a follow-up focus group research study, you will receive $25 for your time and effort.

Which group do you belong to?

1. Virginia Tech Undergraduate Student
2. Virginia Tech Graduate Student
3. Virginia Tech Faculty
4. Virginia Tech Staff
5. None of the above

Are you a distanced learning student? (are taking on or more classes virtually through Zoom or other video conferencing)

1. Yes
2. No

What is your involvement with immersive technology in a higher education setting?(Immersive technologies refer to virtual reality (VR), augmented reality (AR), extended reality (XR), virtual environments)

1. Have been involved in the development of an immersive technology (commissioned, built, or somehow involved in facilitating development)
2. Have only been a user of immersive technology
3. Have never used immersive technology in higher education

Further questions on immersive technology development for one or more projects
For what specific activity was the immersive technology/technologies intended? [Select All]

1. Classroom/education activity
2. Research
3. Recruitment
4. Performance/Recreation
5. Productivity/Communication

6. Other

Please a short description of the immersive technology projects (i.e. specific functionalities, goals of the project)

____

What colleges/programs/departments were these immersive technologies developed for? [Select All]

1. College of Agriculture and Life Sciences
2. College of Architecture, Arts, and Design
3. Pamplin College of Business
4. College of Engineering
5. College of Liberal Arts and Human Sciences
6. College of Natural Resources and Environment
7. College of Science
8. Other (program/department)

What resources were used to develop the immersive activity/activities? [Select All]

1. ARIES
2. Department development team
3. Third party developers
4. VT Library
5. Student workers
6. Other

What type of immersive technology development tools were used? [Select All]

1. Unity
2. Unreal Engine
3. Mozilla Hubs
4. ARKit and ARCore
5. Blender
6. Maya
7. Other

What immersive technology hardware was used? [Select All]

1. Dedicated XR-capable computer
2. VR Headset
3. AR Glasses
4. Mixed Reality Headset
5. AR-Capable Smartphones

6. External Motion Tracking Systems
7. Additional Trackers
8. Other

How did students/users access the immersive technology? [Select All]

1. Personal equipment
2. Long term borrowed equipment
3. Temporarily borrowed equipment
4. Other

How long did the development process take from design to implementation? (Multi-select if applicable to multiple projects)

1. 1-3 months
2. 3-6 months
3. 6-12 months
4. Longer than 12 months
5. One or more projects are ongoing

How do you perceive the success of the XR activity development project/projects in meeting project goals?

- 1 (did not meet goals)
- 2
- 3
- 4
- 5 (meet all goals)

Were you ever involved with facilitating an immersive tool in higher education? (Teaching with the tool, helping others use the experience at an event)

1. Yes
2. No

What challenges did you encounter facilitating the immersive technology experience? [Select All]

1. Usability and user experience of the tool
2. Evaluating the effectiveness of the tool
3. Technical issues
4. Maintenance issues
5. Student/user adoption
6. Limited hardware
7. Physical accessibility

8. Digital accessibility
9. Integration with existing activities
10. Other

Please briefly describe experiences facilitating immersive technology activities (specific activities/challenges)

____

Are you interested in being contacted for follow up questions on your XR development project?

1. Yes
2. No

Have you also been a user of immersive technologies in higher education? (i.e. classroom, remote learning)

1. Yes
2. No

Further questions on experiences using immersive technology in higher education
For what specific activity was the immersive technology/technologies intended? [Select All]

1. Classroom/education activity
2. Research
3. Recruitment
4. Performance/Recreation
5. Productivity/Communication
6. Other

As an end user, I thought the immersive technology capabilities met my requirements.

- 1 (did not meet)
- 2
- 3
- 4
- 5
- 6
- 7 (met all)

As an end user, I thought the immersive technology was easy to use.

- 1 (not easy)
- 2
- 3
- 4

- 5
- 6
- 7 (easy)

Please consider what support you believe to be most important for immersive technology development for higher education.Rank the following types of support (you do not need to rank an item you don't consider important)

1. Pedagogical training (for effective tool integration) __________
2. Immersive tech expert collaboration __________
3. Assessment/evaluation methods __________
4. Tech support (for troubleshooting and maintenance) __________
5. Funding (for immersive tool research/development) __________
6. Development software access __________
7. Hardware access (i.e. VR headsets, AR mobile phones) __________
8. Immersive tech developers __________
9. Training for development skills __________
10. Usability/User experience testing __________
11. Student/user training (for immersive tech adoption) __________

What other resources/support for immersive technology development do you consider important? (N/A if fully covered by previous ranking question)

____

Please rate how much you agree with the following statements (5-Likert: 1 being 'Strongly Disagree'; 5 being 'Strongly Agree')

I am interested in using immersive technologies in a classroom setting

❏ 1 ❏2 ❏3 ❏4 ❏ 5

I am interested in using immersive technologies for research

❏ 1 ❏2 ❏3 ❏4 ❏ 5

I am interested in using immersive technologies for recruitment (i.e. recruitment for different majors/colleges at Virginia Tech)

❏ 1 ❏2 ❏3 ❏4 ❏ 5

I believe immersive technologies can enhance the teaching experience.

❏ 1 ❏2 ❏3 ❏4 ❏ 5

I believe immersive technologies can improve student engagement and motivation while learning

❏ 1 ❏2 ❏3 ❏4 ❏ 5

What are your concerns or barriers when considering the adoption of immersive technologies in education? (Select all that apply)

1. Cost of implementation
2. Lack of technical expertise
3. Lack of access to necessary equipment
4. Concerns about privacy and data security
5. Limited immersive content/pre-built materials available
6. Resistance to change from students or professors
7. Other

What are motivations you consider with the adoption of immersive technologies

1. Increased engagement
2. Active learning
3. Simulating the real world
4. Accessibility
5. Competitive advantage (over other programs or schools)
6. Research opportunities
7. Accommodating large numbers of students/users
8. Other

Which category best describes you?

1. White (Eg: German, Irish, English, Italian, Polish, French
2. Hispanic, Latino or Spanish origin (Eg: Mexican or Mexican American, Puerto Rican, Cuban, Salvadoran, Dominican, Colombian)
3. Black or African American (Eg: African American, Jamaican, Haitian, Nigerian, Ethiopian, Somalian)
4. Asian (Eg: Chinese, Filipino, Asian Indian, Vietnamese, Korean, Japanese)
5. American Indian or Alaska Native(Eg: Navajo nation, Blackfeet tribe, Mayan, Aztec, Native Village or Barrow Inupiat Traditional Government, Nome Eskimo Community)
6. Middle Eastern or North African (Eg: Lebanese, Iranian, Egyptian, Syrian, Moroccan, Algerian
7. Native Hawaiian or Other Pacific Islander (Eg: Native Hawaiian, Samoan, Chamorro, Tongan, Fijian)
8. Other/Prefer Not to Say

What is your sexual orientation?

1. Asexual
2. Bisexual
3. Gay
4. Heterosexual or straight
5. Lesbian
6. Pansexual

7. Queer
8. Other/Prefer Not to Say

How do you identify your gender?
1. Man
2. Non-binary
3. Woman
4. Other/Prefer Not to Say
5. What college do you belong to/are you affiliated with?
6. College of Agriculture and Life Sciences
7. College of Architecture, Arts, and Design
8. Pamplin College of Business
9. College of Engineering
10. College of Liberal Arts and Human Sciences
11. College of Natural Resources and Environment
12. College of Science
13. Other (If you do not work directly with a college, include what entity you work with at Virginia Tech)

What department do you belong to/are you affiliated with?

____

Are you interested in participating in a focus group on immersive technology use at Virginia Tech? (1.5 hour, $25 compensation)
1. Yes
2. No

Would like to be entered in the raffle (Selected participants will receive $50)
1. Yes
2. No

Appendix B: Focus Group Protocol

XR_Community of Practice Workshop Event

Date:
Moderator:
Moderation Support:
Participant Name: Last, First

Activity Timeline:

Introduction (5 min).
Hello, and welcome to the Technology-Enhances Learning & Online Strategies (TLOS) XR Community of Practice Focus Group. My name is Tony Lee, an M.S. Human Factors & Systems Engineering GRA supporting this initiative.

This session is part of Virginia Tech's Phase III XR_CoP, which aims to establish a framework for systematic eXtended Reality adoption at Virginia Tech.

Objectives of the Phase III is:

- Identify a system structure for integrating XR into teaching and learning activities;
- Explore a use case XR implementation in teaching and learning.
- Disseminate best practices and findings to the university stakeholder.

In the higher education domain, XR offers opportunities for enhanced learning through hands-on immersive scenario-based simulations, interactive visualizations, and experiential learning environments.XR could be utilized as a supplemental tool to aid traditional learning methods in increasing students' self-efficacy.

- *Self-efficacy is a person's belief in their ability to complete a task or achieve a goal. It's also a measure of how confident someone is in their ability to control their behavior, often influenced by their environment.*

The purpose of this focus group is to better understand various stakeholder needs for effectively integrating XR into classrooms.

Insights from faculty across disciplines will help us create a detailed XR Implementation Guide and Recommendations, aiming to minimize barriers and repeated mistakes, thus reducing stress and frustration among innovative educators. We'll discuss stakeholder needs, identify barriers, and gather inputs on XR implementation.

We encourage you to share your experiences and opinions, regardless of your level of familiarity with XR and immersive technologies.

During this session we will be recording audio and notes.

Icebreaker (5 min).

1. Share your name, department/role, and any previous experiences with XR (whether through research projects and/or class activities).

Review of XR Integration Document (30 min)

Envisioning the Future

2. How do you envision education and classrooms evolving in the next 5 years?

Barriers & Challenges

3. What are some concerns you have about XR usage in classrooms?
4. Based on your previous experiences, what worked well and what didn't?

Active Stakeholders: individuals or organizations that will actively interact with the system once it's operational and in use.

We've identified 8 active stakeholders: Educators (Faculty/Staff), In-Person Students , Distant Learning Students, Students with disabilities, Teaching Assistants (TA), IT Support Staff, University Library/ICAT Personnel, and Adversaries (malicious entities).

Passive Stakeholders: other entities that don't actively interact with the system in operation, yet influence its success during development and once deployed.

On the other hand, we've identified 8 passive stakeholders: Content Developers (internal vs. external), Vendors/Industry Partners (Hardware & Software), Funding Providers (Alumni, Provost), Administrators, Policy makers, Teaching Support Staff/Trainers, VT Researchers, and Competition (other institutions)

Missing Stakeholders

5. Who else should be involved as active or passive stakeholders in XR implementation? If any?

Faculty Needs

6. Are there any other needs not identified that should be included?
7. Are there any liability issues to consider?
    a. How do you think faculty or staff can be held liable, what should VT do to protect you?

8. Do you have sufficient access to XR hardware and software right now?
    a. How do you envision this type of access?
9. What kind of training or support do you need to successfully integrate XR into your curriculum?
10. What are some ethical concerns (e.g., data privacy and security) related to XR technology?
    a. How would you recommend solving this issue?
11. Are there financial barriers that need to be addressed?
    a. How should faculty get the funding for developments? External development tends to be costly but provides quick and high-quality content; and Internal may be cheaper but could take longer to develop.
12. What barriers exist in terms of approvals (i.e., approved vendor payment processes, etc.)
13. From the administrative and faculty perspective, what should be considered AND what is the threshold when measuring the success of XR implementation?

HFE-UX (20 min)

We were able to create an XR Environmental Health and Safety Portable Fire Extinguisher Training Module that is designed to be a supplemental tool on top of the traditional learning modality that already exists. We contracted VictoryXR to develop this content – it took approximately 2 weeks to test the first prototype, and 2 weeks for the second iteration. These videos are based on the second iteration and we are now waiting on the third iteration. In this module, users are spawned into a warelab environment. The first task is to identify potential fire hazards across the virtual environment. Next, users are trained on the basic knowledge, trained on how to use the fire extinguisher, and lastly, once users feel comfortable with the controls, they are tasked to complete scenario-based training by deciding either to extinguish the active fire or evacuate.

Review the XR EHS Portable Fire Extinguisher Module

14. Do you have any specific feedback on what could be improved?
15. How do you think XR can benefit your curriculum?
16. Do you prefer Fully Digital Twin vs. Supplemental Tool?
17. Can you provide examples of what you would like to create using XR?
18. Frequency of usage?

Closing Remarks (5 min)

19. Any Questions?

Appendix C: Semi-Structured Interview Protocol

XR_CoP Interview Protocol

Date:
Moderator:
Moderation Support:
Participant Name: Last, First

[Brackets/Blue text = Facilitation notes or Optional follow-up]
Remember to:

- *Keep it conversational and natural.*
- *Dive deeper into their response if they say something interesting/unique.*
- *Keep up with the time limit per section.*
- *Keep participants engaged and bring them back when sidetracked.*

Background [5 min]

[Probe] Thanks for taking the time to chat with me today about your perspectives. This project is funded by TLOS, aimed at establishing a framework for systemic eXtended Reality adoption at Virginia Tech.

Objectives of the Phase III is:

- Identify a system structure for integrating XR into teaching and learning activities;
- Explore a use case XR implementation in teaching and learning.
- Disseminate best practices and findings to university stakeholders.

In the higher education domain, XR offers opportunities for enhanced student learning through hands-on immersive scenario-based simulations, interactive visualizations, and experiential learning environments. We believe that XR could be utilized as a supplemental tool to aid traditional learning methods in increasing students' self-efficacy.

The purpose of this interview is to better understand various stakeholders' needs (like yourself) for effectively integrating XR into classrooms. We will discuss your needs, requirements, and perspectives on XR implementation. We encourage you to share your experiences and opinions, regardless of your level of familiarity with immersive technologies.

[Review consent.] *Your participation is entirely voluntary, and you can refuse to answer any questions and withdraw from the study at any time for any reason without penalty. This session will be video/audio recorded and the session should last no longer than 45-minutes. Do you have any questions?*

Warm-up. Let's start with your work.

1. Tell me a bit about your role and what your responsibilities are.
2. How familiar are you with immersive technologies (i.e., AR, VR, MR)?

Section A: Technical Infrastructure & System Integration.

3. What hardware, software, and technical infrastructure would be required for effective XR implementation?
4. What training support would be required to effectively use XR?
    a. **[Probe]** What type and duration of training would you need?
    b. **[Probe]** How should training be structured and delivered?
5. How should XR systems integrate with existing learning management systems (LMS), student information systems (SIS), and other institutional infrastructure?
6. From your perspective, what would indicate successful XR implementation, particularly in terms of ongoing support and troubleshooting?

Section B: Implementation Requirements & Systems Design.

7. What interoperability standards or technical specifications are critical for your context?
8. How should the XR system scale across different departments, courses, or user groups?
9. How should XR content be created, maintained, and updated?
10. Who should be responsible for developing and managing XR content?
11. What approval processes or vendor policies would need to be navigated?
12. What compliance requirements (institutional, regulatory) should XR systems meet?
13. What are your primary data privacy and security concerns with XR?
14. How should user data be handled and protected?

Section C: Adoption, Change Management & Success.

15. What does the process typically look like for integrating new technology into higher education at VT?
    a. **[Probe]** What are the key decision-making steps?
16. Based on your experience with recent technology integrations (e.g., Zoom, AI tools), what worked well and what didn't? What specific barriers did you encounter?
17. What would be required to gain buy-in from your department?
18. Who are the key influencers or decision-makers whose support is critical?
19. What type of incentives or support structures would encourage adoption?
20. What are the biggest risks to XR implementation
    a. **[Probe]** How should they be mitigated?
21. Are there any regulatory or institutional changes that could impact XR implementation?
22. From your perspective, what would indicate successful XR implementation?

Appendix D: Stakeholder Needs Document

TECHNOLOGY-ENHANCED LEARNING AND ONLINE STRATEGIES
VIRGINIA TECH

XR Community of Practice (XR CoP)
Stakeholder Needs Documentation

eXtended Reality (XR) Implementation at a R1 HEI
A Systems Engineering Perspective | Case Study

Tony Lee
XR CoP | Virginia Tech

1. Purpose and Scope

This document provides a structured Stakeholder Needs Documentation for the implementation of Extended Reality (XR) technologies within a research-intensive (R1) higher education institution (HEI). It is grounded in an empirical, multi-stakeholder case study and analyzed through a Systems Engineering (SE) lens, drawing on the socio-technical systems framework.

The documentation serves three primary functions:

- Identify and classify all stakeholders involved in the XR implementation lifecycle, differentiating between active and passive roles.
- Articulate each stakeholder's core needs as they relate to the System of Interest (SOI) — the institutional XR implementation ecosystem.
- Provide a reference artifact that supports planning, governance, and coordination of XR initiatives across academic, technical, and administrative domains.

This document does not prescribe specific technical solutions or system architectures. Rather, it maps what stakeholders need and why, to inform system design, policy development, and institutional decision-making.

2. Systems Engineering Context

XR implementation in higher education is best understood as a socio-technical systems challenge. This document frames XR not as a standalone technology deployment, but as a complex system whose performance emerges from the coordinated interaction of social, organizational, technical, and governance components.

Key SE constructs applied in this document:

- **SOI:** The institutional XR ecosystem encompassing hardware, software, content, workflows, policies, and people.
- **Stakeholder identification:** Active and passive roles across the XR implementation lifecycle (ideation, development, deployment, maintenance, and governance).
- **Needs:** Stakeholder needs are derived from qualitative data collected across 199 coded instances (focus groups, SME interviews, and surveys) as part of the XR CoP case study.

The findings underscore that the primary constraint on XR adoption is not technological capability, but institutional coordination. XR systems fail not because they cannot be implemented, but because the supporting socio-technical systems are insufficiently integrated.

3. Stakeholder Classification

Stakeholders are classified into two categories based on their mode of engagement with the XR System of Interest during operational phases:

- **Active Stakeholders:** Individuals or organizations that directly and continuously interact with the XR system during implementation and operation. Their engagement is hands-on and operational.
- **Passive Stakeholders:** Entities whose influence is episodic, upstream, or governance-level. They shape the conditions of implementation without direct, day-to-day system operation.

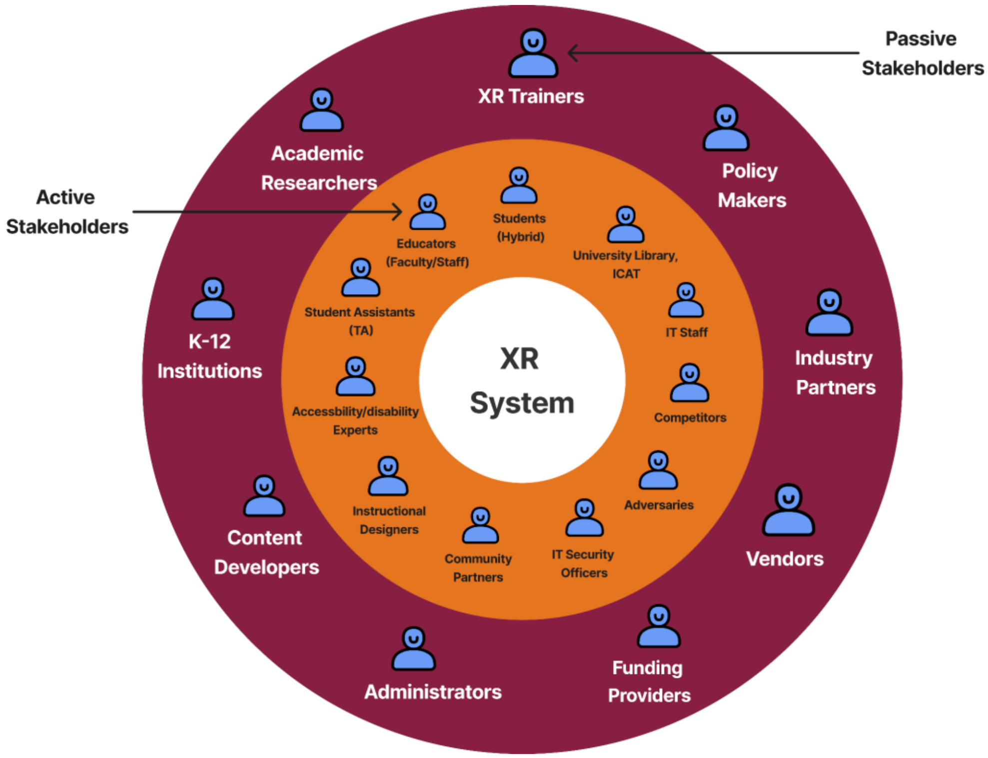

Figure 1. Stakeholder ecosystem involved in XR implementation, illustrating active and passive roles across academic, technical, and institutional domains.

Note: This classification is scoped to XR implementation within a HEI context. A stakeholder's classification may shift across different phases of the system lifecycle.

3.1 Active Stakeholders

Stakeholder	Description / Role
Educators (Faculty / Staff)	Responsible for creating XR content, integrating modules into curriculum, and facilitating immersive learning experiences. Initiate the XR development workflow and define instructional goals.
Students (Hybrid: In-Person & Remote)	Actively interact with XR modules to achieve learning outcomes. Includes in-person, distance-learning, and students with disabilities who require accessible modalities and accommodations.
Student Assistants (TAs / RAs)	Support faculty in the development, testing, maintenance, and facilitation of XR content. Serve as a primary development labor resource; assist in troubleshooting and student onboarding.
IT Support Staff	Responsible for the technical management of XR systems, network infrastructure, security enforcement, and troubleshooting. AV and IT domains are increasingly converged by XR dependencies.

Stakeholder	Description / Role
University Library / ICAT	Maintains, loans, and manages XR hardware/software inventory. Provides faculty/staff training, organizes workshops, curates centralized XR resource repositories, and pursues funding opportunities.
Instructional Designers & Accessibility Experts	Ensure XR experiences are pedagogically aligned, scenario-based, and designed with universal accessibility from the outset (ADA Title II, FERPA). Critical bridge between instructional intent and technical implementation.
Community Partners	External community entities that collaborate on XR initiatives, provide real-world context for scenario-based content, and support outreach and pilot programs (e.g., K–12 institutions, community colleges).
Adversaries	Unauthorized users, hackers, or bad actors who may exploit XR systems — including FERPA/data privacy violations, content hijacking, or biometric data misuse. Recognized to drive proactive security design.

3.2 Passive Stakeholders

Stakeholder	Description / Role
Administrators (School / Department)	Approve XR systems, projects, and budgets. Ensure cost-effectiveness, scalability, compliance, and policy alignment. Provide institutional support structures for sustained XR adoption.
Content Developers (Internal / External)	Develop XR modules as instructed by faculty and institutional clients. Responsible for iterative, accessible, and pedagogically aligned product design within defined project scope, branding, and data agreements.
XR Trainers	Provide professional training services for faculty and staff on XR tools, pedagogical strategies, and hardware use. May be internal personnel or contracted external specialists.
Academic Researchers	Conduct usability studies, efficacy research, and data analysis on XR systems to improve user experience, validate pedagogical outcomes, and generate evidence of effectiveness for institutional adoption.
Policy Makers	Develop, review, and enforce institutional and regulatory policies governing XR use (FERPA, ADA, copyright, data privacy). Define standards for content approval, vendor selection, and ethical use.

Stakeholder	Description / Role
IT Security Officers (ITSO)	Oversee cybersecurity posture for XR systems. Address biometric/behavioral data governance, CIA triad risks, vendor security assessments, penetration testing, and FERPA compliance in XR contexts.
Industry Partners / Vendors	Provide XR hardware, software platforms, and development services. Influence system capability, pricing, content ownership terms, and long-term platform viability. Subject to institutional vendor risk assessment.
Funding Providers (Alumni, Provost, Grants)	Provide financial resources for XR acquisition, development, and maintenance. Include internal and external sources. Sustainability of funding is a key concern.
K–12 Institutions	Potential downstream beneficiaries and outreach partners. XR systems developed in higher education may extend to K–12 contexts, supporting proof-of-concept and community value demonstrations.
Competitors (Other Institutions)	Other higher-education institutions pursuing XR implementation. Their practices inform benchmarking, technology selection, and the broader higher-ed XR landscape.

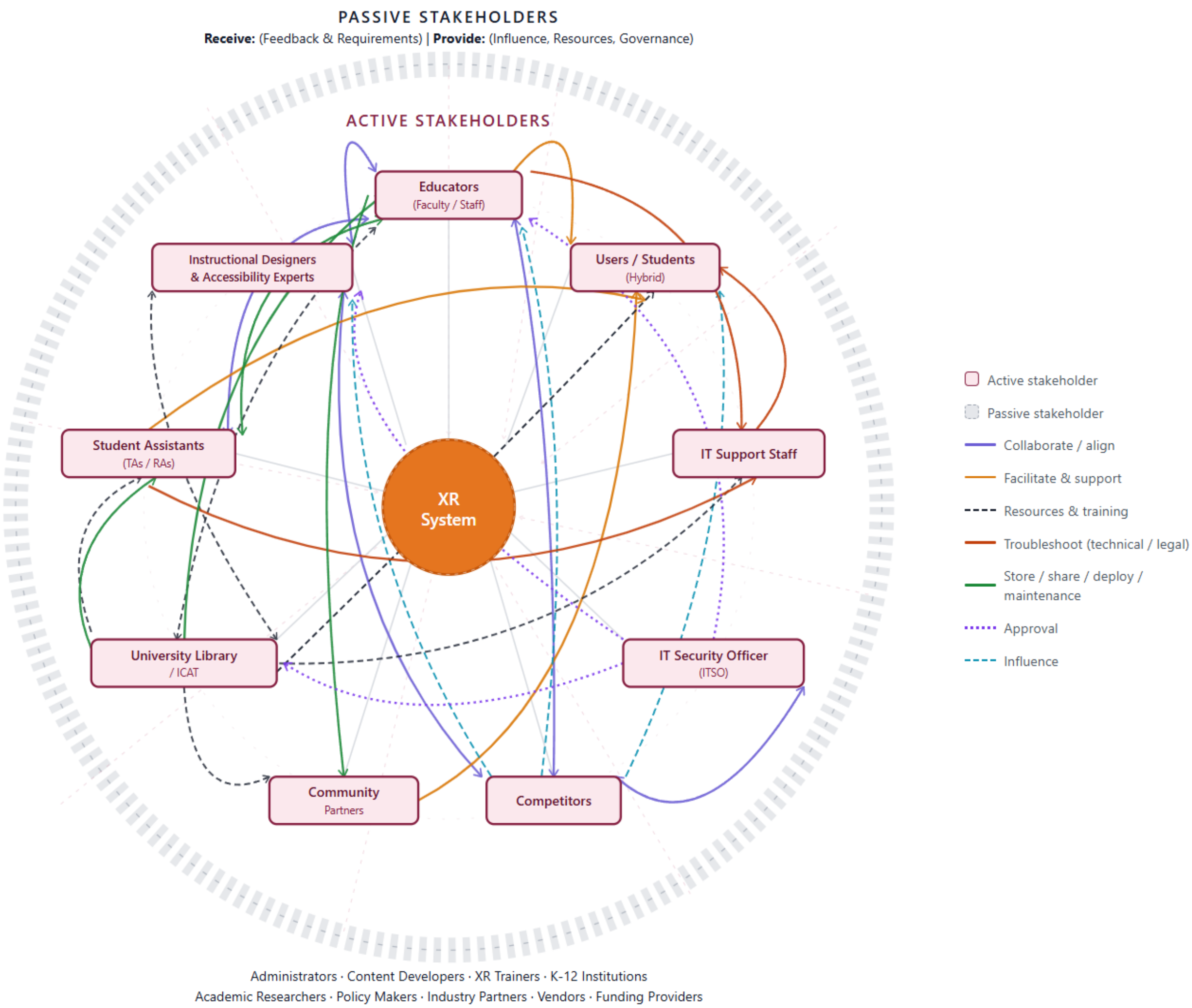

Figure 2. Visual representation of an R1 university stakeholder relationship mapping illustrating coordination pathways and inter-dependencies across XR implementation roles. Note. Arrows indicate 'receiver.'

Stakeholder Relationship:

This table below shows the relationship of all active stakeholders in detail.

Provider	Action (Legend)	Receiver
Community Partners	Facilitate & support	Users / Students
Competitors	Collaborate / align	Educators
Competitors	Collaborate / align	Instructional Designers & Accessibility Experts
Competitors	Collaborate / align	IT Security Officer (ITSO)
Competitors	Influence	Educators
Competitors	Influence	Users / Students
Competitors	Influence	Instructional Designers & Accessibility Experts
Educators	Collaborate / align	Instructional Designers & Accessibility Experts
Educators	Collaborate / align	Student Assistants
Educators	Collaborate / align	Competitors
Educators	Facilitate & support	Users / Students
Educators	Resources & training	University Library / ICAT
Educators	Troubleshoot (technical / legal)	IT Support Staff
Educators	Store / share / deploy / maintenance	Student Assistants
Educators	Store / share / deploy / maintenance	Community Partners
Educators	Store / share / deploy / maintenance	University Library / ICAT
Instructional Designers & Accessibility Experts	Collaborate / align	Educators
Instructional Designers & Accessibility Experts	Collaborate / align	Competitors
Instructional Designers & Accessibility Experts	Resources & training	University Library / ICAT
IT Security (ITSO)	Collaborate / align	Competitors
IT Security (ITSO)	Approval	Educators
IT Security (ITSO)	Approval	Instructional Designers & Accessibility Experts
IT Security (ITSO)	Approval	University Library / ICAT
IT Support Staff	Troubleshoot (technical / legal)	Users / Students

Provider	Action (Legend)	Receiver
Student Assistants	Collaborate / align	Educators
Student Assistants	Facilitate & support	Users / Students
Student Assistants	Troubleshoot (technical / legal)	IT Support Staff
Student Assistants	Store / share / deploy / maintenance	Educators
University Library / ICAT	Resources & training	Educators
University Library / ICAT	Resources & training	Instructional Designers & Accessibility Experts
University Library / ICAT	Resources & training	Student Assistants
University Library / ICAT	Resources & training	Community Partners
University Library / ICAT	Resources & training	IT Support Staff
University Library / ICAT	Resources & training	Users / Students
University Library / ICAT	Store / share / deploy / maintenance	Educators
University Library / ICAT	Store / share / deploy / maintenance	Student Assistants

Note. bi-directional connections are listed redundantly.

4. Stakeholder Needs

The following stakeholder need statements are derived from empirical data collected in XR CoP case study, including focus groups (FG1, FG2), subject matter expert interviews (AE, IT, ITSO), and campus-wide surveys. Need statements are presented per stakeholder and reflect the conditions required for each group to effectively engage with and support the XR system.

4.1 Active Stakeholders

Educators (Faculty/Staff)

#	Stakeholder Need Statement
N1	Faculty needs to be able to develop XR modules (either internally or externally).
N2	Faculty needs financial support to develop XR modules.
N3	Faculty need to be able to easily implement XR module(s) into their curriculum.
N4	Faculty need XR facilities to be easily accessible and ready for use.
N5	Faculty needs access to XR hardware and software.

#	Stakeholder Need Statement
N6	Faculty need to be aware of and compliant with XR standards and policies (FERPA, ADA Title II).
N7	Faculty need training on basic XR knowledge (maintenance, troubleshooting).
N8	Faculty need students to successfully and equitably interact with XR modules.
N9	Faculty needs support for resolving dynamic technical challenges over time.
N10	Faculty need protection from XR-related liability (lawsuits, data breaches, FERPA violations).
N11	Faculty need XR module(s) to be aligned with instructional design principles and syllabi.
N12	Educators need an incentive and support system to encourage sustained adoption of XR technologies.
N13	Faculty need transitional support if issues arise with the continuity of a platform.
N14	Faculty need a feedback and assessment mechanism integrated within XR modules.
N15	Faculty needs an effective way of maintaining XR hardware that is charged and software is updated prior to facilitation.
N16	Faculty needs an effective way of sanitizing XR hardware between uses.
N17	Faculty need XR module(s) to be customizable, easy to update, and sustainable over time.
N18	Faculty need XR module(s) to accommodate both large and small class sizes as well as distance and in-person students.
N19	Faculty needs immediate and agile technical support for XR-related issues.
N20	Faculty needs documentation and training materials designed for users with no prior XR knowledge, to reduce facilitation friction.
N21	Faculty need administrative support to ensure project continuity and mitigate risks from sudden platform, hardware, or regulatory changes.

Students (Hybrid)

#	Stakeholder Need Statement
N1	Students need easy access to XR hardware and software.
N2	Students need XR activities ready and operational for class.
N3	Students need access to XR hardware for a prolonged period of time.
N4	Students need to be oriented to XR controls, navigation, and safety protocols.
N5	Students need XR modules designed to be equitable, accessible, and available in multi-modal formats.
N6	Students need reliable XR experiences that protect their data and privacy.
N7	Students need transparency of any additional costs associated with XR usage.
N8	Students need XR modules designed with consideration for mental well-being, minimizing simulation sickness and anxiety.
N9	Students need XR activities that support both remote and in-person learning environments.
N10	Students need opportunities to provide feedback on their XR experiences to drive continuous module improvement.
N11	Students need XR experiences customizable to individual learning styles and paces.
N12	Students need access to supplemental XR resources (tutorials, guides, FAQs) to support effective use.
N13	Students need access to reliable technical support to troubleshoot XR hardware and software issues.

Student Assistants (TAs/RAs)

#	Stakeholder Need Statement
N1	TAs need XR modules to be tested for functionality before student-facing activities.
N2	TAs need to be able to troubleshoot basic hardware and software problems that arise during XR activities.
N3	TAs need basic training on XR module development, facilitation, and troubleshooting.

#	Stakeholder Need Statement
N4	TAs need to maintain and sanitize XR hardware and relevant equipment for classroom facilitation.
N5	TAs need to orient students on XR navigation controls and safety procedures.
N6	TAs need access to detailed instructional resources and guides to effectively support XR module integration.
N7	TAs need collaborative platforms to coordinate with faculty and other stakeholders.
N8	TAs need user-friendly interfaces for XR software to streamline training and support tasks.
N9	TAs need mechanisms to provide feedback on XR module performance and usability.

IT Support Staff

#	Stakeholder Need Statement
N1	IT Support Staff need training in advanced XR hardware and software knowledge (troubleshooting, maintenance, and user support).
N2	IT Support Staff need knowledge of XR implementation processes to coordinate with faculty and support units.
N3	IT Support Staff need an XR-compatible IT infrastructure (network, computer, storage).
N4	IT Support Staff need to remain informed of all XR development activity within their supported disciplines.
N5	IT Support Staff need effective communication channels with faculty and University Library/ICAT personnel.
N6	IT Support Staff need to enforce security protocols, ensure data privacy, and maintain audit logs for XR systems.
N7	IT Support Staff need ongoing training to stay current with evolving XR technologies and security practices.
N8	IT Support Staff need comprehensive documentation and clear guidelines for XR system maintenance and user support.

University Library / ICAT / TLOS

#	Stakeholder Need Statement
N1	The University Library/ICAT needs to establish a system to log, store, and maintain XR hardware and software efficiently.
N2	The University Library/ICAT needs an effective inventory and rental/loan management system that accommodates large quantities of hardware.
N3	The University Library/ICAT needs a plan for the long-term maintenance, upgrade, and lifecycle management of XR hardware and software.
N4	The University Library/ICAT needs to provide faculty and staff training services on XR technologies and pedagogical strategies across disciplines.
N5	The University Library/ICAT needs to maintain clear and effective communication channels with IT support staff, IT security, and educators.
N6	The University Library/ICAT needs to organize regular workshops and seminars to keep faculty and staff updated on XR technologies and pedagogical strategies.
N7	The University Library/ICAT needs XR content and hardware lifecycle practices to be sustainable (recycling, energy-efficiency, e-waste planning).
N8	The University Library/ICAT needs to create and maintain a centralized repository of XR resources to support interdisciplinary initiatives.
N9	The University Library/ICAT needs to actively pursue funding and grant opportunities for XR acquisition, maintenance, and development.
N10	The University Library/ICAT needs to establish partnerships with industry leaders and XR technology providers to minimize equipment obsolescence.
N11	The University Library/ICAT needs a reliable, secure space and network infrastructure to store and transmit XR data.

Instructional Designers & Accessibility Experts

#	Stakeholder Need Statement
N1	Instructional Designers need to be integrated into XR projects from the ideation phase, not engaged reactively after design decisions are made.
N2	Instructional Designers need faculty to provide clear learning objectives and syllabus alignment before XR development begins.

#	Stakeholder Need Statement
N3	Accessibility Experts need XR systems to be designed with multi-modal access, cognitive scaffolding, and disability inclusion from the outset.
N4	Instructional Designers need faculty and IT staff to participate in iterative review cycles throughout the development process.

4.2 Passive Stakeholders
Administrators

#	Stakeholder Need Statement
N1	Administrators need XR modules to be cost-effective and provide a demonstrable return on investment in student learning outcomes.
N2	Administrators need XR modules to be scalable and support large numbers of simultaneous and recurring users.
N3	Administrators need XR modules to integrate seamlessly with existing campus systems (LMS, network, AV infrastructure).
N4	Administrators need XR modules to be inclusive and accessible in compliance with ADA and university accessibility guidelines.
N5	Administrators need XR modules to comply with all relevant university policies, including data privacy and ethics standards.
N6	Administrators need standardized criteria for XR content development and measurable thresholds for success.
N7	Administrators need tools to track and analyze XR module performance, usage, and outcomes for data-driven decision-making.
N8	Administrators need effective ethical considerations including user consent, data security, and responsible technology practices.
N9	Administrators need open communication channels with all stakeholders to gather feedback and address XR concerns.
N10	Administrators need to support continuous professional development for faculty and staff on XR technologies and teaching strategies.
N11	Administrators need to support large-scale XR implementations and financially assist stakeholders incorporating XR into classrooms.

#	Stakeholder Need Statement
N12	Administrators need to promote interdisciplinary collaboration and encourage the use of XR across departments.

Content Developers

#	Stakeholder Need Statement
N1	Content Developers (external) need institutional approval covering VT branding, data privacy agreements, and content ownership terms before work begins.
N2	Content Developers need clear documentation outlining the instructional design, accessibility standards, and compliance requirements.
N3	Content Developers need clear onboarding documentation to be aware of the project goals, history, progression, and future directions.
N4	Content Developers need a clear project scope, budget, and expectations.
N5	Content Developers need a user feedback mechanism to produce products that are easy to use and support iterative improvement.
N6	Content Developers need detailed information from educators on the course objectives and syllabus alignment to develop an effective XR module.
N7	Content Developers need to offer scalable and customizable tools that can accommodate updates and varying user volumes.

Policy Makers

#	Stakeholder Need Statement
N1	Policy Makers need developed XR modules to adhere to VT guidelines covering privacy, ethics, and accessibility (FERPA, ADA).
N2	Policy Makers need to establish copyright and IP ownership frameworks for XR modules created with institutional resources.
N3	Policy Makers need to confirm that industry partners and vendors adhere to VT guidelines before institutional engagement.
N4	Policy Makers need to define security protocols to prevent misuse of XR systems and protect against data exploitation.

#	Stakeholder Need Statement
N5	Policy Makers need to establish standards for XR content compatibility and interoperability across platforms.
N6	Policy Makers need ways of partnering with approved vendors to reduce procurement cost and streamline implementation processes.
N7	Policy Makers need an effective way of protecting university stakeholders from XR-related legal liability.
N8	Policy Makers need an established framework in ownership and data governance to protect sensitive data generated within XR environments.
N9	Policy Makers need to establish contingency plans for technological failures, platform discontinuation, or regulatory changes affecting XR.
N10	Policy Makers need to develop clear usage policies for the ethical and responsible use of XR technologies by all institutional users.

Academic Researchers

#	Stakeholder Need Statement
N1	Researchers need system transparency and access to XR usage data to conduct rigorous usability and behavioral studies.
N2	Researchers need to conduct usability testing on XR modules to improve user experience and validate learning outcomes.
N3	Researchers need to collaborate with content developers and industry partners to design and evaluate effective XR modules.
N4	Researchers need funding for XR research initiatives and interdisciplinary collaboration across fields.
N5	Researchers need an established IRB protocol to adhere to ethical guidelines for XR research involving human subjects.

IT Security Officers (ITSO)

#	Stakeholder Need Statement
N1	ITSO needs comprehensive cybersecurity protocols governing XR data collection, storage, transmission, and access.

#	Stakeholder Need Statement
N2	ITSO needs to establish data ownership and governance frameworks for XR-generated student data (movement, gaze, biometrics).
N3	ITSO needs proactive penetration testing of XR applications to identify vendor-side and platform-level vulnerabilities.
N4	ITSO needs security logging systems capable of tracking individual user identity (not just machine-level activity) across shared XR devices.
N5	ITSO needs standardized XR vendor risk assessment processes with defined timelines to reduce implementation delays.

Funding Providers

#	Stakeholder Need Statement
N1	Funding Providers need XR proposals to clearly articulate measurable educational outcomes and return on investment.
N2	Funding Providers need XR funding structures to support long-term maintenance and lifecycle costs, not only initial acquisition.
N3	Funding Providers need transparent reporting on XR project outcomes, usage, and financial accountability.

Industry Partners / Vendors

#	Stakeholder Need Statement
N1	Vendors need to provide continuous product support, maintenance documentation, and content portability options throughout the contract lifecycle.
N2	Vendors need to provide comprehensive training materials and onboarding resources compatible with the institution's technical environment.
N3	Vendors need to offer affordable and flexible pricing options, licensing terms, and data ownership agreements tailored to academic institutions.
N4	Vendors need to provide timely technology updates and ensure compatibility with existing institutional infrastructure.
N5	Vendors need to adhere to institutional and legal standards for protecting user data (FERPA, ADA, HIPAA where applicable).

#	Stakeholder Need Statement
N6	Vendors need to enable academic institutions to pilot and test XR modules prior to full implementation.

5. Cross-Stakeholder Key Themes & Insights

Analysis of stakeholder needs across the XR ecosystem reveals several cross-cutting themes and interdependencies that must be addressed at the system level. These are not isolated stakeholder concerns but systemic conditions that shape implementation outcomes.

5.1 Institutional Coordination and Siloing

Stakeholder-related themes were most frequently associated with institutional coordination failures, including institutional siloing (n = 14) and faculty training and support deficits (n = 13). Faculty, TAs, IT staff, and instructional designers operate across fragmented workflows, creating coordination gaps that limit scalability. A centralized XR support structure with defined communication pathways cross-stakeholder is critical.

5.2 Resource Constraints and Lifecycle Planning

Funding and sustainability concerns and hardware/infrastructure barriers were the most frequently reported prohibitive factors (n = 19 each). Stakeholders across both active and passive roles share a need for long-term resource planning, lifecycle management, and sustainable procurement models. Short-term grant funding without lifecycle planning leads to equipment abandonment and institutional knowledge loss.

5.3 Accessibility and Equity by Design

Accessibility needs were identified across students, faculty, accessibility experts, and IT Support staff. Physical/sensory barriers (n = 13) and cognitive/cultural accessibility concerns (n = 6) underscore that accessibility cannot be retrofitted. XR systems must be designed from the ideation phase with multi-modal access, ADA Title II compliance, and proactive inclusion of all users.

5.4 Governance, Data Privacy, and Security

Cybersecurity and data privacy concerns (n = 13) and FERPA compliance constraints (n = 11) were frequently mentioned by the educators, administrators, IT Support, and IT Security. XR systems' capacity to collect biometric and behavioral data creates governance challenges that existing FERPA frameworks may not fully address. Data governance must be a foundational design requirement, not an afterthought.

5.5 Pedagogical Alignment as an Institutional Capacity

Pedagogical design concerns (n = 13) and faculty training deficits (n = 13) intersect across educators and administrator’s needs. Instructional design and accessibility experts must be treated as a system-level function integrated from the earliest development phases.

5.6 Vendor Dependency and Platform Fragility

Vendor risk and dependency (n = 10) was flagged across educators, administrators, IT Support, and IT Security needs. Platform discontinuation (e.g., Mozilla Hubs) represents an institutional risk. Stakeholders need clearly defined content ownership, data portability, and platform transition protocols embedded in all vendor agreements/partnerships.

6. Document Notes & Usage Guidance

The needs identified here represent a baseline applicable to R1 HEIs pursuing XR adoption. Institutions are encouraged to add context-specific need statements as warranted and updated as the XR implementation ecosystem evolves. Stakeholder needs are descriptive, not prescriptive. They document what is required, not how it should be achieved.

When using this document for a new institutional context, stakeholder classification and need statements should be validated with local stakeholders to ensure contextual accuracy.

Appendix E: External XR Development Guide

XR Community of Practice (XR CoP)
External XR Development Guide

Educational eXtended Reality (XR) Development
Iterative Product Design | Case Study

Tony Lee
XR CoP | Virginia Tech

Section 1: Overview of External XR Development

This guide is intended for Virginia Tech faculty, staff, and students considering collaboration with an external vendor to develop eXtended Reality (XR) content for educational purposes. It is grounded in the qualitative findings of the XR Community of Practice (XR CoP) and the documented case study of the Environmental Health & Safety (EHS) Portable Fire Extinguisher (PFE) training XR module, developed in partnership with VictoryXR.

XR development is a complex, resource-intensive endeavor. When undertaken through an external vendor partnership, it introduces additional dimensions of coordination, dependency, and constraint that institutions must navigate deliberately. This guide provides a structured framework for understanding when external development is appropriate, how to manage the process effectively, and what to anticipate at each stage of collaboration.

The case study described throughout this guide involved the development of a supplemental XR training module aligned with university EHS syllabus for PFE certification standards. The module was designed not as a digital twin of existing training, but as an experiential, scenario-based supplemental tool since XR is most effective when used to augment, rather than replace, traditional pedagogy.

Key roles used throughout this guide:

- **GRA / Project Lead:** The institutional representative responsible for coordinating development, managing communication, and translating instructional goals into XR requirements.
- **Faculty Advisor / Manager:** The academic lead responsible for providing strategic oversight, ensuring alignment with instructional and research objectives, and guiding project direction, while supporting decision-making, resource coordination, and integration within institutional priorities.
- **Higher Education Director at XR Vendor:** The vendor-side liaison responsible for business development, contract negotiation, and high-level project coordination.
- **Lead Developer of Simulations:** The primary technical developer assigned to the project, responsible for building and iterating XR environments.
- **EHS Associate Director:** The subject matter expert (SME) responsible for validating the instructional content and safety training objectives embedded in the XR module.

Section 2: When to Use External Development

Before committing to an external vendor, institutions should conduct a deliberate cost-benefit analysis. External XR development is neither universally superior nor universally appropriate. The decision depends on the institution's timeline, budget, in-house technical capacity, long-term goals, and the nature of the instructional content to be developed.

2.1 Key Decision Factors

The following factors should be weighed when considering whether to pursue external development:

- **Timeline:** If a faculty member requires a functional XR experience within one to two semesters and no in-house developer is available, external development is typically the most viable path. A functional prototype was delivered within approximately two weeks of contract finalization in the case study - a timeline that internal development pipelines cannot typically match. Survey data from the XR_CoP study indicates that the majority of internal XR development efforts require at least three to six months, with many exceeding a year.
- **Specialized Expertise:** External vendors bring professional expertise in 3D modeling, spatial computing, gaming design, user experience design, and platform-specific deployment that is rarely available within a single academic developer. They maintain up-to-date knowledge of hardware compatibility and development frameworks.
- **Budget:** External development involves direct financial cost but avoids the indirect costs of recruiting, training, and retaining specialized in-house developers. Detailed cost benchmarks from the case study are documented in Section 5. Institutions should be aware that scope changes or additional iteration cycles may incur additional costs, making thorough design-phase planning essential.
- **Content Ownership and Licensing:** External development may not result in institutional ownership of the developed content. In the case study, a pro-rated partnership agreement was used in which the module would be made publicly available through the vendor's platform without full Virginia Tech ownership. Institutions must clarify content ownership, licensing terms, and data access rights before contract finalization.
- **Long-Term Maintenance:** External vendors may provide ongoing support, including bug fixes and incremental updates, but this is subject to the vendor's availability, business continuity, and pricing structure. Vendor dependency is a documented risk; if a vendor exits the market or discontinues a platform (e.g., Mozilla Hubs), previously developed content may become inaccessible without transitional support.

2.2 Internal vs. External: Decision Flow

The following questions may help institutions determine the most appropriate development pathway. Work through these sequentially:

- **Timeline constraint:** Do you require a deployable XR experience within one semester or sooner?
  - If yes, consider external development. If not, proceed to the next question.

- **In-house capacity:** Does the institution have access to skilled XR developers (i.e., dedicated unit or student workers with sufficient experience) who are available within the required timeframe?
    - If yes, consider internal development. If not, consider external development.
- **Budget availability:** Does the project have dedicated funding sufficient for external development, including potential iteration costs beyond the initial contract?
    - If not, explore internal development options or seek supplemental funding before engaging a vendor.
- **Content ownership requirements:** Does the institution require full ownership and control of the developed content for future modification, redistribution, or long-term use?
    - If yes, negotiate for full IP ownership before contracting, or consider internal development. If a licensing arrangement is acceptable, external development remains viable.
- **Scalability and sustainability:** Is this a one-time pilot, or does the institution intend to scale or adapt the XR experience over multiple semesters?
    - Long-term, scalable projects benefit from internal development capacity or clearly negotiated vendor support agreements. Short-term, bounded projects are well-suited to external development.

2.3 Pros vs. Cons

Table 1 summarizes the key advantages and limitations of external XR development, informed by the case study and focus group findings.

Table 1. External XR Development: Advantages and Considerations

Advantage	Explanation	Consideration	Explanation
Specialized Expertise	External teams include experts in 3D modeling, UX design, and spatial computing, maintaining current knowledge of XR platforms and hardware.	**Higher Direct Costs**	Vendors charge premium rates for custom content. Initial quotes may exclude fees for additional iteration cycles, licensing, or post-launch updates.
Accelerated Timelines	Dedicated development processes and scalable teams enable high-fidelity and faster prototyping.	**Limited Control & Oversight**	Daily progress may be difficult to track. Miscommunication or lack of a shared vision can hinder alignment with institutional goals and content requirements.
Reduced Recruitment & Onboarding Time	Institutions bypass the time required to recruit, onboard, and train internal developers - paying only for the services directly needed for the project.	**Vendor Dependency**	Vendors may juggle multiple client projects simultaneously. Delays in communication or progress can impact project timelines and data collection schedules.

Advantage	Explanation	Consideration	Explanation
Quality Assurance Infrastructure	Established vendors employ best practices, QA protocols, and experience-driven problem-solving to mitigate common XR development pitfalls.	**Potential Knowledge Gaps**	Heavy reliance on external teams means the institution's internal staff may not develop the XR skills needed for future independent initiatives.
Fresh Perspective & Innovation	Vendors working across industries can introduce creative solutions that may not emerge from within a single academic context.	**Security & Compliance Risks**	Sharing institutional data or proprietary instructional content with external parties introduces data privacy and FERPA-related compliance considerations.

Note: The case study demonstrated that the reduction in recruitment and onboarding time can be significant, particularly for institutions without established in-house XR development teams. This should be weighed against the ongoing vendor dependency and limited institutional knowledge transfer that typically result from purely externally developed content.

Section 3: Collaboration & Communication Model

Effective collaboration in externally developed XR projects depends on clearly defined responsibilities, regular communication, and proactive documentation. The following patterns were observed and documented throughout the case study.

3.1 Roles and Responsibilities

Operational responsibilities across the development lifecycle are summarized below.

Table 2. Stakeholder Roles and Responsibilities in External XR Development

Role	Primary Responsibilities
GRA / Project Lead	Coordinate development; translate instructional goals into XR requirements; manage communication and feedback; facilitate stakeholder alignment.
Higher Education Director (V.XR)	Manage business relationships; negotiate contracts; communicate institutional partnership opportunities; coordinate development teams.
Lead Developer (V.XR)	Coordinate development; translate instructional goals into XR requirements; manage communication and feedback; facilitate stakeholder alignment.

3.2 Communication Workflow

Communication in the case study occurred primarily through asynchronous email, supplemented by scheduled video calls at key project milestones. The following patterns were observed:

- **Initial engagement:** Formal project meetings were scheduled approximately two to three weeks apart during the scoping and contracting phase. The vendor proactively followed up when communication gaps exceeded one week.
- **During prototyping:** Communication was initiated by the developer when design decisions required clarification. The GRA responded within one to two days. Turnaround on developer questions was critical to maintaining the prototype delivery timeline.
- **During iteration:** Feedback was submitted in structured written format and included both priority ranking and explanatory rationale for each request. This format reduced back-and-forth and enabled the developer to triage efficiently.
- **Post-launch:** Communication was initiated by the GRA when bugs or data collection issues were identified. The developer was consistently responsive, often providing same-day or next-day acknowledgment and resolution timelines.

A minimum communication frequency of at least once per week is recommended during active development phases. Institutions should establish a primary point of contact on both the institutional and vendor sides and ensure that communication channels remain open even when there are no active issues to resolve.

3.3 Translating Instructional Goals into XR Features

A critical function of the GRA in the case study was serving as the translator between instructional objectives and technical requirements. This role required:

- Converting EHS syllabus goals (e.g., 'Assess a situation and determine whether to use an extinguisher or evacuate') into concrete interaction design specifications (e.g., a branching decision scenario with graded outcomes)
- Researching and documenting domain-specific content (e.g., fire extinguisher type compatibility with fire classes) that the vendor needed to implement accurate mechanics
- Synthesizing feedback from focus group participants into prioritized, actionable design requests that could be implemented within the remaining iteration budget
- Mediating between stakeholder 'ideal features' and practical development constraints, as demonstrated when a focus group suggestion for pocket-mounted phones was evaluated and declined based on developer input

Institutions engaging external vendors should designate a single point of contact with sufficient domain knowledge to perform this translation function. Ambiguous or incomplete requirements are among the most common sources of development delay and misalignment.

Section 4: Budgeting & Negotiation Insights

Budget management is among the most consequential and least-discussed aspects of external XR development in higher education contexts. The case study provides concrete reference points and practical insights grounded in a documented negotiation process.

4.1 Cost Reference Points

The following cost benchmarks were documented in the case study:

Table 3. Cost Reference Points from the Case Study

Cost Item	Amount	Notes
Full institutional ownership development (estimated)	\$50,000–\$100,000	Vendor estimate for a custom module with full VT content ownership. Not pursued due to budget constraints.
Multi-module discount quote	\$18,000 (×2), \$24,000 (×3)	Vendor offered reduced per-module pricing for multiple simultaneous builds.
Second vendor quote (single module)	\$10,000	Quoted price for one experience with existing OSHA/PPE training assets as basis. Some discounts applied for partnership potential.
Final negotiated price	\$7,000	Inclusive of one custom fire extinguisher simulation and two one-year platform licenses. Partnership model (public availability of content) enabled this reduction.
Platform licensing	Included	Two 1-year licenses included. Additional licenses are available at \$150 per device per year.

4.2 Negotiation Strategies

The case study illustrates several effective negotiation strategies:

- **Scope reduction:** Narrowing from multiple modules to a single module was the first and most impactful cost-reduction strategy. Institutions with limited budgets should begin with the highest-priority module rather than attempting to develop multiple experiences simultaneously.
- **Partnership model:** Agreeing to allow the vendor to publish the developed module in its public asset library — thereby expanding the vendor's portfolio and marketability — was the primary mechanism through which the cost was reduced from ~\$10,000 to \$7,000. Institutions should assess whether this trade-off is acceptable given their institutional IP and content control requirements.
- **Deadline-based incentives:** The vendor offered an additional 10% discount if the contract was finalized before the end of the month. Time-sensitive incentives are common in vendor negotiations and can result in meaningful savings when the institution is prepared to commit.
- **Clarity of design document:** Providing a detailed, well-organized design document prior to the formal vendor meeting enabled the vendor to assess the scope accurately and reduce pricing uncertainty. Vague or incomplete requirements typically result in higher initial quotes that include contingency buffers.

4.3 Budget Planning Considerations

Institutions should account for the following in their budget planning:

- **Iteration cost risk:** The base contract price typically includes a defined number of revision cycles. Feature additions beyond the contracted scope (i.e., when the audio-guided PASS method instructions were proposed) will incur additional charges. Institutions should negotiate explicit iteration allowances upfront.
- **Licensing renewals:** Platform licenses are recurring costs. The case study included two one-year licenses; ongoing use of the platform beyond the initial license period will require renewal at the vendor's current pricing.
- **Contingency allocation:** Budget planning should include a contingency reserve of at least 15–20% of the contracted development cost to accommodate unplanned iterations or scope adjustments identified during pilot testing.
- **Institutional payment processes:** University procurement processes can introduce payment delays. In the case study, the vendor followed up regarding payment status, as its Net 30 payment terms required timely institutional processing. Institutions should initiate the purchase order or payment authorization process immediately upon contract finalization.

Section 5: Development Phases

External XR development is best understood as an iterative, phased process rather than a linear pipeline. The following phases reflect the workflow observed and documented throughout the EHS PFE module development and are consistent with recommended practices from focus group and interview data.

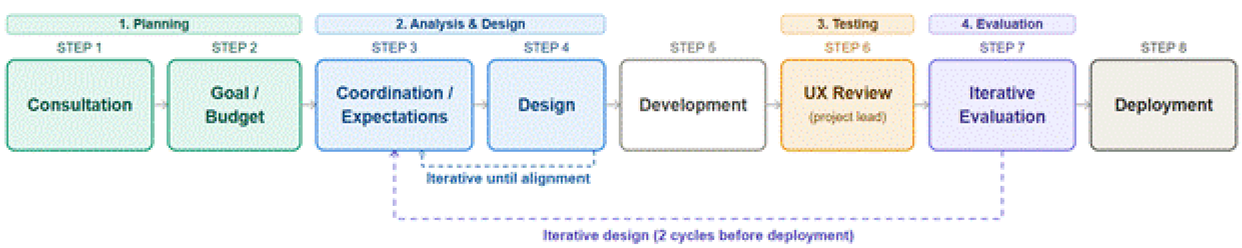

Figure 1. External XR EHS PFE Module development workflow

Phase 1: Needs Identification

The development process begins with a clear articulation of instructional needs. Faculty or institutional representatives should identify the specific learning gap or training objective that XR is intended to address. Stakeholder input - including from domain experts, faculty advisors, and potential end users - should be gathered prior to vendor engagement. In the case study, this process was constrained by limited availability from the EHS domain expert, requiring the project team to proceed based on available module documentation rather than direct stakeholder co-design. This constraint underscores the importance of securing stakeholder commitment before initiating development.

Deliverables at this stage include:

- A module outline or syllabus specifying learning objectives, outcomes, and assessment criteria
- A preliminary list of instructional content, scenarios, and interaction types
- Documentation of technical and platform requirements (e.g., hardware compatibility, accessibility needs)
- Identification of institutional compliance requirements (e.g., FERPA, data privacy policies)

Phase 2: Scoping & Vendor Engagement

Once instructional needs are defined, institutions should approach vendor engagement with a well-prepared design document. In the case study, the GRA shared a Google Drive folder containing slide decks with detailed design requirements prior to the initial vendor meeting to maximize efficiency and help developers align with the intended module vision. The folder included documentation for four EHS modules (HAZCOM, PPE, Power Tools, and Portable Fire Extinguisher), with the intention of developing an interactive XR experience spanning all four training types.

Initial vendor contact should include:

- A project overview and background, explaining the institutional context and motivation
- A review of the vendor's portfolio and existing asset library for relevant pre-built content
- Preliminary discussion of scope, budget range, and timeline expectations

In the case study, initial discussions indicated that a full VT-owned development would cost substantially more than the available budget. Through a partnership arrangement in which the content would be made publicly available through the vendor's platform library, the cost was reduced significantly. See Section 5 for detailed cost figures. Institutions should explore similar partnership models when full ownership is not a critical requirement.

Phase 3: Contracting & Negotiation

Contract finalization should occur only after the scope, timeline, budget, content ownership terms, and communication expectations have been explicitly agreed upon. Based on available funding, one module, the Portable Fire Extinguisher training, was selected for its high potential value as an interactive experiential learning experience. The instructional goals were drawn directly from the EHS syllabus and translated into two discrete XR activities: a hazard identification activity and a scenario-based fire extinguisher use assessment. For full negotiation details and cost figures, see Section 4.1.

Key contractual considerations include:

- **Content ownership and intellectual property:** Clarify whether the institution retains rights to modify, redistribute, or reuse the content.
- **Iteration allowances:** Specify the number of revision cycles included in the base contract price.

- **Licensing terms:** Document the number of device licenses included, the license renewal timeline, and the process for adding users or organizations.
- **Support and maintenance:** Establish expectations for post-launch bug fixes, platform updates, and long-term content management. In the case study, the Lead Developer continued to provide bug fixes and minor adjustments after deployment without additional charge — though this was based on a collaborative relationship rather than a formal contractual obligation.
- **Communication cadence:** Establish a minimum communication frequency (e.g., weekly email updates) and preferred channels.

Phase 4: Prototyping

Following contract finalization, the Lead Developer confirmed design ideas, environment settings, and overall goals before beginning active development. In the case study, the Lead Developer was the sole developer assigned to the project, given the scale of the engagement. A functional prototype was delivered approximately six days after the development kickoff. This quick turnaround was made possible by adapting an existing warehouse environment from the vendor's asset library. Institutions should look to utilize vendors' pre-existing assets that can be adapted rather than building from scratch.

During prototyping, the development team engaged in several clarifying exchanges with the GRA, including:

- **Environment selection:** The vendor proposed adapting an existing warehouse environment rather than building a new laboratory setting from scratch. The project team confirmed this was acceptable given the instructional context.
- **Fire extinguisher type logic:** Detailed discussion was required to determine how multiple extinguisher types would be represented, how incorrect selections would be handled, and whether the application should permit multiple correct answers per fire class.
- **Platform compatibility:** Decisions were made regarding target hardware (Meta Quest 2, with Quest 3 forward-compatibility), desktop application support, and VR mode.
- These interactions highlight the importance of providing detailed instructional documentation before prototyping begins. Ambiguities resolved through back-and-forth during development are less efficient than ambiguities resolved during the scoping phase.

Phase 5: Testing & Iteration

The testing and iteration phase involves internal quality assurance, pilot user testing, structured feedback collection, and developer response. In the case study, two formal iteration cycles were completed within the contract scope:

Iteration 1 (26 days)

Following initial prototype review, the GRA submitted a structured feedback document covering:

- **Activity 1 (Hazard Identification):** Requests for additional hazard items, non-fire hazard distractors, hazard randomization across retries, and explanation of incorrect selections.
- **Activity 2 (Fire Extinguisher Use):** Requests for a tutorial video for fire hose mechanics, a fix for a pin-removal sequencing bug, improvements to grabbing interaction mechanics, and additional contextual prompting.
- **Information Panels (Global):** Requests for font and size standardization, increased text spacing and margins, and addition of a navigation back button.
- **General UX:** Requests for a global restart function and verification of background audio functionality.

The developer requested that feedback items be ranked by priority to enable triage within the iteration budget. Seven priority items were identified, with the most critical being a sequencing bug that prevented progress if a user removed the fire extinguisher pin prematurely. One requested feature, the grab-and-lock interaction system, was deferred to post-launch because the vendor determined it would require substantial new development that risked introducing game-breaking bugs.

Iteration 2 (10 days)
The second iteration addressed visual and navigational UX concerns identified during focus group sessions and pilot testing, including:

- Reducing the size and distance of information panels that were obscuring the user's view of the virtual environment.
- Removing repetitive side panels during Activity 2 to improve spatial awareness.
- Addressing an intermittent bug in which additional fires are activated in the background during the tutorial phase.
- Evaluating the feasibility of making UI panels dynamically resize based on user distance; deferred due to visual stuttering caused by interaction with the rotation-tracking script.

One of the requested capabilities, audio-guided step-by-step PASS method instructions proposed by a focus group usability expert, was presented to the vendor during this phase. The vendor indicated this addition would exceed the contracted development scope and would require additional funding. Given budget constraints, the project team declined the enhancement. This exchange illustrates a common constraint in externally developed XR: iteration budgets are finite, and late-stage feature additions typically incur additional cost.

Phase 6: Deployment

Deployment involves finalizing the building, publishing to the vendor's platform, and establishing user access. In this case study, the final build was released on November 25, 2024, and published to the vendor's VXR Labs application under the module title 'Fire Safety.'
Deployment considerations included:

- **Account and organization setup:** Institutions should establish a lab- or department-owned email account rather than using an individual researcher's email to ensure continuity beyond a single user.

- **License assignment:** In the case study, two one-year licenses were included in the contract. Licenses were allocated at the organizational level, enabling the project team to assign them to designated instructor and participant accounts. In this case study, access was granted to the GRA and the lab VT email account.
- **Analytics access:** The vendor's proprietary platform (i.e., Nexus) provides performance metrics, including completion time, scenario grade, evacuation time, sweep score, and fire extinguisher type used. Analytics are accessible by the 'instructor' account.

Phase 7: Maintenance & Post-Launch Support

Post-deployment maintenance is an often-underestimated component of external XR development. In the case study, several issues emerged during pilot testing after the official product release:

- An evacuation time threshold was found to be too strict for first-time VR users, which can impact research data validity. The developer worked with the GRA to determine an appropriate threshold (40 seconds) and implemented the change in the next app-wide patch cycle.
- An additional data point, the type of fire extinguisher used in each scenario, was added at the project team's request without additional cost.
- A critical post-patch bug was identified in which the '911 dial' button disappeared during the scenario-based training phase, rendering that activity incompletable. The developer investigated and resolved the issue.

These interactions underscore that post-launch support is a critical component of the vendor relationship. Institutions should ensure that post-launch support expectations, the process for requesting patches, and the timeline for vendor responsiveness are clarified during the contracting phase.

Section 6: Summary of Key Requirements for Successful External XR Development

Successful external XR development in higher education depends on more than vendor selection or budget approval. It requires deliberate alignment across pedagogical intent, institutional infrastructure, stakeholder commitment, and process discipline. The following five high-level themes consolidate the requirements, constraints, best practices, and pitfalls identified across the case study and focus group findings. Each theme is framed as both what to do and what to avoid.

6.1. Pedagogical Clarity and Instructional Alignment

XR development must be anchored to explicitly defined learning objectives before any vendor conversation begins. Experiences driven by technological novelty rather than instructional intent consistently produce poor outcomes. In the case study, each activity was mapped directly to EHS syllabus goals: 1) hazard identification; and 2) scenario-based fire extinguisher use. Ensuring that every virtual interaction served a measurable learning purpose. This pedagogical grounding also shaped what could and could not be feasibly built within the contracted scope.

What to Do

- Develop a structured learning experience document specifying module goals, activity-level objectives, assessment logic, and measurement criteria (e.g., task completion time, accuracy, score thresholds) before approaching vendors.
- Map each XR interaction directly to a syllabus objective. If an interaction cannot be tied to a learning goal, reconsider its inclusion.
- Frame XR as augmenting, not replacing, the traditional learning. The most effective modules are scenario-based supplements, not full digital twins. Target pilot-level module development first, then scale bigger as needed.
- Involve instructional designers and accessibility experts early in the design phase, before development begins, not during iteration.

What Not to Do

- Do not pursue XR development driven by platform novelty or institutional prestige. Without clear pedagogical intent, iteration cycles waste budget on features that do not improve learning.
- Do not treat all user-requested enhancements as equally important. The iteration budget is finite. Features that address learning objectives and fix functional defects should be prioritized over cosmetic or convenience improvements.

6.2. Documentation Quality and Stakeholder Commitment

The quality of design documentation provided to the vendor is directly proportional to the efficiency and accuracy of the development output. Ambiguous or incomplete requirements are among the most common sources of development delay, scope creep, and misalignment. Equally important is securing a “Champion” stakeholder commitment before development begins.

What to Do

- Share a comprehensive design package before the first vendor meeting. This should include module syllabus and learning outcomes, activity sequences and interaction logic, domain-specific technical content the developer will need, and reference videos, annotated screenshots, or examples from existing training.
- Secure explicit commitments — including response timelines for feedback — from all stakeholder groups before vendor engagement begins. Identify a backup SME in case the primary contact becomes unavailable.
- Designate a single institutional point of contact with sufficient domain knowledge to translate instructional goals into technical requirements. Ambiguities resolved during scoping are far more efficient than those surfaced during prototyping.
- Identify one "champion" stakeholder who has both domain authority and the capacity to participate throughout the development lifecycle.

What Not to Do

- Do not rely on a single stakeholder for all domain expertise. The limited availability of any one expert during development can create critical documentation gaps that delay the project.
- Do not begin vendor engagement without a complete design document. Vague or incomplete requirements lead vendors to build contingency buffers into their quotes, increasing costs and misalignment risk.

6.3. Contract Discipline and Budget Realism

Budget and contractual constraints are the most consequential operational factors in external XR development. The case study demonstrates that meaningful XR content can be developed at research-accessible costs (approximately $7,000 in this instance), but only through careful scoping, deliberate negotiation, and realistic planning for iteration limits and recurring costs. Late-stage feature additions and unplanned iteration cycles are the most common sources of budget overrun.

Table 6. Cost Reference Points from the Case Study

Cost Item	Amount	Notes
Full VT-owned, complex, custom module	$50,000–$100,000	Not pursued due to budget; used as an anchor for negotiation.
Single module (second vendor quote)	$10,000	Included partnership discount for use of existing OSHA/PPE assets.
Final negotiated price	$7,000	Inclusive of one custom simulation and two one-year platform licenses. The partnership model (public content release) enabled a reduction.
Platform licensing (additional)	$150/device/year	Recurring cost beyond the initial contract term.
Recommended contingency reserve	15–20% of contract	To cover unplanned iterations or scope adjustments identified during pilot testing.

What to Do

- Begin scope reduction early. Narrowing from multiple modules to the highest-priority single module was the most impactful cost-reduction lever in the case study.
- Negotiate explicitly for: the number of revision cycles included, content ownership and IP terms, platform license duration and renewal process, and post-launch support expectations.

- Explore partnership models. Allowing the vendor to publish the module to their public asset library reduced the cost from ~$10,000 to $7,000. Meaningful if full IP ownership is not required.
- Provide a detailed, well-organized design document before formal negotiation. This enables accurate vendor scoping and reduces contingency markups in quotes.
- Initiate the institutional purchase order or payment authorization process immediately upon contract finalization to avoid payment delays that strain the vendor relationship.
- Build a 15–20% contingency reserve into the budget to accommodate unplanned iterations or scope adjustments identified during pilot testing.

What Not to Do

- Do not assume that post-launch support and bug fixes are unlimited or free. The responsiveness observed in the case study was a product of the collaborative relationship, not a contractual guarantee. Formalize support expectations before signing.
- Do not conflate feature requests with bug fixes. Requests for new functionality after the contract scope is defined will typically incur additional costs. Defects (which vendors are obligated to fix) are distinct from enhancements (which require supplemental negotiation).
- Do not underestimate recurring costs. Platform licenses renew annually; institutions should account for these in multi-year planning.

6.4. Structured Iteration and Communication

External XR development is an iterative process, not a linear delivery. The quality of institutional communication - both in responsiveness and in the structure of feedback - directly determines how efficiently iteration cycles are used. In the case study, two formal iteration cycles were completed within the contracted scope. This cadence was sufficient to address critical issues but insufficient to implement all enhancements identified through focus group feedback. Disciplined triage and clear communication were essential to making the most of the available iteration budget.

Communication Standards

- Establish a primary point of contact on both the institutional and vendor sides before development begins.
- Maintain a minimum communication frequency of once per week during active development phases, even when there are no active issues to resolve.
- Respond to developer questions within 24 - 48 hours during prototyping. Delays directly compress the developer's implementation window and extend delivery timelines.
- Report bugs with specificity: describe the steps taken before the bug occurred, the device used, and whether the issue is reproducible. This significantly reduces developer investigation time.

Feedback Structure

- Organize feedback by activity or feature area, with separate categories for critical bugs, UX enhancements, and optional improvements.

- Rank all feedback items explicitly by priority so the developer can triage within the iteration budget. The case study identified seven priority items across Iteration 1, enabling the developer to focus on the sequencing bug that prevented users from progressing.
- Submit feedback promptly following prototype review. Delayed feedback compresses the developer's available implementation window.

What Not to Do

- Do not submit vague, unprioritized, or delayed feedback. This is among the most common causes of iteration inefficiency in externally developed XR projects.
- Do not introduce high-cost feature requests late in the iteration cycle without acknowledging the budget implications. The requested audio-guided PASS method enhancement, identified during focus group testing in Iteration 2, exceeded the contracted scope and could not be implemented within the available budget.
- Do not treat iteration cycles as unlimited. Plan for two to three formal iteration cycles in the contract scope and prioritize accordingly. Critical bugs and functional correctness should be prioritized before any UX enhancements, but UX enhancements should be prioritized before cosmetic preferences.

6.5. Technical Readiness, Platform Management, and Vendor Dependency

Platform and infrastructure readiness is a consistently underestimated component of external XR development. In the case study, account configuration, license assignment, and analytics access setup required multiple vendor exchanges and took longer than anticipated. Vendor dependency — reliance on a single developer, a proprietary platform, and externally managed analytics — introduces structural risks that institutions must anticipate and mitigate through contractual protections and internal infrastructure planning.

Technical Infrastructure Requirements

- Confirm VR hardware compatibility before deployment. The case study module was built for Meta Quest 2 and Quest 3; compatibility with other platforms was not evaluated.
- Establish the organizational account on the vendor platform before the contract is signed. This includes designating the leader account, verifying analytics access, and testing the onboarding process with a test account.
- Verify analytics data format, granularity, and exportability (e.g., CSV) before deployment. Analytics may be accessible only through the vendor's proprietary platform; institutions should confirm they can retrieve usable data formats for research or institutional reporting purposes.
- Use an institutional or lab-level email account, not an individual researcher's personal account, to ensure platform access continuity beyond any single team member.

Managing Vendor Dependency

- Negotiate for content portability and data export rights wherever feasible. If the vendor's platform is discontinued or significantly changed, previously developed content may become inaccessible without transitional support.

- Treat post-launch maintenance as a planned phase, not an afterthought. In the case study, several critical issues emerged after the official release: an overly strict evacuation time threshold, a disappearing "911 dial" button introduced by a vendor patch, and an additional analytics data point added at the project team's request. Build buffer time between product delivery and formal data collection.
- Do not rely on a single vendor developer for all project continuity. Personnel changes, project reassignment, or vendor business changes can affect the quality and consistency of post-launch support.

What Not to Do

- Do not begin formal data collection before pilot testing is complete. Critical bugs identified after data collection has begun compromise study validity and require additional participants to maintain statistical integrity.
- Do not underestimate the platform and account setup process. This step took longer than anticipated in the case study and required multiple exchanges with the vendor's onboarding team. Begin immediately after contract finalization.
- Do not assume that internal staff will develop transferable XR skills through external vendor partnerships. Heavy reliance on external teams means institutional capacity for future independent development may remain limited. Institutions with long-term XR ambitions should plan for parallel internal capacity development.