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To the Infinity and Beyond: Foundations and Methods for Engineering Socio-Technical Educational Metaverse

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"Io non mi stanco, no, no
E vengo a cercarvi in un sogno amaranto.
Questo cuore sparpagliato per il mondo se ne va
Questo cuore disperato, è delicato."

A nonno Manfredi, nonna Teresa e nonno Aldo.
Vi cerco dove il tempo non arriva.

"You're the sunflower
I think your love would be too much"

A mia sorella, il mio *sunflower*.
Seguendo la tua luce.

“Ti dirò che ti amo quando appari sospesa fra mari disfatti e temporali di luce. Intanto, lontane, intravedo le maestose spalle degli Alburni già inondate di sole e popolana foschia.

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A Salerno,
alla Salernitana
e alla Salernitanità.
"[...] Salerno è il nostro amore e noi siamo gli Ultrà. SA-LE-RNO."

"You might be lonely, but you're never alone
You're right here where you're supposed to be
Right here with all the Losers
the ones like you
and the ones like me."

Dedicato a chi, nella vita
ha la costante sensazione di essere un fallito
a chi si considera un perdente
a chi si sente inadeguato
e a chi combatte contro sé stesso.

Arrecuordete sulo 'e na cosa:
Ca nun staje maje sule tu.

ABSTRACT

The increasing interest in the *metaverse* has positioned immersive virtual environments as a promising paradigm for social interaction, collaboration, and education. By integrating technologies such as *virtual reality*, *artificial intelligence*, and *distributed infrastructures*, the metaverse enables more engaging and interactive digital learning experiences beyond the limitations of conventional online platforms. However, despite extensive exploration, existing research and development efforts often prioritize technological novelty over systematic design, evaluation, and long-term sustainability, resulting in fragmented solutions that insufficiently address social, ethical, and organizational concerns. As a consequence, although the literature increasingly acknowledges a wide range of socio-technical challenges — privacy, security, inclusiveness, governance, and mental health — most studies remain largely conceptual or predominantly technology-centric. This gap is particularly evident in educational settings, where enabling technologies are frequently proposed without clear guidance on how they should be systematically integrated, governed, and empirically evaluated within real learning environments.

This dissertation addresses these limitations by framing the metaverse as a socio-technical system and introducing *metaverse engineering* as a structured, engineering-oriented approach to the design and development of metaverse environments, with education adopted as a meaningful context of application. This thesis pursues three main objectives: (i) to systematically characterize the socio-technical issues and enabling technologies shaping the metaverse landscape; (ii) to define a coherent engineering process that integrates these issues into the lifecycle of metaverse systems; and (iii) to operationalize and empirically evaluate this process within the educational domain.

The work combines systematic literature analyses, conceptual frameworks, and empirical studies. It proposes structured taxonomies and a

metaverse engineering roadmap, which are validated through the design and implementation of SENEM, an engineered educational metaverse. The empirical evidence shows that the proposed approach supports the systematic integration of enabling technologies such as blockchain and artificial intelligence, while making socio-technical concerns explicit, manageable, and empirically observable. As a key contribution, this dissertation provides a theoretical foundation, an engineering-oriented framework, and empirical evidence for the design, development, and assessment of responsible, sustainable, and evaluable educational metaverse systems.

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LISTINGS

PART I

INTRODUCTION AND BACKGROUND

1

INTRODUCTION

1.1 CONTEXT AND MOTIVATION

The concept of the metaverse has generated significant interest as a frontier in the evolution of the internet [229], merging technologies such as Virtual Reality (VR), Augmented Reality (AR), and advanced digital computing [233]. Within these shared virtual environments, users can socialize, work, play, and learn, progressively blurring the boundaries between physical and digital experiences [101, 112, 190, 274, 321]. As a possible step in the development of online interaction, the metaverse has been associated with new opportunities for communication, collaboration, and interaction with digital content [93, 115]. This potential has led major technology companies to invest heavily in its advancement: for example, META reorganized its corporate identity around metaverse initiatives, while companies such as NVIDIA, MICROSOFT, APPLE, and SONY have collectively invested more than $18 billion to pursue their ambitions in this area [90].

Despite this rapid progress, recent studies show that the metaverse faces several technical limitations that hinder its reliability and large-scale adoption. These challenges include the need for scalable infrastructures capable of supporting massive real-time interactions, the absence of interoperable standards, unresolved issues in rendering and network performance, and persistent threats to security and privacy [154, 226, 312]. Technical complexity is further increased by the platform-based nature of metaverse ecosystems, where opaque algorithms, data processing practices, and surveillance-oriented architectures raise concerns about trust, transparency, and accountability [36, 37].

However, the most critical challenges extend beyond technological boundaries. The literature has shown that the metaverse is not a neu-

tral artifact but a system shaped by social, political, and economic forces [35]. As a result, it raises important societal concerns related to privacy, crime, data ownership, algorithmic governance, and forms of control that may reduce user autonomy [226, 356]. The immersive and pervasive nature of these environments also introduces ethical and psychological issues, including exposure to surveillance capitalism, cyber-syndromes, addiction, isolation, and negative effects on mental well-being [117, 188].

Taken together, these studies highlight an important limitation of current research: although the literature frequently identifies the technical and social issues of the metaverse, most contributions remain conceptual. They often propose high-level visions of how enabling technologies—such as artificial intelligence, machine learning, and blockchain—could address these issues, but rarely provide practical, integrated instantiations within functioning metaverse environments. As a result, there is limited evidence on both the theoretical foundations and the engineered methods needed to embed, configure, and empirically evaluate these technologies in real systems. This gap reinforces the view of the metaverse as a socio-technical problem, whose complexity requires approaches that jointly consider technological architectures and the social dynamics surrounding their use.

To deal with these complexities, this dissertation argues for the definition of a new discipline: *metaverse engineering*. We conceptualize metaverse engineering as a multidisciplinary effort grounded in virtual reality, human–computer interaction, artificial intelligence, and software engineering. Its objective is to provide systematic processes and tools capable of integrating technical requirements with social, ethical, and organizational constraints. Emerging technologies such as artificial intelligence, machine learning, and blockchain can contribute to this objective by supporting reliable data management, assisting content production, and improving security and traceability when adopted under appropriate governance. When viewed through a socio-technical lens, these technologies provide concrete means to address several limitations that hinder the dependable and responsible use of metaverse systems.

While metaverse engineering defines the principles and processes needed to address these challenges, the next step is to examine how these principles can be applied in a concrete domain of application. Among the various contexts in which the metaverse has been investigated, the educational domain has received particular attention. During the COVID-19 pandemic, several institutions adopted virtual and immersive platforms to maintain teaching activities, revealing both potential benefits for student engagement and a number of open issues related to accessibility, ethics, and technical feasibility [116, 190, 213, 229]. These considerations make education a suitable and meaningful setting for studying how enabling technologies can be introduced, integrated, and assessed within an engineered metaverse environment.

The considerations discussed above motivate the research objectives that structure the dissertation, summarized as follows.

1.2 RESEARCH STATEMENT

The primary and most relevant objective of this dissertation is to provide a systematic and comprehensive overview of the socio-technical issues that characterize the current metaverse landscape. These issues concern several dimensions, including interaction, infrastructure, privacy and security, accessibility and inclusiveness, usability, social and ethical norms, communication and networking, mental health, and even rendering and visualization. Addressing these aspects is essential because the term metaverse, originally introduced as a fictional construct, has been progressively associated with a broad set of virtual technologies and practices that still lack a coherent **theoretical foundation**. Scientific literature has often emphasized the potential of the metaverse and its enabling technologies [229], e.g., artificial intelligence and blockchain, yet has rarely provided **engineering-oriented methods and empirical approaches** explaining *how* and for *what* purposes these technologies can concretely support end users.

From this analysis, two major research gaps emerge: the first gap concerns the lack of structured awareness of the socio-technical challenges of the metaverse. The existing literature does not provide a solid and systematic characterization of the social and technical issues that the metaverse and its enabling technologies must address to be reliably and responsibly adopted across various application contexts.

⚠ Lack of Theoretical Foundation

Current research lacks a structured, comprehensive foundation for organizing the socio-technical challenges of the Metaverse. Existing contributions remain fragmented and technology-driven, lacking an inclusive theoretical model to guide the interpretation of such complexities.

The second gap concerns the absence of clear procedures for its engineering-oriented development. In particular, current research does not outline processes for integrating these challenges into a structured design and development workflow to support the realization of prototypes and systems that require continuous evolution.

⚠ Lack of Engineering-oriented Methods and Evaluations

The literature lacks engineering-oriented methods and development processes that integrate socio-technical issues into the realization of metaverse systems. As a result, there is no established pathway for designing, implementing, and iteratively evaluating reliable metaverse prototypes.

Building on the two research gaps identified above, this dissertation aims to address the lack of theoretical foundations concerning the *role* of enabling technologies within the metaverse and the *socio-technical* challenges associated with their design and development. Although metaverse technologies can be applied across a broad spectrum of domains, the cur-

rent literature still lacks a solid foundation in socio-technical aspects that can shape the development of metaverse systems.

> ***RQ$_A$**: What are the roles of metaverse enabling technologies and which socio-technical challenges arise with them?*

Once the socio-technical challenges and enabling technologies have been identified, the next step is to define a rigorous engineering process capable of guiding the design and development of metaverse systems. This step is essential because the metaverse integrates heterogeneous technologies and concerns, and therefore requires shared methods that can be adopted across different communities involved in its evolution. Establishing such a process ensures that socio-technical issues are not treated as isolated problems, but are systematically incorporated into the entire development lifecycle.

> ***RQ$_B$**: How can identified socio-technical challenges and enabling technologies be addressed through an engineering-driven process for the design and development of Metaverse systems?*

The third research question builds on the engineering perspective introduced in RQ_A, and RQ_B, and addresses the lack of engineering-oriented methods in the current metaverse literature. After defining a structured process for integrating socio-technical challenges and enabling technologies, it becomes essential to examine how such a process can be applied and evaluated within a concrete application domain. Among the various domains in which the metaverse has been explored, the educational context has gained particular relevance, especially due to its potential to support learning and engagement experiences during the COVID-19 pandemic. For this reason, education represents a meaningful scenario in which to evaluate how enabling technologies can be operationalized within the metaverse.

> ***RQ$_C$**: How can enabling technologies be integrated, operationalised, and empirically evaluated within an educational metaverse environment?*

By addressing these questions, this dissertation aims to provide a unified and rigorous perspective on the metaverse, bridging theoretical insights, engineering perspectives, and applied technological contributions. The next section outlines how each of these research questions is addressed through the scientific contributions developed throughout this work.

1.3 RESEARCH CONTRIBUTION

In light of the limitations shown in the previous section, this dissertation structures its contributions—and their corresponding research questions—into two complementary components: **theoretical foundations** and **engineering and empirical evaluation of educational metaverse**. This distinction reflects the overall ambition of the work, namely, to provide a coherent trajectory that moves from conceptual clarity to engineering and empirical depth, ultimately addressing the gaps that currently hinder a structured understanding and development of the metaverse. Before discussing each contribution in detail, the following paragraphs present the core sense of the dissertation.

THEORETICAL FOUNDATIONS. Part II addresses RQ_A and RQ_B, as it gathers a set of theoretical contributions that collectively establish the conceptual scaffolding on which the dissertation is built. In greater detail, this part of the dissertation presents a set of theoretical contributions that frame the metaverse as a socio-technical system shaped by its enabling technologies and by the communities that study and deploy them. The contributions first outline these technologies and the related socio-technical issues, showing how a structured process—i.e., metaverse engineering—can provide a *structured approach* to addressing them. The educational context is used as a concrete scenario to illustrate how these issues materialize in practice. Other works then examine the enabling

technologies in depth, focusing on blockchain, artificial intelligence, and machine learning, as well as the accessibility and interaction requirements for users with disabilities. This part introduces the first engineered prototype of an educational metaverse, namely SENEM, demonstrating how the proposed principles can be translated into an operational system. Finally, the SENEM prototype laid the foundation for the ethical use of AI and emotion recognition in the educational context.

ENGINEERING AND EMPIRICAL EVALUATION. Part III addresses RQ_C, building upon the theoretical framework developed in Part II and advancing the engineering-oriented, and evaluation dimension of the dissertation. To this end, the dissertation investigates practical techniques for constructing 3D spaces and offers an empirical comparison among photogrammetry, manual modeling, and AI-assisted content generation—highlighting their respective affordances and limitations. In parallel, the blockchain framework outlined in the previous part is implemented and validated within SENEM, demonstrating how theoretical design principles can be translated into a functioning architectural component. Finally, this part culminates in an empirical comparison of learning and experience across three modalities—metaverse, face-to-face, and remote learning. The study evaluates both learning outcomes and quality of experience, providing a comprehensive assessment of the educational implications of metaverse-based instruction.

1.4 THESIS STRUCTURE

Along the same lines, this section outlines the overall structure of the dissertation, clarifying the role of each contribution and how they collectively articulate the trajectory of the thesis. Each chapter is positioned to show how the individual components—both theoretical and engineering and empirical evaluations-contribute to a coherent understanding of the metaverse and its application in educational contexts. For completeness, Table 1.1 offers a concise summary of all contributions and their placement within the broader structure of the dissertation, while Table 1.2 offers de-

tails about the Conference, Journal, and Workshop, such as the name of the venue, and the ranking[1] category where each chapter of the dissertation was submitted and accepted. Finally, Figure 1.1 provides an overview of the overall structure of this dissertation and its main contributions. It is worth noting that these contributions are not isolated, but rather interconnected, reflecting the dependency relationships that exist among them. As the figure shows, the theoretical foundations underpin the entire thesis, serving as the basis upon which the subsequent research activities and contributions are developed.

THEORETICAL FOUNDATIONS. This part of the thesis comprises six chapters, each contributing to the theoretical foundations required to conceptualise and engineer the Metaverse. Chapter 3 explores artificial intelligence—particularly machine and deep learning—in a visionary perspective, examining its role as an enabling technology and reflecting on its opportunities and risks across technical, social, and psychological dimensions. Chapter 4 serves as the conceptual anchor of the dissertation, offering a structured and comprehensive overview of the Metaverse from multiple perspectives and culminating in the introduction of the metaverse engineering notion. Chapter 5 investigates blockchain as a mechanism to strengthen integrity, security, and trust within educational metaverse systems, providing both a conceptual framework and a design proposal aligned with the requirements identified in prior analyses. Chapter 6 then broadens the lens to the social dimension, emphasising inclusiveness and accessibility as fundamental conditions for a genuinely human-centred Metaverse. Chapter 7 presents SENEM, the first engineered prototype of an educational metaverse, developed in accordance with the principles and insights established throughout the preceding chapters. Finally, Chapter 8 concludes Part II, which focuses on emotion recognition in the SENEM Metaverse, emphasising the ethical and social implications of deploying such technology in sensitive educational settings.

[1] Ranking provided using *Scimago Journal Rank* for Journals, and *Core Ranking* for Conferences

ENGINEERING AND EMPIRICAL EVALUATION. Through a series of five empirical and design-oriented studies, this part investigates how enabling technologies can be operationalised and evaluated within Metaverse environments, with particular attention to educational scenarios. Chapter 9 examines practical techniques for building virtual environments, presenting an empirical comparison between photogrammetry and manual 3D modelling. Chapter 10 extends this analysis by exploring how artificial intelligence can support the generation of virtual assets, positioning AI as a mechanism for scalable and efficient content production. Chapter 11 advances the SENEM prototype by integrating gamification elements, showing how theoretical design principles can translate into concrete improvements in engagement and interaction. Chapter 12 operationalises the blockchain framework introduced in Chapter 5, embedding it into SENEM and validating the proposed architecture through a functioning implementation. Finally, Chapter 13 provides the culminating contribution of Part III by designing an educational lesson grounded in established learning principles and delivering it through the Metaverse. A controlled experiment compares learning outcomes and user experience across three modalities—Metaverse, face-to-face, and remote—offering empirical evidence on the pedagogical value and socio-technical implications of Metaverse-based instruction.

Table 1.1: Overview of Thesis Contributions Across Papers, Research Questions, and Chapters of the Thesis

ID	Paper Title	Contribution	RQs	Chapter	Venue
C01	*Machine Learning for Educational Metaverse: How Far Are We?*	Overview of how machine learning supports the educational metaverse, highlighting technical, psychological, and social challenges.	RQ_A	Ch. 3	Conference
J01	*Another Brick in the Wall: A Systematic Mapping Study Toward Defining Metaverse Engineering Through Socio-Technical Issues*	Systematic Mapping Study defining enabling technologies, socio-technical issues, and research communities of the Metaverse, introducing the *Metaverse Engineering* perspective.	RQ_A, RQ_B	Ch. 4	Journal
C03	*Toward a Secure Educational Metaverse: A Tale of Blockchain Design for Educational Environments*	Analysis of blockchain in education and definition of a secure, blockchain-based framework for an educational metaverse.	RQ_A	Ch. 5	Conference
C04	*Breaking Barriers in the Metaverse: A Comprehensive Exploration of Accessibility for Users with Disabilities*	Review of accessibility challenges in the metaverse and synthesis of solutions to enhance inclusion for users with disabilities.	RQ_A	Ch. 6	Workshop
J02	*SENEM: A Novel Software Engineering-Enabled Educational Metaverse*	Application of a metaverse engineering approach to elicit requirements and develop SENEM, a validated educational metaverse platform.	RQ_A, RQ_B	Ch. 7	Journal
C05	*Collecting and Implementing Ethical Guidelines for Emotion Recognition in an Educational Metaverse*	Extraction of ethical guidelines for emotion recognition and implementation of privacy-aware FER within SENEM.	RQ_A, RQ_B	Ch. 8	Workshop
C06	*Accelerating 3D Scene Development for the Metaverse: Lessons from Photogrammetry and Manual Modeling*	Empirical evaluation of photogrammetry to accelerate 3D scene development, offering engineering insights for metaverse construction.	RQ_C	Ch. 9	Conference
J04	*Towards AI-Powered Automatic 3D Scene Generation for the Metaverse: A Comparative Analysis of Manual and Photogrammetry Techniques*	Extension of the previous study evaluating AI-assisted photogrammetry, comparing tools and refining guidelines for efficient 3D scene generation.	RQ_C	Ch. 10	Journal
C07	*MetaSERGE—A Serious Game for Risk Management in an Educational Metaverse*	Adaptation of a risk-management serious game within the SENEM metaverse to support structured, interactive learning.	RQ_C	Ch. 11	Conference
C08	*Better Now: Bridging Theory and Practice in Blockchain-Enabled Educational Metaverse*	Operationalization of the blockchain framework from C03 through decentralized lecture management within SENEM.	RQ_C	Ch. 12	Workshop
J03	*The Good and the Bad of Teaching Social Debt and Community Smells Using Virtual Reality*	Comparison of immersive VR and traditional teaching using learning-outcome and quality-of-experience metrics.	RQ_C	Ch. 13	Journal

Table 1.2: Conferences, Journals, and Workshop, characteristics for each contribution of the dissertation

ID	Paper Title	Venue Type	Venue Name	Ranking
C01	*Machine Learning for Educational Metaverse: How Far Are We?*	Conference	*International Conference on Consumer Electronics* (ICCE)	B
J01	*Another Brick in the Wall: A Systematic Mapping Study Toward Defining Metaverse Engineering Through Socio-Technical Issues*	Journal	*Computing Survey* (CSUR)	Q1
C03	*Toward a Secure Educational Metaverse: A Tale of Blockchain Design for Educational Environments*	Conference	*Euromicro Conference Series on Software Engineering and Advanced Applications* (SEAA)	B
C04	*Breaking Barriers in the Metaverse: A Comprehensive Exploration of Accessibility for Users with Disabilities*	Workshop	*Workshop on Artificial Intelligence with and for Learning Sciences* (WAILS)	N/A
J02	*SENEM: A Novel Software Engineering-Enabled Educational Metaverse*	Journal	*Information and Software Technologies* (IST)	Q1
C05	*Collecting and Implementing Ethical Guidelines for Emotion Recognition in an Educational Metaverse*	Workshop	*International Workshop on User-Centered Practices of Knowledge Discovery in Educational Data* (UKDE)	N/A
C06	*Accelerating 3D Scene Development for the Metaverse: Lessons from Photogrammetry and Manual Modeling*	Conference	*International Conference on Intelligent Metaverse Technologies and Applications* (iMeta)	N/A
J04	*Towards AI-Powered Automatic 3D Scene Generation for the Metaverse: A Comparative Analysis of Manual and Photogrammetry Techniques*	Journal	*Cluster Computing*	Q1
C07	*MetaSERGE—A Serious Game for Risk Management in an Educational Metaverse*	Conference	*International Conference on Software Engineering* (ICSE)	A*
C08	*Better Now: Bridging Theory and Practice in Blockchain-Enabled Educational Metaverse*	Workshop	*Workshop on Artificial Intelligence with and for Learning Sciences* (WAILS)	N/A
J03	*The Good and the Bad of Teaching Social Debt and Community Smells Using Virtual Reality*	Journal	*Empirical Software Engineering* (EMSE)	Q1

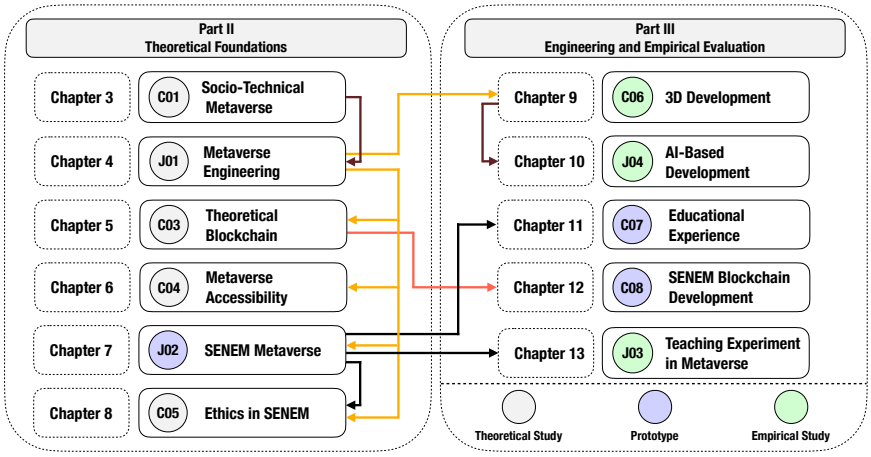


Figure 1.1: Overview of the dissertation structure and the relationships among its main contributions. The figure shows how the theoretical foundations support the development of the subsequent studies.

1.4.1 *Publicly Available Tools and Replication Packages*

This section provides an overview of all the publicly available tools and replication packages associated with the contributions presented in this dissertation. The goal is to offer the research community complete and transparent access to the resources needed to ensure *reproducibility* and *replicability*, thereby validating and extending our studies. For all contributions involving human participants—such as expert evaluations, controlled experiments, or user studies—ethical approval was obtained from the appropriate institutional ethical boards, ensuring compliance with established research standards.

Below is the list of online appendices and replication materials.

- J01 - *Another Brick in the Wall: A Systematic Mapping Study Toward Defining Metaverse Engineering Through Socio-Technical Issues*—Online Appendix [103]
- C03 - *Toward a Secure Educational Metaverse: A Tale of Blockchain Design for Educational Environments*—Online Appendix [100]

- C04 - *Breaking Barriers in the Metaverse: A Comprehensive Exploration of Accessibility for Users with Disabilities*—Online Appendix [107]
- J02 - *SENEM: A Novel Software Engineering-Enabled Educational Metaverse*—Online Appendix [271]— SENEM Metaverse [272]
- C06 - *Accelerating 3D Scene Development for the Metaverse: Lessons from Photogrammetry and Manual Modeling*—Online Appendix [268]
- J04 - *Towards AI-Powered Automatic 3D Scene Generation for the Metaverse: A Comparative Analysis of Manual and Photogrammetry Techniques*—Online Appendix [269]
- C07 - *MetaSERGE — A Serious Game for Risk Management in an Educational Metaverse*—Online Appendix [288]
- C08 - *Better Now: Bridging Theory and Practice in Blockchain-Enabled Educational Metaverse*—Online Appendix [106]
- J03 - *The Good and the Bad of Teaching Social Debt and Community Smells Using Virtual Reality*—Online Appendix [105]

2

BACKGROUND AND RELATED WORK

This chapter will explore the basics of the Metaverse concept and look at existing works related to this thesis. Section 2.1 provides a comprehensive background on the concept of the Metaverse, defining its essential characteristics and examining the current state of technologies utilized for its implementation. Subsequently, Section 2.2 will discuss related works and prototypes developed in the context of the educational Metaverse, highlighting their unique features and objectives. By doing so, the aim is to contextualize the study within the broader context of educational Metaverse applications.

2.1 BACKGROUND

2.1.1 *Metaverse's Definition*

The term Metaverse was first introduced by Neil Stephenson in his 1992 science fiction novel Snow Crash, where it described a hybrid world blending virtuality and reality, allowing individuals to interact through avatars [317]. Since then, the concept has evolved considerably, encompassing a wide range of features, technologies, and applications [193, 255, 290]. Numerous definitions have been proposed in the literature, each emphasizing different dimensions depending on the application domain [290]. Broadly, the Metaverse can be understood as a three-dimensional online environment in which users—represented by avatars—interact with one another within virtual spaces that transcend the physical limitations of the real world [290]. Dionisio et al. [369] identified a set of key characteristics that outline the essential elements for achieving a fully functional Metaverse, summarized below:

- *Realism*: To provide users with an engaging and convincing experience, a Metaverse must ensure a high degree of realism. This is primarily achieved through the sensory dimensions of sight, hearing, and touch, which enhance immersivity and foster stronger psychological and emotional engagement.

- *Ubiquity*: A Metaverse platform should guarantee broad accessibility and seamless availability across diverse devices and platforms. This is increasingly feasible today thanks to advancements in ubiquitous computing [28], enabling users to access the same environment and profile from desktops, tablets, smartphones, and even web browsers—thus removing the dependency on dedicated installations or frequent updates.

- *Interoperability*: Interoperability refers to the ability of different virtual worlds to exchange data and information seamlessly. Achieving this requires common standards for formats, data structures, communication protocols, digital identities, locators, and virtual currencies, ensuring consistency and fluidity across platforms.

- *Scalability*: Scalability is essential to support a large number of concurrent users without compromising performance or user experience. A scalable Metaverse must allocate sufficient computational resources and network capacity to sustain massive interactions while maintaining efficiency and responsiveness.

2.1.2 *Key Concepts and Components of the Metaverse*

After defining the primary attributes that characterize a Metaverse, it is essential to illustrate its key components and underlying concepts. The following subsection presents and discusses these elements, providing a comprehensive overview of the fundamental building blocks that constitute a Metaverse.

- *Avatar*: An avatar represents the user's digital embodiment within the Metaverse, serving as the main interface for interaction with the virtual environment. Avatars must be controllable in real time and synchronized as closely as possible with the user's actions and expressions. Their design and representation have been widely debated in the literature [79, 177, 359]. Depending on both user preference and platform policy, avatars can replicate the user's physical appearance or adopt entirely different, even non-human, forms [193]. Kim et al. [177] investigated how varying levels of avatar realism affect user experience and surprisingly found that higher realism tends to reduce the sense of social presence while increasing perceived psychological distance. Beyond design considerations, avatar representation also raises important legal issues such as fraud, identity theft, and defamation [79], as well as ethical concerns related to the portrayal of diversity and disability to prevent discriminatory practices [359].

- *Dimensions*: As introduced in Section 2.1.1, the Metaverse is commonly described as a "three-dimensional virtual world." However, the characteristics of such environments can differ significantly. Smart et al. [311] proposed a classification framework that identifies four key dimensions of the Metaverse, which help in understanding its diverse technological and experiential contexts. These dimensions, summarized in Figure 2.1, are defined along two axes: the degree of *Externality*—referring to information and control of the external world—versus *Intimacy*—referring to the identity and actions of individual objects—and the degree of *Augmentation*—enhancement of existing systems—versus *Simulation*—creation of new digital environments. Table 2.1 summarizes each dimension.

- *Digital Twin*: A digital twin is a virtual representation of a real-world object, process, or system [308]. Within the Metaverse, digital twins enhance immersion by bridging the physical and digital domains, allowing users to experience dynamic and context-aware environments. The design and integration of digital twins rely on multiple

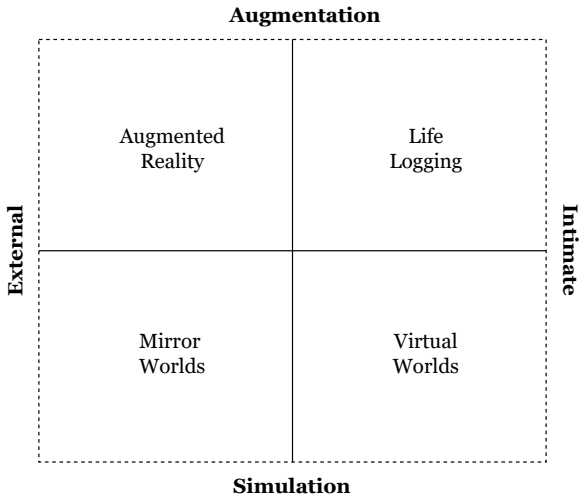


Figure 2.1: Classification of the Metaverse into four dimensions.

disciplines, including material science, signal processing, the Internet of Things (IoT), pattern recognition, and rendering technologies [112]. A Metaverse platform must therefore determine which physical elements are worth mirroring and how their digital counterparts can effectively contribute to real-world improvement [112].

- *Content Creation and Virtual Economy*: One of the defining features of the Metaverse is the possibility for users to generate and personalize digital content. This capacity should not be restricted to professional designers but extended to all users, enabling a participatory ecosystem in which platform operators provide the core infrastructure, and users enrich it through user-generated content (UGC) [112, 361]. Such participatory content creation fosters cultural diversity, supports intergenerational exchange, and contributes to preserving digital heritage [193]. In addition, the Metaverse typically incorporates a virtual marketplace where users can buy, sell, and trade digital assets, supporting the emergence of a decentralized virtual economy [193, 255]. Momtaz [222] describes this economic model as one driven by UGC and non-fungible tokens (NFTs), high-

Table 2.1: Summary of the possible dimensions of a Metaverse.

Metaverse Dimensions	Definition	Classification
Augmented Reality	Enhancement of the physical world through location-aware systems and digital overlays, providing users with contextual information and interactive content in real time.	External – Augmentation
Life Logging	Technologies for recording and documenting users' and objects' states, behaviors, and life histories, supporting self-observation, memory, and behavior modeling.	Intimate – Augmentation
Mirror Worlds	Digital representations of the physical world enriched with virtual mapping, modeling, and annotation tools.	External – Simulation
Virtual Worlds	Fully digital environments that support complex economic and social activities, progressively blurring the boundaries between virtual and physical realms.	Intimate – Simulation

lighting its potential to reshape marketing, advertising, and even sustainability practices through novel economic paradigms.

- *Social Acceptability, Security, and Privacy*: Social interaction lies at the heart of any Metaverse experience. However, this also entails addressing a wide range of ethical and societal challenges. *Social acceptability* reflects collective behaviors, norms, and perceptions that shape the social fabric of the Metaverse [193]. Factors such as fairness, diversity, and inclusivity critically influence how users perceive and participate in virtual societies. Establishing appropriate governance frameworks is essential to prevent discrimination, cyberbullying, and other forms of virtual misconduct [284]. Equally important are the issues of *security* and *privacy*. Each user possesses a distinct digital identity, which requires robust authentication mechanisms [193]. Moreover, vast amounts of user data—potentially sensi-

tive—are continuously generated, exposing systems to risks such as data leaks and unauthorized profiling. Therefore, safeguarding privacy and ensuring secure data handling are fundamental to building trustworthy and ethically responsible Metaverse platforms [109].

2.1.3 *Hardware and Software Technologies for the Metaverse*

As introduced in Section 2.1.2, a Metaverse constitutes a potentially complex ecosystem that integrates multiple interdependent components. It requires a three-dimensional rendering engine to generate immersive virtual environments, as well as tools for modeling avatars, objects, and scenes. A fully functional Metaverse must also rely on a robust large-scale persistence management system capable of ensuring scalability and supporting the concurrent participation of numerous users. Furthermore, it must effectively address issues related to privacy and security, while incorporating mechanisms for purchases and economic transactions.

Beyond these structural aspects, the Metaverse can harness VR and AR technologies to enhance realism and immersion, offering users a significantly more engaging experience than traditional software applications. Given the diversity of these requirements, it becomes crucial to understand how such a platform can be implemented and which technologies are most commonly employed to achieve this goal. The following subsection provides an overview of the primary hardware devices used in Metaverse applications and the software solutions most frequently adopted to fulfill its core functional and experiential requirements.

2.1.3.1 *Hardware Components*

One of the defining characteristics of the Metaverse is its ubiquity, which implies the need for accessibility across a wide range of devices [369]. Achieving such ubiquity, however, may sometimes come at the expense of immersion and realism, as a truly universal Metaverse should ideally operate on common hardware such as desktop computers, laptops, tablets, and smartphones. Nevertheless, advances in hardware technologies are

progressively enabling more immersive and multisensory Metaverse experiences that provide visual, auditory, and even tactile feedback.

Head-Mounted Display (HMD) devices, in particular, have gained increasing popularity for the implementation of immersive Metaverse environments. These wearable devices can be broadly categorized into three types: (i) *non–see-through* HMDs, which completely occlude the real world to offer a 360-degree view of a fully virtual environment—commonly employed in VR applications, such as the Meta Quest by Meta or the HTC Vive by Valve; (ii) *optical see-through* HMDs, which overlay virtual elements onto the user's real-world view—such as the Microsoft HoloLens or Google Glasses—typically used in AR applications; and (iii) *video see-through* HMDs, which capture the real world through cameras and augment it with virtual objects—such as the wide field-of-view device proposed by Takagi et al. [323] [96, 255].

Non–see-through devices, in particular, enable complete immersion, providing a level of engagement that traditional 2D displays cannot match. However, their widespread adoption remains limited by several challenges. Caserman et al. [68] examined the phenomenon of *cybersickness*, characterized by symptoms such as nausea, disorientation, confusion, and headaches resulting from prolonged HMD use. Their findings indicate that 60–95% of participants experience some form of cybersickness during virtual exposure, with 6–12.9% terminating the session prematurely due to discomfort. Moreover, the high cost of advanced HMDs represents a major barrier to achieving an accessible and ubiquitous Metaverse [96].

In contrast, see-through devices tend to be lighter, less obtrusive, and more affordable. Typically resembling conventional eyeglasses, they are designed to overlay annotations or virtual elements on top of the real environment. Applications leveraging AR technologies have become increasingly widespread, as shown in the study by Olsson and Salo [246], who conducted an online qualitative survey on user satisfaction with mobile AR applications, reporting generally positive responses. Similarly, Fernandes et al. [9] compared two multimodal interfaces in an immersive video game scenario: (i) a fully virtual VR interface using an HMD, and (ii) an AR

interface employing see-through glasses. Their results revealed that while VR provided higher immersion and engagement, AR significantly reduced cybersickness and disorientation.

In addition to visualization systems, input devices play a fundamental role in shaping user experience within the Metaverse. Alongside traditional interaction mechanisms—such as mouse, keyboard, touchscreen, and joystick—specific input devices have been developed to support richer and more natural interactions in VR and AR environments. These devices enable real-time communication between the user and the virtual world, serving as essential tools for controlling avatars, exploring environments, and interacting with digital objects.

According to the taxonomy proposed by Park et al. [255], input devices can be classified into three categories: (i) *hand-based*, (ii) *non–hand-based*, and (iii) *motion input* devices. Hand-based devices are designed to be held or worn on the user's limbs. They typically combine buttons, triggers, and sensors that capture position and rotation, translating physical movements into virtual actions. These controllers often provide haptic feedback, enhancing the sense of touch and overall immersion. The second category, non–hand-based devices, complements the previous one by introducing alternative input modalities such as eye-tracking or voice commands—allowing users, for instance, to rotate their avatar's head using gaze direction or to issue verbal commands even when using an HMD. Finally, motion input devices encompass systems capable of tracking full-body movements, enabling users to walk and move freely within the virtual environment, thereby reinforcing spatial awareness and embodiment. Despite their potential, such devices remain expensive and can pose risks of physical strain or injury, limiting their short-term scalability and adoption. In conclusion, current hardware devices for accessing and interacting with the Metaverse each present distinct advantages and limitations. While visualization and input technologies are evolving rapidly, several challenges remain—particularly concerning cost, accessibility, comfort, and safety—that must be addressed before truly immersive, realistic, and ubiquitous Metaverse platforms can achieve widespread adoption.

2.1.3.2 *Software Technologies*

When it comes to software technologies for the implementation of a Metaverse platform, the core component lies in the three-dimensional rendering engine. All the main elements of a Metaverse—such as *virtual environments*, *avatars*, and *digital twins*—are inherently three-dimensional objects and models that must be created, textured, rigged, and rendered in real time [193, 255, 369]. Among the most widely adopted 3D engines, *Unity3D*[1] represents one of the leading solutions. Unity3D is a cross-platform, free-to-use development engine that allows applications to be deployed across multiple devices, including smartphones, personal computers, and browsers through cloud-based streaming. It also provides access to a vast asset store, which facilitates the development of diverse environments and avatars.

Another popular alternative is the *Unreal Engine*[2], particularly renowned for its ability to render high-fidelity, photorealistic graphics. This makes it especially suitable for applications that demand strong visual realism and complex world-building capabilities. The engine offers advanced development tools for managing large-scale virtual environments and supports a wide range of customization options.

For the creation of 3D assets, specialized modeling software is typically employed, such as the open-source platform *Blender*[3] or licensed solutions including *Maya*[4] and *ZBrush*[5]. These tools allow for modeling, sculpting, texturing, and rigging of 3D models that can subsequently be imported into development engines, forming the foundation for the Metaverse's visual and interactive components.

However, the Metaverse requires much more than a rendering engine capable of handling graphics and animation. It must also rely on technologies that ensure scalability, decentralization, and secure data management. Given the vast amount of data that such a platform is expected to generate,

[1] *Unity3D website*: https://unity.com
[2] *Unreal Engine website*: https://www.unrealengine.com
[3] *Blender website*: https://www.blender.org
[4] *Maya website*: https://www.autodesk.it/products/maya
[5] *ZBrush website*: https://www.maxon.net/en/zbrush

relying on a single centralized server becomes impractical. To address these challenges, blockchain technology has recently emerged as a promising solution.

A *blockchain* is a distributed ledger that organizes data into blocks rather than traditional database tables [132]. In a blockchain-based system, users—referred to as nodes—generate and store data within these interconnected blocks. The network typically follows a peer-to-peer (P2P) architecture, where each node simultaneously acts as a client and server, enabling resource sharing without central mediation. Each block is cryptographically linked to the previous one, forming an immutable chronological chain. All participating nodes maintain a synchronized copy of this chain through a consensus mechanism, a protocol used to establish agreement among nodes regarding the validity and order of transactions [132].

This distributed architecture ensures two key features essential to the Metaverse: *decentralization* and *security*. If a single node fails or becomes compromised, the system can restore integrity by cross-validating data across other nodes. Due to its decentralized nature, blockchain represents a powerful approach for addressing large-scale data storage and sharing challenges within the Metaverse. Zyskind et al. [368], for instance, proposed a decentralized data management framework that leverages blockchain to guarantee secure and privacy-preserving access, allowing users to share encrypted data through authorization keys. Despite its promise, blockchain still faces technical and scalability challenges that must be overcome for widespread adoption in complex Metaverse infrastructures [132].

Beyond blockchain, the vast field of *Artificial Intelligence* (AI) also plays a pivotal role in enhancing Metaverse functionality. AI technologies can be applied across multiple layers of the system to enable intelligent behavior, personalization, and automation. A common use case involves the implementation of *non-playable characters* (NPCs)—AI-driven entities that interact autonomously within virtual environments. These characters may act as assistants, collaborators, or adversaries, thereby enriching the

user experience and contributing to environmental realism [112]. NPC behavior is typically governed by advanced AI approaches, including Deep Learning (DL), Reinforcement Learning (RL), and Natural Language Processing (NLP), the latter enabling human-like conversation and context understanding.

Populating the Metaverse with intelligent agents improves social presence and engagement. Supporting this view, Soni et al. [315] demonstrated that users preferred interacting with robot entities trained to mimic human behavior rather than traditional computer-controlled opponents, emphasizing the social value of AI-driven agents.

Moreover, as discussed in Subsection 2.1.2, one of the fundamental elements of the Metaverse is the *digital twin*. Digital twins are not merely 3D models replicating physical objects but dynamic, data-driven entities that evolve in real time. For this reason, if the physical object's state changes in the real world, the corresponding digital twin must update accordingly [308]. Achieving this synchronization requires AI algorithms capable of continuous mapping, tracking, and updating. By integrating such algorithms, digital twins can remain in constant alignment with their real-world counterparts, ensuring a responsive and interconnected ecosystem [193].

Finally, *Computer Vision* (CV) technologies also play an essential role in bridging virtual and physical contexts. These algorithms allow computing systems to interpret and process visual information from cameras or sensors, enabling spatial and contextual awareness within mixed-reality environments. In the Metaverse, Computer Vision can support numerous functionalities, including scene understanding, object recognition, automatic avatar generation from user facial images, and intelligent correction or enhancement of 3D textures and models [230].

In conclusion, the rapid evolution of software technologies continues to expand the boundaries of what can be achieved within the Metaverse. From rendering engines and decentralized storage to artificial intelligence and computer vision, these technologies collectively shape the functional, aesthetic, and ethical dimensions of the Metaverse.

2.1.4 *Metaverse for Education*

A Metaverse platform can be conceived and applied across multiple domains, including gaming, simulation, remote work, communication, and marketing [193, 255]. However, for the purposes of this dissertation, the focus is placed on the Metaverse's impact within the educational context—specifically, how it has been explored so far and what key findings have emerged.

The interest in adopting Metaverse-related technologies for education significantly increased following the outbreak of the COVID-19 pandemic. The rapid spread of the virus and the resulting lockdown measures turned traditional in-person learning into a considerable public health risk. Consequently, approximately 98.6% of students worldwide were affected, forcing educational institutions to identify alternative methods to ensure pedagogical continuity while protecting students, teachers, and staff [276]. Distance learning platforms emerged as a practical response, enabling schools, colleges, and universities to migrate their activities online.

During this transition, educational institutions extensively adopted 2D remote communication platforms [229] such as MICROSOFT TEAMS, GOOGLE MEET, and ZOOM, ensuring that academic activities could continue [276]. The widespread implementation of remote and blended learning approaches brought several notable advantages. Remote education increased accessibility for a broader audience, including students with physical impairments who could participate from home with minimal mobility requirements [29]. Additionally, Soblechero et al. [206] studied the introduction of distance learning within an Administrative Management vocational program, observing that enrollment rates increased following the implementation of remote modalities, thereby allowing individuals with full-time jobs or other obligations to participate in education more flexibly.

Despite these benefits, the quality and engagement level of online learning still present significant challenges. The urgency of the pandemic required rapid deployment of digital solutions, leaving limited time to design

pedagogically sound and immersive systems [29]. Although numerous digital tools now support online education, they often fail to replicate the immersive and interactive characteristics of face-to-face learning experiences [253]. As noted by Mystakidis [229], current 2D learning environments suffer from several critical limitations:

- *Low self-perception*: In 2D settings, users have a diminished sense of embodiment, appearing as static profile images or webcam feeds with limited personalization and expressiveness.
- *Lack of presence*: Web conferencing sessions are often perceived as transactional video calls rather than shared learning spaces. Over time, this leads to reduced engagement and increased distraction.
- *Inactivity*: Interaction among participants remains minimal. Without deliberate intervention from instructors, students tend to assume passive roles with limited opportunities for active engagement.
- *Crude emotional expression*: Users have few means to convey affective states, relying mainly on text symbols or emojis, which limits emotional and social communication.

Using real-time, realistic 3D environments for educational purposes offers a potential pathway to overcome these limitations. Although considerable progress has been made in designing and implementing such environments, achieving experiences that fully replicate the cognitive, emotional, and social dynamics of in-person education remains an open challenge. The Metaverse, by its nature, appears as a promising solution: it provides an inherently immersive and interactive environment that fosters social exchange and supports the representation and manipulation of educational content in novel ways.

Research on educational Metaverse systems is still in its infancy. Further studies are needed to understand their pedagogical potential, address technical challenges, and define effective learning strategies. Nonetheless,

Dwivedi et al. [115] proposed a set of key guidelines that an educational Metaverse should fulfill:

1. **Replication of real-world learning environments:** An educational Metaverse should serve as a mirror world that reproduces the key dynamics of in-person learning. This involves not only recreating recognizable 3D spaces but also designing avatars with expressive and synchronized behaviors that reflect real human interactions.

2. **Extension beyond physical constraints:** The Metaverse should merge the benefits of face-to-face and online learning, offering experiences impossible to achieve in physical settings. Through simulation and visualization, students can explore complex phenomena and abstract concepts in an interactive 3D space.

3. **Pedagogical adaptation:** Instructors must revise teaching approaches and course structures to align with the affordances of the Metaverse. Effective instruction in immersive environments requires new digital competencies and an understanding of how spatial and social presence influence learning.

4. **Development of new assessment metrics:** Given the vast amount of behavioral and interaction data available in Metaverse platforms, educators should develop new indicators to evaluate learning outcomes and engagement. With appropriate privacy safeguards, data such as facial expressions, gaze patterns, and movement trajectories can provide meaningful insights into student experiences.

5. **Technological training and institutional support:** Educational institutions must invest in technological infrastructure and provide specific training to educators. The adoption of the Metaverse requires teachers to master new tools and integrate them into their pedagogical practices effectively.

In conclusion, the Metaverse offers a substantial advancement over traditional 2D distance learning systems, while also expanding the possibilities of in-person education. Through immersive 3D environments,

enhanced social presence, and embodied interaction, it allows for deeper engagement and new forms of experiential learning. Table 2.2 summarizes how the Metaverse can address the limitations of conventional online platforms. Although research in this area remains in its early stages and no single solution yet satisfies all identified requirements [229], the trajectory of ongoing developments suggests a promising future for educational applications of the Metaverse.

Table 2.2: Limitations of traditional 2D platforms and possible solutions in the Metaverse.

Limitations of 2D platforms	**Possible solutions offered by the Metaverse**
Low self-perception	Representation of oneself through customizable and real-time controllable avatars
No presence	Presence within an immersive 3D world, joining a collective environment where the perception of oneself and others in the space is immediate
Inactivity	Real-time social interactions and the ability to actively engage in educational activities, resulting in an immersive experience that maintains a high focus factor
Crude emotional expression	Greater expression possibilities through various interactions of the avatars, complete control over them, and the ability to give and receive immediate feedback among users

2.2 RELATED WORK

The scientific debate surrounding the metaverse has expanded rapidly in recent years, permeating domains as diverse as computer science, human–computer interaction, psychology, ethics, and education. This proliferation of studies, however, has not been matched by a corresponding consolidation of knowledge. Instead, existing contributions often appear fragmented, thematically dispersed, and anchored to disciplinary silos that

prevent the emergence of a unified and systematic understanding of the metaverse. From the perspective of software engineering, this fragmentation is particularly evident: while substantial technological advancements have been reported, the literature still lacks the theoretical and methodological foundations necessary to conceptualize, design, and evaluate metaverse systems as coherent socio-technical artefacts.

This section synthesizes prior work along two complementary dimensions that mirror the two major gaps addressed by this dissertation: (1) the need for **theoretical foundations** capable of framing the metaverse as a disciplined engineering object, and (2) the need for **engineered and empirical validation** effort aimed at operationalizing these foundations through systematic practices, particularly within educational environments, which constitute one of the richest application domains for studying metaverse dynamics.

2.2.1 *Theoretical Foundations for Metaverse Engineering*

First, a pervasive limitation emerging from the literature concerns the absence of shared theoretical foundations for defining and engineering the metaverse. Although several studies—such as those by Green et al. [142] and Almoqbel et al. [8]—attempt to map definitions, taxonomies, or enabling technologies, they reveal profound discrepancies in how the metaverse is conceptualized. These contributions often diverge on aspects as fundamental as its boundaries, its technological stack, or the role of its users. As a result, what should be a cohesive conceptual space becomes instead a constellation of partially overlapping interpretations, each offering valuable but isolated perspectives.

Beyond definitional ambiguity, a considerable strand of research investigates the metaverse through the lens of its ethical, psychological, and regulatory challenges. Studies such as those by Bale et al. [21] and Zhang et al. [359] highlight pressing issues related to user safety, accessibility barriers, discrimination risks, and the psychological implications of prolonged immersion. A parallel line of work, exemplified by Stark et al. [316],

Hernandez et al. [156], and Katirai [174], critically examines the adoption of emotion recognition technologies within immersive environments, pointing to unresolved ethical dilemmas involving privacy, informed consent, representation, and the handling of sensitive emotional data. While these studies provide essential warnings, they rarely connect such concerns to structured design principles or engineering processes capable of anticipating and mitigating them.

Similarly, contributions on enabling technologies—most notably blockchain—often remain technologically focused. Research by Nizamuddin et al. [238], Mozumder et al. [228], and Mourtzis et al. [227] demonstrates how immutability, decentralization, and smart contracts can support certification, trust, or traceability in educational contexts. Yet these works typically treat blockchain as a self-contained solution rather than as one component within a broader socio-technical architecture. As a consequence, they stop short of articulating how such capabilities should be systematically integrated into metaverse infrastructures—what interfaces they require, what constraints they impose, and how they interact with pedagogical, organizational, or regulatory requirements.

Taken together, these contributions highlight a critical gap: despite the wealth of isolated insights, the literature lacks a comprehensive socio-technical perspective that interprets the metaverse as an engineering object composed of interdependent technological, social, organizational, and ethical dimensions. In other words, although many works describe what the metaverse could be, very few attempt to explain *how* it should be built—in a principled, systematic, and methodologically sound manner. This gap constitutes the conceptual foundation of the present dissertation.

2.2.2 *Engineering and Empirical Validation for Educational Metaverse*

Education has rapidly emerged as one of the most fertile grounds for experimenting with metaverse technologies. In this domain, researchers have explored immersive learning, virtual campuses, collaborative classrooms, and simulation-based training. Yet, as with the theoretical literature, exist-

ing contributions tend to remain methodologically narrow, focusing on isolated functionalities rather than on comprehensive engineering workflows.

Early work frequently relied on third-party platforms such as Second Life, which offered immediate access to virtual spaces but limited flexibility for engineering structured educational scenarios. Studies by De Lucia et al. [94], August et al. [17], and Aydogan and Aras [18] illustrate how these environments enabled the creation of virtual campuses, lecture halls, and interactive laboratories. However, these platforms inherently constrained design choices and largely precluded a requirements-based approach to system engineering.

Subsequent research shifted toward bespoke metaverse environments developed from scratch. Works such as Duan et al. [112], Jovanović et al. [170], Shen et al. [304], and Sin et al. [307] propose diverse solutions—ranging from avatar-centric interaction to classroom replication and content sharing. While these systems showcase important technological capabilities, they generally emphasize one dimension (e.g., social presence, instructional content, or visualization) at the expense of others. Crucially, they stop short of adopting software engineering principles—such as requirements elicitation, architectural design, modularity, or validation—that are essential to constructing scalable and maintainable metaverse systems.

Parallel strands of research explore the role of virtual reality in software engineering education. Moreno-Lumbreras et al. [225] and Akbulut et al. [3] examine how immersive visualizations support understanding of development workflows and metrics. Gulec et al. [143] and Rodríguez et al. [291] investigate VR-based simulations for team dynamics and agile practices. Although these studies validate VR as an effective pedagogical medium, they concentrate almost exclusively on technical or procedural learning, overlooking socio-technical phenomena such as communication patterns, organizational structure, or community-related issues.

Complementary research focuses on the production of 3D environments through photogrammetry, computer vision, and automated modeling

pipelines. Foundational comparisons—such as those by Baltsavias [24], Thoeni et al. [326], and Buill et al. [57]—evaluate accuracy and feasibility of reconstruction methods, while recent works [1, 139, 281] explore their applicability to immersive platforms. Yet even here, methodological considerations remain primarily technical, with limited discussion of how such pipelines integrate into broader metaverse development workflows.

Overall, existing studies confirm the promise of metaverse technologies for education, but they still provide limited support for their systematic design, development, and empirical evaluation. Most contributions remain prototype-oriented, platform-dependent, or methodologically narrow, without offering engineering-oriented pathways for building reliable and evolvable educational metaverse systems. This dissertation addresses this limitation by introducing an engineered perspective grounded in structured development processes, concrete system realization, and empirical validation. Addressing this deficiency constitutes the central methodological trajectory of this dissertation.

PART II

THEORETICAL FOUNDATIONS

3

MACHINE LEARNING FOR EDUCATIONAL METAVERSE: HOW FAR ARE WE?

This chapter builds upon the paper published at the *International Conference on Consumer Electronics* (ICCE) [38], where the author of this thesis was the main contributor. The content reported in this chapter strictly follows the original publication.

Connection with Chapters

Grounded in the background and related works introduced in the previous chapter, this chapter offers a preliminary discussion of the role of AI-based techniques in the educational metaverse, outlining their potential while also reflecting on the risks and open issues that still characterize their adoption.

3.1 INTRODUCTION

Consumer technology refers to the definition of any kind of novel technology usable by a large variety of users [236]. While several notable advances have been proposed in the last decades, one of the next frontiers is represented by the use of *Metaverse*. In particular, the concept of the metaverse builds upon the idea of having a persistent, online 3D universe where people from all around the world can interact, socialize, and work toward common goals. Major companies, e.g., META believe that the metaverse will be the largest technological revolution since the advent of the Internet and, for this reason, they are investing billions of dollars in the creation of instruments that can effectively enable the metaverse.

The advances made in research fields like virtual/augmented reality, software engineering, and artificial intelligence, the availability of com-

putational resources, along with the rise of social distancing due to the COVID-19 pandemic have further accelerated the technological transition, especially in contexts where people need to develop their own skills and personalities through learning, engagement, and socialization [229].

Education represents a *unique* use case because today's students are digital natives, having new attitudes toward the learning process, different learning styles, and higher expectations for teaching and learning [180]. For this reason, the metaverse would not limit itself to the presentation of an exact digital replication of the surrounding educational world, but would also empower it from multiple perspectives, providing novel learning instruments enabled by the digital environment, social and psychological monitoring systems based on student's activities and, perhaps more importantly, lowering the architectural barriers for students with disabilities. In addition, metaverse may potentially help mitigate logistic issues and reduce didactic costs, thereby positively contributing to environmental and economic sustainability.

Despite these promises, little is known about the development of new consumer technologies for education metaverses. Machine learning techniques will represent a key component, as these may enable online participation of students, other than increasing user engagement and experience.

In this paper, we aim at conducting the first step toward the definition of new machine-learning techniques for educational metaverses. We first overview the current research on the matter and then discuss limitations and further research opportunities to build an effective education metaverse.

3.2 MACHINE LEARNING IN EDUCATIONAL METAVERSE

The metaverse can build secure, scalable, and realistic virtual worlds on a reliable and always-on platform by combining AI with other technologies such as AR/VR, blockchain, and networking. Several **Machine Learning** (ML) and **Deep Learning** (DL) algorithms have been implemented from two perspectives. The first relates to the metaverse infrastructure, which

includes the use of ML techniques in 5G systems and upcoming 6G systems to handle a variety of difficult tasks, including automatic resource allocation, traffic offloading, attack prevention, and network failure detection. The second concerns the human-relational perspective, in which simple human movements and complex actions can be analyzed and recognized using wearable technology based on sensors and other devices. As a result, users' physical movements are translated into actions in virtual worlds, giving them complete control over how their avatars interact with other objects in the metaverse. In addition, these avatars can interact with various real-world modalities, including speech recognition and dynamic analysis, which are supported by artificial intelligence in terms of accuracy and processing speed. These modalities include facial expressions, emotions, body movements, and physical interactions. The state of art related to machine learning and deep learning highlights some methodologies that can be included within the metaverse. In fact, Huynh-The et al. [162] have considered the main technical aspects and algorithms of ML and DL and how they improve user experience in the virtual world, by highlighting two approaches: Machine Vision and Neural Interfaces.

MACHINE VISION is a technology that allows machines to visually understand their surroundings by using one or more vision sensors in combination with application-specific software. While machine vision itself can solve a number of problems in many engineering fields, it is often used in combination with machine learning methods to make manufacturing smarts. In fact, the raw data perceived from visual environments may be captured and processed to infer higher-level information, which can be then displayed to users via head-mounted devices or any other intelligent devices.

THE NEURAL INTERFACE aims to further reduce the gap between the physical and digital worlds. In fact, virtual reality employs some physical devices (e.g., keyboards, mouse, headsets, and visor controllers) as devices to control the virtual world. Through the use of neural interfaces and machine learning algorithms, it is possible to increasingly

reduce the adoption of physical devices and have direct contact through neural impulses *a.k.a. Brain Machine Interfaces* (BMI). Many BMIs use external electrodes or optical sensors that are attached to the skull and other parts of the human body to detect neural signals. BMIs can manipulate thoughts with transcranial electromagnetic pulses, exploiting these noninvasive devices, which can only read and control minds on a rudimentary level.

3.3 LIMITATIONS AND RESEARCH OPPORTUNITIES

ML AND METAVERSE: THE TECHNICAL SIDE. Current machine and deep learning approaches are not tailored to the dynamics of the metaverse. This aspect makes their employment within an educational metaverse a critical challenge to address. While machine vision offers great potential, researchers should further analyze the way it can be as effective as possible in the context of a metaverse. Indeed, the specific environmental conditions characterizing the educational context, e.g., the continuous interaction between teachers and students and among students, represent novel perspectives that should be taken into account when defining novel machine vision instruments that may support those new conditions. In this sense, we envision new empirical investigations into the needs that should be fulfilled by machine vision approaches applied to the metaverse, other than the definition of new techniques tailored to those needs.

Furthermore, access to the metaverse is typically allowed through neural interfaces, which are known to produce negative physical effects in certain circumstances. For instance, VR/MR headsets can cause headaches, and eye strain is worn for an extended period of time. Previous literature has already attempted to mitigate these effects: as a matter of fact, various machine-learning algorithms have been employed to optimize images so that the sense of visual fatigue is reduced. Nonetheless, the educational context would require the durable use of neural interfaces, e.g., high-school students may need to wear VR/MR headsets for an

extended time period on a daily basis. This leads to major challenges for researchers working in the context of neural interfaces, who are called to investigate further this matter and possibly propose alternative interfaces that limit the negative effects that these may have on health.

ML AND METAVERSE: THE PSYCHOLOGICAL SIDE. Further challenges relate to psychological concerns. An educational metaverse intrinsically implements the concept of social distancing, possibly forcing students and teachers to be isolated. This aspect may lead to psychological issues, including depression, as we witnessed too often in the news during the pandemic. On the one hand, this perspective cannot be ignored by machine learning experts: novel neural interface and machine vision techniques should be devised and assessed to take their impact on psychological properties into account: for instance, we envision notable advances in the field of emotion recognition, where techniques able to identify psychological stress and depression could be used to alert the teacher or even inform machine vision techniques and allow to adapt themselves to recommend when to take a break. On the other hand, further empirical research is needed to understand the natural limitations of the metaverse, possibly leading to improved knowledge on when and how to use the metaverse for education and when, instead, a physical interaction would be preferred.

ML AND METAVERSE: THE SOCIAL SIDE. Last but not least, it is important to remark that the currently available neural interfaces may be expensive and out of reach for most users. While this mainly pertains to hardware engineers, some considerations can be drawn on the software side as well. First, little is known about the best mechanisms to enter the metaverse. Neural interfaces can indeed provide an immersive experience, yet the amount of empirical studies targeting human-computer interaction aspects within the metaverse is still limited. As such, we envision a number of additional works along this line of research in order to define the best instruments and ways to engage with the metaverse. Perhaps more importantly, several factors (e.g., learners' knowledge levels,

cognitive styles, preferences, motivations, self-efficacy and regulation, and learning attitudes) could affect the acceptance and performance of new technology from learners and teachers. In this sense, the metaverse is a brand new concept in education, and, for this reason, it requires further empirical research to understand how different learners interact and progress in metaverse-based educational experiences, how they can be continuously advised with immediate personalized feedback, and whether they benefit from metaverse-based experiences.

4

ANOTHER BRICK IN THE WALL: A SYSTEMATIC MAPPING STUDY TOWARD DEFINING METAVERSE ENGINEERING THROUGH SOCIO-TECHNICAL ISSUES

This chapter builds upon the paper published at *Computing Surveys* (CSUR) [102], where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the preliminary AI-oriented perspective discussed in Chapter 3, this chapter broadens the analysis by situating the metaverse within a wider socio-technical framework, thereby providing the conceptual basis for the notion of metaverse engineering.

4.1 INTRODUCTION

The concept of *"metaverse"* has generated significant interest as a frontier in internet evolution [229], merging technologies like virtual reality (VR), augmented reality (AR), and digital computing [233]. Within this shared virtual space, users engage in activities such as socializing, gaming, working, and learning, blurring the lines between the physical and digital worlds [101, 112, 190, 274, 321]. As a potential internet evolution, the metaverse opens new possibilities for communication, collaboration, and entertainment [93, 115]. Major tech companies are heavily investing in this space. For instance, META (formerly FACEBOOK) rebranded to emphasize its focus on the metaverse, while companies like NVIDIA, MICROSOFT, APPLE, and SONY have collectively invested over $18 billion to further their ambitions in this emerging field [90].

Unfortunately, such technological advances do not come for free. The metaverse has been shown to impact mental and psychological well-being, as spending more time in virtual environments may reduce face-to-face interactions, negatively affecting mental health and relationships [38, 243, 305]. Its immersive nature could blur the lines between reality and virtuality, leading to addiction, isolation, and detachment from real-world experiences [245]. In addition, the metaverse may exacerbate socioeconomic disparities, as access may be restricted to those who can afford the necessary technology, further widening gaps in education, employment, and social connections [50, 320, 354].

To deal with these critical challenges to the widespread diffusion of the metaverse, we argue for the definition of a brand new discipline: **"metaverse engineering"**. We envision this discipline as *inherently multidisciplinary*, drawing upon expertise in virtual reality, artificial intelligence, human-computer interaction, and software engineering. Its goal is to create innovative processes and tools that balance the social and technical requirements of the metaverse, promoting fairness, equity, and sustainability. This paper provides the first step toward metaverse engineering, formalizing its **multi-disciplinary** and **socio-technical** nature. We first give an overview of the *current status of metaverse research*, identifying key expertise areas and publication venues. Then, we define a comprehensive catalog of *socio-technical issues* impacting metaverse development. These issues require collaboration across disciplines to ensure both social and technical aspects are adequately addressed. To meet these objectives, we conducted a systematic mapping study following established guidelines [182], synthesizing the current knowledge base.

The rationale behind using this research method stems from the current state of the body of knowledge. Research has advanced in areas such as (1) immersive concerns [110, 210, 263, 292], (2) virtual environments [210, 359], and (3) the mental and psychological impact of the metaverse [21, 47, 51, 89]. However, these diverse insights have not yet been fully synthesized or applied to create an integrated research community or practical tools to address fundamental design challenges. By characterizing the **research**

community and defining key **socio-technical issues**, this paper aims to foster collaboration and serve as a resource for researchers in advancing metaverse engineering.

More specifically, our systematic mapping study identifies 63 primary resources from an initial pool of 2,323. The key findings show that the subject of the metaverse has been explored from multiple perspectives, touching areas related to computer vision, artificial intelligence, human-computer interaction, and software engineering. Furthermore, our work catalogs 19 social and 18 technical issues. Based on these results, we finally outline a research roadmap to metaverse engineering, describing how the identified issues might be addressed and the multidisciplinary efforts required. To sum up, this paper provides (1) a systematic overview of metaverse research, identifying key areas and publication venues to raise community awareness and foster interdisciplinary collaboration; (2) a taxonomy of socio-technical issues that can guide future research and inform practical implementation for the metaverse; (3) the introduction of the concept of "metaverse engineering" as a conceptual research asset that may integrate diverse expertise to address socio-technical issues in metaverse development; (4) a research roadmap outlining multidisciplinary effort and steps to tackle socio-technical challenges: (5) an online appendix [103] providing access to the material analyzed, supporting reproducibility, transparency, and collaboration within the research community.

4.2 RESEARCH METHOD

The *goal* of the study was to elicit the socio-technical issues to face when engineering a metaverse, with the *purpose* of letting emerge a set of social and technical properties that would be worth considering to make a metaverse more fair, equitable, and economically sustainable. The *perspective* is that of researchers and tool vendors. The former are interested in gathering insights into the key socio-technical aspects that affect the engineering of a metaverse and that may represent the next research avenues to pursue. The latter are interested in identifying the features whose inclusion in the

existing metaverse would make the user's experience more comfortable and safe. To reach the objective of our study, we conducted a Systematic Mapping Study (SMS) [182, 275, 347], that is, a rigorous research method aiming at collecting and synthesizing the existing body of knowledge available in the scientific literature with respect to the matter of interest, i.e., the socio-technical issues when engineering a metaverse in our case. To conduct our SMS, we followed the guidelines by Kitchenham et al. [182].

4.2.1 *Search Strategy*

Defining a search strategy is crucial for an SMS, as it ensures the completeness and accuracy of collected articles. It should include relevant keywords and descriptors, along with a careful selection of databases.

4.2.1.1 *Research Goals and Questions*

Our research questions ofstem from the metaverse's aim to blend physical reality with virtual reality, where physical reality comprises the tangible world governed by natural laws, and virtual reality offers an immersive, multi-dimensional experience beyond human senses [357]. This characteristic facilitates global connectivity through avatars, representing users in virtual environments. Consideration of avatars' appearance, surroundings, and interactions is crucial, as extensive research underscores their significant impact on individuals' sense of presence in virtual spaces [39, 40, 205]. Presence, once defined as the sensation of being in a virtual environment, now extends to "telepresence", reflecting the degree of connection individuals feel to virtual environments compared to physical ones [318]. Technology plays a pivotal role in creating presence, with the interface of the virtual world seamlessly integrating with engaging interactions, transforming it from a technological construct into a social entity [205]. Despite its potential, the metaverse faces multifaceted issues encompassing social and technical aspects, including issues related to cognition, emotion, and behavior [310]. Furthermore, its use of advanced technologies such as digital twins, blockchain, and Artificial Intelligence (AI) [203], alongside

various interaction methods like VR, AR, and MR with different devices [362], further complicates its development and implementation.

Based on these considerations, our goal was to identify, synthesize, and categorize the key challenges impacting the development of the metaverse while also outlining an engineering framework. Specifically, we formulated three central research questions that guide our investigation.

Our first research question ($\mathbf{RQ}_1$) represented a *preliminary, demographic* analysis into the research community around the metaverse. The goal of this analysis is twofold. On the one hand, it could provide an overview of the researchers involved and the connections among them, which are instrumental elements to characterize the multidisciplinary nature of metaverse engineering. On the other hand, it could analyze the publication landscape, identify venues where metaverse research is being disseminated, such as journals and conferences, and help researchers identify relevant outlets for their work. Following these arguments, we therefore asked:

> ***RQ1**: What is the current status of metaverse research in terms of **researchers involved** and **publication venues**?*

As a second step of our study, we aimed to identify the social issues arising when developing metaverses. The ultimate goal was to catalog the health, safety, and psychological aspects that metaverse researchers and tool vendors should consider when developing a metaverse. More particularly, we asked:

> ***RQ2**: What are the current **social issues** to consider when building a metaverse?*

Our last research question ($\mathbf{RQ}_3$) aimed at identifying the technical aspects concerned with the development of the metaverse. Even though the technology is evolving rapidly, it is crucial to determine which technologies—e.g., artificial intelligence, cloud computing, blockchain—can be used for the metaverse and what potential risks they may pose to users. As such, we formulated the following research question:

> ***RQ$_3$**: What are the current **technical issues** to consider when building a metaverse?*

4.2.1.2 *Identify Search Terms*

To define relevant search terms, we considered a variety of synonyms used in the literature for the metaverse. This step was crucial, especially in an emerging field like this one.

We proceeded by first drafting an initial set of synonyms for each of the key terms of our study:

- **Metaverse**: ("*metaverse*" OR "*virtual world*" OR "*cyberworld*" OR "*digital universe*" OR "*augmented reality*" OR "*multiverse*" OR "*alternate reality*" OR "*immersive environment*" OR "*virtual reality*" OR "*mixed reality*")
- **Issue**: ("*issue*" OR "*problems*" OR "*difficulty*" OR "*debate*" OR "*incident*" OR "*obstacles*" OR "*challenge*" OR "*strife*" OR "*opposition*" OR "*resistance*")
- **Social**: ("*social presence*" OR "*human interaction*" OR "*interaction*" OR "*communication*" OR "*collaboration*" OR "*cooperation*" OR "*engagement*" OR "*interpersonal aspect*" OR "*relational context*")
- **Technical**: ("*technological*" OR "*architecture*" OR "*engineering*" OR "*design*")

We experimented with a search string composed of the terms above. However, this yielded around 15,000 results, which were impractical to analyze manually. To improve precision, we adopted an alternative approach, selecting only the most relevant keywords. We employed the Delphi method [91], a structured process for synthesizing expert opinions. In general, the Delphi method involves two specific roles: *domain experts* and a *facilitator*. In our study, the domain experts were responsible for selecting relevant terms for the mapping study. At the same time, the

facilitator collected feedback from the experts and determined whether consensus had been reached or if additional rounds were needed. The first two authors acted as domain experts, as they have expertise in software engineering and specific experience in the metaverse domain, with low to medium years of seniority. The third author, although with limited experience in the metaverse, has many years of expertise in software engineering and research methods, and was therefore assigned the role of facilitator, managing the overall process and ensuring methodological consistency and rigor. At the end of each cycle, the facilitator aimed to reach consensus. In this regard, we relied on the work of Lilja et al. [200] and Okoli and Pawlowski [244], who highlight that the Delphi method does not define a fixed consensus threshold; instead, agreement levels typically range from 51% to 80%, depending on the study's objectives. In our case, the first round did not reach the minimum level of agreement, so a second round was conducted. During the second round, a satisfactory level of consensus was reached. We considered this result, supported by external references, a valid indicator of consensus.

After the Delphi cycles, some terms were removed because they were redundant or not distinct enough within the context of the metaverse and its social and technical challenges. For example, words like "obstacles" or "difficulty" were considered synonyms of concepts already represented in the final list, such as "issues" or "challenges". To validate the final set of keywords, we consulted four senior faculty members, each with over 20 years of experience in at least one of the following domains: virtual reality, human-computer interaction, artificial intelligence, and software engineering. They reviewed the identified terms and suggested no additional ones, confirming the soundness and completeness of the keywords generated by the Delphi method. For ethical purposes, it is important to remark that we submitted and received approval from the ethical board of our university. The final list of terms used was:

- **Metaverse**: ("*metaverse*" OR "*multiverse*" OR "*cyberworld*")
- **Issues**: ("*issue*" OR "*challenge*")

- **Social**: ("*social presence*" OR "*relational context*" OR "*communication*" OR "*collaboration*")
- **Technical**: ("*technological*" OR "*architecture*" OR "*engineering*" OR "*design*" OR "*develop*")

As a last step, we aggregated the terms above using logical operators, defining our final search query:

> ***Query**: (("metaverse" OR "multiverse" OR "cyberworld") AND ("issue*" OR "challenge*") AND ("social presence" OR "communication" OR "collaboration" OR "relation context") AND ("technological" OR "architecture" OR "engineer*" OR "design" OR "develop"))*

4.2.1.3 *Resources to be Searched*

We selected the *ACM Digital Library*,[1] *Scopus*,[2] *IEEE Xplore*,[3] *Web of Science*,[4] and *Springer Link*[5] as our search databases, focusing on computer science. We limited the search to this field for three reasons: computer science intersects with disciplines like psychology and sociology, it covers areas where technology and social science converge (e.g., human-computer interaction), and broadening the scope would have made the review impractical. Our goal was to catalog socio-technical issues relevant to *metaverse engineering*, which can be addressed using computer science methodologies.

4.2.2 *Article Selection Process*

Figure 4.1 overviews the steps conducted during the systematic process, highlighting how the number of primary studies evolved while executing the selection process.

[1] https://dl.acm.org
[2] https://www.scopus.com/search/form.uri?display=basic#basic
[3] https://ieeexplore.ieee.org/Xplore/dynhome.jsp?tag=1
[4] https://www.webofscience.com/wos/woscc/basic-search
[5] https://link.springer.com

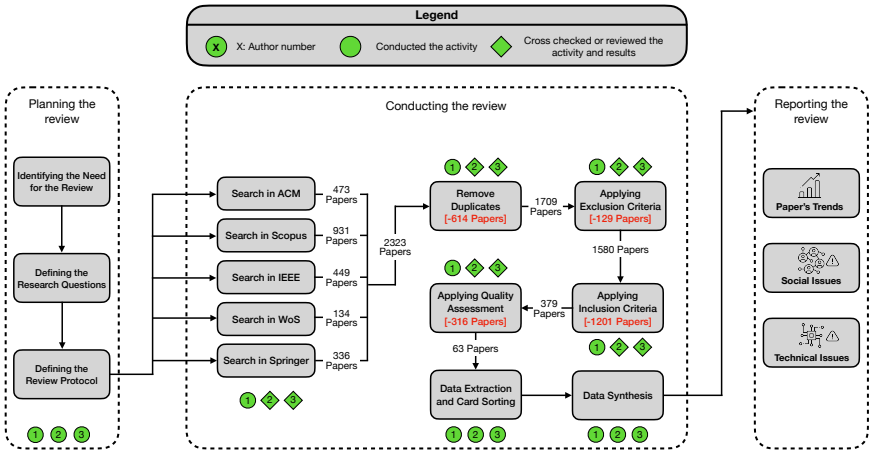


Figure 4.1: Research Overview of the Steps Conducted

4.2.2.1 *Inclusion and Exclusion Criteria*

The first step of the article selection process involved defining the inclusion and exclusion criteria to obtain useful papers that would answer the research questions.

Exclusion criteria: Primary studies that met the following criteria were *excluded* and discarded from the subsequent data extraction and analysis phases: (1) Articles that were not peer-reviewed; (2) Article that were not written in English; (3) Poster articles or similar; (4) Articles that were not available for free; (5) Articles that were not published between 1992 and 2024. Such a temporal criterion was established to gather all relevant papers published after the inception of the term "metaverse", which was indeed in 1992.

Inclusion Criteria: Primary studies that met the following criteria were *included* and used in the subsequent data extraction and analysis phases: (1) Articles reporting about *socially relevant issues* in the context of metaverse; (2) Articles reporting about *technically relevant issues* in the context of metaverse.

4.2.2.2 *Quality Assessment*

In addition to exclusion and inclusion criteria, we implemented a quality assessment procedure to ensure the selected studies were reliable and suitable.

For quantitative analysis, we used bibliometric filtering to exclude low-quality resources. We applied the *CORE Rank*[6] for conferences and the *Scimago Journal Rank*[7] (SJR) for journals, ensuring high-impact studies were selected.

For qualitative analysis, we followed the *ACM/SIGSOFT Empirical Standards*[8], acknowledging that venue metrics alone do not guarantee quality. We introduced additional criteria to assess each article's rigor, allowing for the inclusion of papers from lower-ranked venues if they met our qualitative standards.

After this filtering process, we assessed the suitability of the resulting papers using the following questions: 1 Does the paper clearly and exhaustively describe the method used to conduct the research?; 2 Does the paper discuss or describe possible limitations or threats to validity?; 3 Does the paper clearly define what the aim of the research is?.

The checklist evaluated the clarity and comprehensiveness of the primary studies, focusing on research methods, limitations, and objectives to ensure the selected studies were suitable for our research. To minimize ambiguity in linguistic nuances [214], we applied Zadeh's fuzzy logic [358], assigning values from 0 to 1 to capture varying levels of completeness in each study. Specifically, the questions of the checklist were evaluated based on a specific range: '*Yes*' with the maximum score of 1, '*Mostly*' with a range between $(0.7-0.9)$, '*Partially*' with a range $(0.4-0.6)$, '*Rarely*' with a range between $(0.1-0.3)$, and '*No*' with the lowest score of 0. Finally, we combined the scores for each quality criterion, and all articles with a final score between 1.7 and 3 were included in our analysis.

[6] http://portal.core.edu.au/conf-ranks/
[7] https://www.scimagojr.com
[8] https://acmsigsoft.github.io/EmpiricalStandards/docs/?standard=SystematicReviews

Table 4.1: Search results for each data source

Data Source	Query Execution	Without Duplicates	Exclusion Criteria	Inclusion Criteria	Quality Assessment
ACM Digital Library	473	364	339	64	11
Scopus	931	530	471	107	23
IEEE Xplore	449	425	408	154	13
Web Of Science	134	85	68	17	2
Springer Link	336	305	294	37	14
Total	**2323**	**1709**	**1580**	**379**	**63**

4.2.2.3 *Search Process Overview*

Table 4.1 summarizes how the number of primary studies evolved as a consequence of the various selection steps performed.

- **Query execution**: We executed the search string against the five databases, identifying a total of 2,323 articles. Afterward, we removed duplicate papers, i.e., those identified when running the search string against multiple databases. The first and second columns of Table 4.1 show the transition from the obtained set of papers to the set without considering duplicates.

- **Exclusion Criteria**: We applied the exclusion criteria to the articles retrieved from the query results. All the papers not satisfying at least one of the exclusion criteria from (1) to (5) shown in Section 4.2.2.1 were discarded. This step led to the exclusion of 129 papers out of the initial 2,323: 20 were excluded when applying exclusion criterion (2), 20 as a consequence of exclusion criterion (3), 82 because of exclusion criterion (4), and 7 after applying exclusion criterion (5). The remaining 1,580 primary studies were considered for the next stage.

- **Inclusion Criteria**: By reading title, keywords, and abstract, the inclusion criteria were verified on the set of 1,5890 primary studies

according to the checklist from ❶ and ❷. In borderline cases, the conclusion section was also assessed. As a result of this stage, 379 papers were considered for further assessment, while 1,201 primary studies were discarded.

- **Quality Assessment**: Each of the 379 papers was assessed in terms of publication venue and verified according to the checklist developed from [1] to [3] in Section 4.2.2.2. A final number of 63 papers were deemed eligible to address the research questions of the study.

The execution was mainly curated by the first author of the paper. All the phases were, however, monitored and verified by the other authors through weekly meetings.

4.2.3 *Data Extraction and Analysis*

Upon completion of the selection process, the 63 primary studies were read throughout in order to extract and analyze relevant data that might have addressed our research questions.

4.2.3.1 *Data Extraction*

For the data extraction process, we followed the guidelines proposed by Kitchenham et al. [182], which recommend systematically organizing information from the collected studies. Accordingly, we recorded each paper's title and assigned a unique identifier to it. We then extracted specific data items relevant to answering RQ_1, RQ_2, and RQ_3. For $\mathbf{RQ}_1$, we collected metadata, including the year of publication, author list, publication venue, ranking, and the source from which the paper was retrieved. For $\mathbf{RQ}_2$, we extracted social issues, while for $\mathbf{RQ}_3$, we focused on technical issues. This structured approach facilitated a consistent data representation and supported an efficient analysis. All the authors were primarily responsible for data extraction. Additionally, each author reviewed the results obtained by the others. In case of disagreement, they organized and participated in joint meetings to resolve the issues.

4.2.3.2 *Data Analysis*

To address our **RQ**s, we analyzed the data extracted in the previous step. Specifically, we computed descriptive statistics to address $\mathbf{RQ}_1$, focusing on the items of the data extraction form related to the metadata. In Section 4.3, we present charts, tables, and statistics that illustrate the distribution of these metadata elements across the primary studies. As for $\mathbf{RQ}_2$ and $\mathbf{RQ}_3$, we had to elicit, synthesize, and catalog the socio-technical issues discussed within the primary studies. To this end, we employed an *open card sorting* method [232], a commonly used qualitative research technique that facilitates the creation of mental models and the development of taxonomies from qualitative data. Such a technique has been employed in previous similar research aimed at eliciting properties from data [53, 155, 259].

The method involved all the authors of this paper (one Ph.D. Student and two Senior Researchers, respectively, with over 10 and 20 years of experience), who undertook this process to organize the social and technical issues that emerge in the metaverse. Specifically, we engaged in three iterative sessions, which are described below.

ITERATION 1: An initial set of 32 papers was selected. Two of the authors — from now on called *inspectors* — analyzed each of them independently. Their task was to review the content of each article and annotate the main issue(s) described, as well as whether these issues pertained to technical or social concerns. The inspectors were left free to manually annotate the identified issues or report them in a file. Once the inspectors had completed their individual assessments of the 32 papers, they scheduled a physical meeting to discuss the outcomes produced so far. For each paper, the inspectors compared their own judgments on the issues identified in an attempt to find a consensus on (i) the procedure employed to perform the elicitation task and (ii) the types and labels to assign to the identified issues. During the meeting, the third author of the article acted as the *external evaluator*, providing feedback on the choices made by the inspectors, suggesting possible improvements

on how the elicitation task was performed, and resolving possible disagreements between the inspectors. The meeting lasted around two hours. The inspectors could first refine their elicitation procedure by exchanging information on how to standardize the operations performed. More importantly, the inspectors obtained a *full agreement* on the issues identified in the 32 papers considered; most of the discussion revolved around the best labels to assign to the issues. The inspectors concluded the first iteration with a provisional taxonomy of the social and technical issues.

ITERATION 2: The initial 32 papers were reviewed and re-classified by the inspectors according to the decisions taken at the previous iteration. In addition, the inspectors repeated the elicitation task on the remaining 31 papers; however, this time they classified the issues identified using the provisional taxonomy that had been generated as an output of the previous iteration. The purpose of this phase was twofold. First, to assess the reliability of the provisional taxonomy, they could use it as a starting point to classify new issues and determine whether existing categories should be merged or redefined. Second, to identify new categories that did not previously emerge. At the end of the task, the inspectors held another physical meeting of approximately two hours, with the involvement of the external evaluator. The inspectors individually summarized the operations performed to assess their consistency with respect to the feedback received in the first iteration. Then, they discussed the types and categories of issues identified. During the discussion, they agreed to introduce a new category concerned with technical issues, while leaving the social ones unchanged. The output of this iteration was a final taxonomy of social and technical issues.

ITERATION 3: In the final stage, the two inspectors performed a double-check of the operations performed. More specifically, they went through each of the 63 papers previously considered, verifying the consistency of the classifications reported. The inspectors agreed that, in case of inconsistencies, a new round of discussion should have been opened. Nonetheless, they did not identify inconsistencies.

ADDITIONAL VALIDATION: While the third iteration confirmed the consistency of the classification process, an additional validation step was conducted to further ensure the reliability of the final taxonomy. Specifically, the third author — who had previously served as an external evaluator — independently reviewed all 63 papers and performed a comprehensive annotation of the issues, using the taxonomy defined in previous iterations. In total, 311 issues were identified across the 63 papers, of which 140 were categorized as social and 171 as technical issues. This step confirmed the exhaustiveness of the taxonomy, as no new categories were added. However, seven minor cases of misalignment between the third evaluator and the previous classification emerged. These disagreements were discussed by the first two evaluators until consensus was reached. To quantify the overall inter-rated agreements of the categorization process, we computed Krippendorff's α [186], obtaining a value of 0.89, which indicates almost perfect agreement.

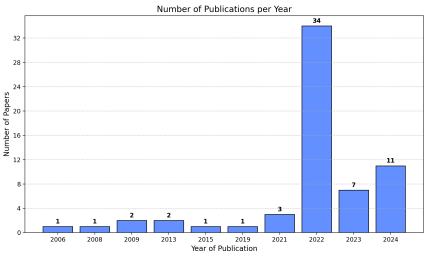
After these iterations, the taxonomy of social and technical issues was confirmed as final, and the card sorting process was concluded. The taxonomy of social and technical issues represents the main outcome of the study. It is organized as a hierarchical taxonomy composed of three layers. In Section 4.3, we firstly address $\mathbf{RQ}_1$, then we address $\mathbf{RQ}_2$, and $\mathbf{RQ}_3$ by discussing the specific issues identified by the card sorting method.

4.3 ANALYSIS OF THE RESULTS

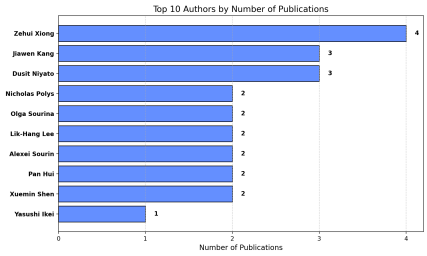
In the following section, we describe the results achieved for each research question.

4.3.1 *RQ_1: What is the Current Status of Metaverse Research in Terms of Researchers Involved and Publication Venues?*

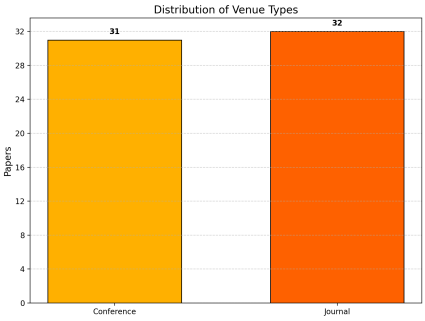
This section outlines the state of metaverse research, highlighting trends, methods, and progress across fields.



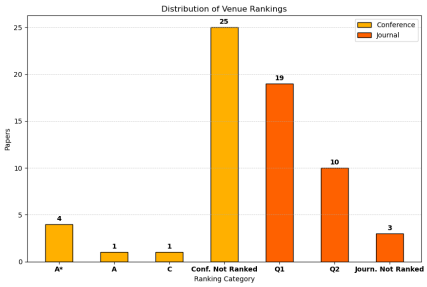
(a) Papers About Metaverse Socio-Technical Issues Over Time.



(b) Top-10 Authors with Socio-Technical Issues Publication



(c) Distribution Conference vs. Journals



(d) Rank Distribution for Conferences and Journals

Figure 4.2: Some statistics about identified studies.

4.3.1.1 *Evolution of the Discipline Over Time.*

While the term metaverse first appeared in 1992, the technology at the time was insufficient to support the concept. Over the years, with the rise of virtual reality, the metaverse has gained traction and become an increasingly relevant topic of interest. Figure 4.2a illustrates the publication trends regarding the metaverse, which can be divided into three key clusters. The first cluster spans from 2006 to 2009, during which an initial exploration of the social and technical issues associated with the metaverse took place. At this stage, the technology was not yet well established; it was still viewed as more of a theoretical concept rather than a practical solution. The second cluster, covering the years from 2013 to 2015, reflects a similar focus on the issues surrounding the metaverse. Although interest persisted, the technology had not yet developed to a point where it could

be considered feasible for widespread use. In contrast, the third cluster, which spans from 2019 to 2024, exhibits a notable increase in interest from the scientific community. This growth can be attributed to several factors. First, there was a significant advancement in virtual reality technologies, including the commercial availability of early HTC headsets. Second, the COVID-19 pandemic created new challenges that highlighted the need for virtual interactions. Finally, Mark Zuckerberg's announcement in late 2021 about rebranding FACEBOOK to META generated considerable excitement and investment in the metaverse. Overall, this progression indicates a shift from initial curiosity to robust and ongoing exploration of the metaverse's potential.

4.3.1.2 *Authors and Research Communities.*

With a total of 266 authors, a diverse range of contributors explores this emerging technology. Among them, some authors distinguish themselves with a significantly higher number of publications; therefore, in Figure 4.2b, we report the top 10 authors based on their contributions to metaverse-related socio-technical issues. Notably, *Zehui Xiong* has the largest number of publications, with 4, followed by *Jiawen Kang* and *Dusit Niyato*, each with 3 publications. *Nicholas Polys*, *Olga Sourina*, *Lik-Hang Lee*, *Alexei Sourin*, *Pan Hui*, and *Xuemin Shen* each have 2 publications, while the remaining authors, such as *Yasushi Ikei*, have contributed with one.

Although the metaverse is a relatively new topic, it attracts diverse research communities. Our analysis reveals that this broad interest stems from both its technological novelty and the potential for various fields to contribute actively.

The most engaged communities include *Human-Computer Interaction* and *Virtual Reality*, which are expected areas given the complexities of interaction in virtual environments. Following these are communities focused on *Software Security* and *Cloud Computing*, working to ensure the metaverse's safety through encryption algorithms, even in a hypothetical cloud-based metaverse. Lastly, communities such as *Artificial Intelligence*,

IoT, *Health*, and *Computer Science Education* also play crucial roles in this diverse research landscape.

However, it is notable that the software engineering community is not yet represented in the publications related to the metaverse. This absence highlights a critical gap in the research, as software engineering principles are essential for connecting all the research communities and developing robust and scalable metaverse applications, leading to the establishment of metaverse engineering. By doing so, we aim to raise greater awareness of the various aspects that the metaverse may encompass, and how to design and implement multidisciplinary solutions within this innovative space.

4.3.1.3 *Venue and Rank.*

Figure 4.2c illustrates the distribution of the 63 studies included in our analysis: 31 were published at conferences, while 32 were published in journals. This distribution indicates that the communities interested in the metaverse publish in both formats, with a slight preference for journals over conferences. Although the difference is minor, the trend suggests growing interest and a likely rise in publications.

Even more interesting is the rank distribution of the various conferences and journals. The results shown in Figure 4.2d indicate that, in addition to favoring journals over other publication types, researchers tend to prioritize top journals ranked as Q1, with 19 papers, and Q2 with 10 papers, according to the SJR indicator. Among the Q1 journals are multidisciplinary titles such as the *International Journal of Human Computer Studies* and *ACM Computing Surveys*, while Q2 includes journals like *Virtual Reality* and *Transactions on Emerging Telecommunications Technologies*. It is worth noting that only three of them are not ranked, indicating they are likely new emerging journals.

On the conference side, four publications took place at A* conferences such as the *CHI Conference on Human Factors in Computing Systems*, while only one was at an A-level conference, the *ACM Internet Measurement Conference*, and one at a C-level conference. A key finding is that 25

publications were presented at non-ranked conferences, indicating that many metaverse studies are submitted to venues not yet recognized by the CORE indicator. A key point is that only one conference, the *International Conference on Intelligent Metaverse Technologies & Applications* (iMETA), is dedicated to the metaverse, highlighting a gap in venues for metaverse research. Given its complexity and interdisciplinary nature, there is a need for more conferences and journals focused on this topic. Such venues would increase visibility, foster community building, and address emerging challenges related to interaction, immersion, and socio-technical issues.

4.3.2 *RQ_2: What are the Current Social Issues in the Metaverse?*

Our goal was to highlight the most critical social issues that the metaverse needs to address. The findings, shown in Figure 4.3, categorize these issues into five key areas: *Interaction and Engagement*, *Accessibility and Inclusivity*, *Privacy and Security*, *Social Norms and Ethics*, and *Mental Health and Well-Being*. Each of these key areas includes multiple categories, which in turn may contain several subcategories.

4.3.2.1 *Interaction and Engagement*

The first category concerns interaction and engagement, covering interface usability, virtual interaction quality, and methods to sustain user immersion.

AVATAR REPRESENTATION AND PERCEPTION. The representation and perception of avatars significantly influence interaction and engagement in virtual environments, affecting issues such as gender identity, privacy, mental health, and addiction. Ensuring equal access to avatar representation and customization in every aspect, such as gender and voice customization, can promote inclusivity, foster a more engaged community, and help reduce social disparities [73, 82, 112, 257, 330]. However, this opportunity can also encourage cultural appropriation, a

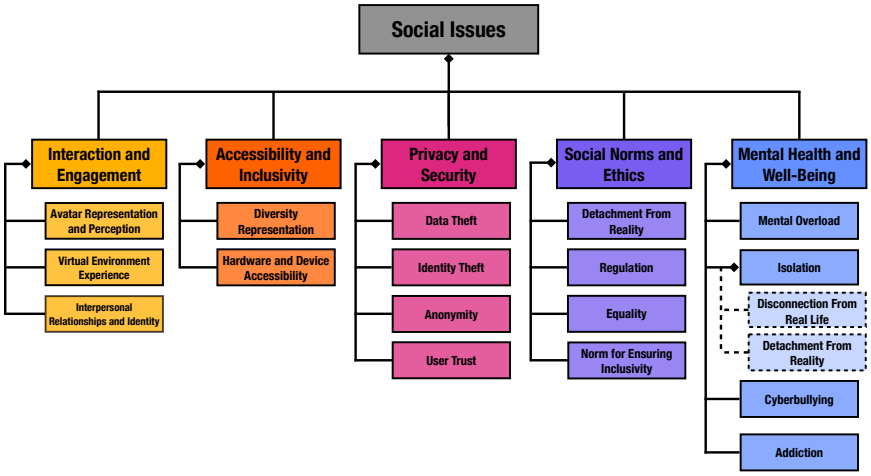


Figure 4.3: Social Issues Taxonomy for the Metaverse – Each social issue is represented using the *IBM Palette Library* for color blindness, with different opacity levels indicating the membership of sublevels within their parent categories. Multiple memberships within the same category are also represented using dashed lines.

phenomenon where elements of one group's culture are adopted by another in a disrespectful or unauthorized manner, leading to insensitivity and racism, with negative consequences for interaction and engagement [98, 179, 252]. Additionally, the discrepancy between one's real identity and the idealized identity of avatars can cause psychological stress, exacerbating issues related to mental health and addiction [256]. For this reason, there is a need for balancing the anonymity that avatar customization could provide with the accountability of the person behind the avatar [60]. Indeed, the enhancement of avatar quality is one of the most critical issues that must be addressed for social interaction [78], but without causing confusion between real and virtual identities [360].

VIRTUAL ENVIRONMENT EXPERIENCE. One of the critical aspects to consider is presence and immersion, meaning the extent to which a user feels present and immersed in the virtual environment [111]. Currently, virtual environments suffer from a significant problem: the lack of a unified metaverse. This leads to the existence of numerous virtual

environments [82], each with a specific purpose but developed with low immersivity [282] and without promoting social interaction and conversation [279]. A critical consideration is connecting multiple virtual environments, creating smooth transitions between them, and ensuring each virtual environment incorporates inclusive design aspects, considering gender-sensitive design elements — e.g., public spaces, virtual buildings, or safe zones where users can report harassment to find support [322]. Additionally, a high level of satisfaction in using graphical interfaces is necessary [81]. Among the various virtual environments, many are related to education. Still, they lack educational approaches that maximize interaction dynamics, leading to low engagement compared to current 2D tool strategies [73, 248, 282].

INTERPERSONAL RELATIONSHIP AND IDENTITY. The interaction between virtual and real experiences significantly impacts interpersonal relationships and identity. Communication difficulties in virtual spaces, such as the lack of non-verbal cues, contribute to potential misunderstandings and increasing complexity between users and avatars [175]. This highlights the need for more intuitive communication methods that mimic real-world interactions [279], which can significantly reduce interpersonal issues related to the authenticity of interactions [93, 111]. Additionally, excessive engagement in the metaverse can blur the line between virtual and real life, potentially compromising users' sense of personal identity [74, 149].

4.3.2.2 *Accessibility and Inclusivity*

This category focuses on metaverse accessibility, ensuring assistive technologies, affordable hardware, and an inclusive environment for diverse user needs.

DIVERSITY REPRESENTATION. One significant social issue that demands considerable attention is the lack of diversity representation in virtual environments. To address this, it is crucial to develop strategies that promote the active involvement of users from diverse backgrounds

and consider gender differences [322]. Embracing practices that enable accurate and realistic 3D representation of individuals, both in terms of physical appearance and gender [93, 130], is essential to achieving enhanced interaction, fostering collaboration, and strengthening social connections [81, 251].

HARDWARE AND DEVICE ACCESSIBILITY. Promoting digital and social inclusivity requires ensuring accessibility to hardware and devices. Inclusive hardware design incorporates tactile feedback and adjustable interfaces to promote independence and productivity for individuals with disabilities. These designs should also be continually refined and updated [66, 350]. In addition, essential assistive technologies like screen readers and voice recognition must be both accessible and affordable for all potential applications in the metaverse [74], eliminating barriers to professional growth and career advancement [144].

4.3.2.3 *Privacy and Security*

This category deals with the issues of safeguarding user privacy and ensuring security within the metaverse, including data protection, secure interactions, and the prevention of unauthorized accesses.

DATA THEFT. Data theft poses significant social issues intertwined with misuse, deception, security concerns, privacy issues, and cyber threats. Data protection and privacy within the metaverse are crucial, as personal information is vulnerable to misuse, necessitating stringent privacy regulations [350]. Indeed, virtual environments have already presented constant threats of harassment, financial theft, fraud, and identity theft, compromising users' privacy and security [74, 224, 327]. The primary cause of these problems can be attributed to various factors, including the use of wearable devices [264] and the potential for improperly customizing and manipulating personal characteristics such as voice representation [60]. Consequently, the metaverse has significant gaps in terms of the manipulation of data within the metaverse [66] and how this data is collected, stored, and used [144].

IDENTITY THEFT. One of the critical areas is the security issues of wearable devices, which store sensitive personal identity data. Although failures or compromise of these devices could lead to leakage of identity information, the use of biometric authentication is an excellent alternative to reduce risks related to identity theft [74]. However, privacy concerns related to biometric data are still significant, as the use of biometric authentication methods, while enhancing security, raises substantial privacy issues. Safeguarding biometric data from misuse is essential to maintaining users' trust and privacy in the digital realm [327]. In addition, identity hacking threatens the security and authenticity of users' identities in the metaverse and is, therefore, a vital area of concern [26]. Finally, intrusion of privacy and identity theft due to a false sense of security often leads to excessive sharing of personal information. This over-sharing, combined with a lack of real constraints, makes individuals vulnerable to identity theft [123].

ANONYMITY. Anonymity is one of the issues that most stem from our days and the misuse of platforms such as Instagram, Facebook, and others. As a social problem, anonymity has several significant consequences that affect individuals and the community. A primary concern is the erosion of personal accountability, where individuals, protected by the cloak of anonymity, may enact behaviors that they would otherwise avoid if their identity were known. This lack of accountability can lead to an increase in cases of cyberbullying and online harassment as perpetrators feel encouraged by their perceived invisibility [334]. Anonymity can foster misinformation by obscuring sources and complicating verification [360].

USER TRUST. User trust is vital for social dynamics, impacting critical areas such as safety, privacy, control, and communication. The foundation of trust lies in ensuring the safeguarding of user information and interactions [327]. This is closely intertwined with upholding privacy, as users anticipate their data to be handled securely and transparently [279]. Furthermore, the perception of control is paramount; users should

feel empowered to control their data and the content they engage with [364]. Clear and honest communication facilitates the alignment of user expectations with actual experiences and strengthens trust [112].

4.3.2.4 *Social Norms and Ethics*

This category concerns establishing social norms and ethics in the metaverse to ensure respectful, safe, and inclusive interactions.

DETACHMENT FROM REALITY. The metaverse presents a range of social and ethical issues related to social norms. The lack of adequate control and regulation creates a fertile ground for abusive behaviors and illegal activities, such as privacy violations and cyberbullying [74]. Social norms that regulate human behavior in the real world are not easily applicable in the metaverse, causing users a sense of anarchy and insecurity [334]. Furthermore, how individuals represent themselves in the metaverse can lead to issues of identity and authenticity, creating dissonance between virtual and real identities [243]. Finally, constant immersion in the metaverse can have adverse effects on users' mental and social health, leading to isolation, addiction, and alienation from reality [149]. Therefore, developing clear rules and regulations to address these issues and ensure a safe and inclusive virtual environment is crucial.

REGULATION. The metaverse introduces numerous regulatory issues that remain unresolved. Effective governance mechanisms are needed to address virtual crimes and AI ethics, while robust community management practices are essential for maintaining a safe and respectful virtual space [198, 338]. As such, legal and ethical complexities arise in regulating virtual economies, with particular attention needed for content moderation, censorship, and misinformation [26, 66]. Avoiding spreading false information is a significant concern in less controlled environments, highlighting the importance of digital citizenship education and ethical guidelines [334]. By emphasizing the importance of these measures, the audience will feel a sense of responsibility and commitment to maintaining a safe virtual space. Understanding the impact of

virtual assets and digital identities on the digital economy, along with establishing fair digital currency systems, is crucial for seamless transactions and positive community in the metaverse [118, 353].

EQUALITY. The equality theme in the metaverse presents several significant issues that require attention to ensure a fair and inclusive virtual environment. Economic and political constraints play a critical role in the development and accessibility of the metaverse. These constraints can limit its growth and hinder the equitable distribution of benefits, making it crucial to navigate these factors carefully [327]. Additionally, understanding the impact of virtual currency and incentivized activities on user behavior is vital. By developing economic models that encourage positive participation, the metaverse can foster an inclusive environment that supports diverse social dynamics [198]. Moreover, ethical and moral challenges arise from the diverse ideologies and worldviews present in the metaverse, which can lead to potential conflicts. Establishing a well-organized metaverse with clear rules and ecosystems is essential to managing these challenges effectively and promoting equality [360].

NORM FOR ENSURING INCLUSIVITY. Respecting cultural differences, fostering gender inclusivity, and ensuring accessibility for all individuals, regardless of physical or mental abilities, are essential guidelines for promoting equity and acceptance within diverse social settings. Emphasizing these aspects can reduce social disparities and foster environments where everyone feels valued and included. Implementing such practices enables organizations and communities to build a more just and cohesive society, reflecting core principles of human rights and dignity [93, 144, 175].

4.3.2.5 *Mental Health and Well-Being*

This category focuses on the issues related to the mental health and well-being, including managing screen time, preventing addiction, and supporting users facing negative psychological effects.

MENTAL OVERLOAD. The immersive nature of the metaverse can lead to an overwhelming amount of information, causing users to experience increased stress and cognitive strain. Navigating complex virtual environments and managing virtual and physical responsibilities can violate personal space and privacy, significantly impacting user experiences and well-being. Furthermore, the constructed realities within the metaverse may reinforce or exacerbate existing cognitive biases, further complicating users' mental processing and decision-making abilities [251, 334].

ISOLATION. The rise of virtual interactions may affect traditional socializing, potentially increasing isolation [95, 144]. The balance between virtual and real social connections is essential to mitigate feelings of loneliness and psychological distress [167]. A clear example comes from the COVID-19 pandemic, in which distance learning and virtual engagements exacerbated isolation among individuals, contributing to anxiety and reduced community engagement [248]. As shown in Figure 4.3, this category can be split into two subcategories, i.e., *Disconnection from Real Life* and *Detachment From Reality*. Although the two sub-categories seem to have the same meaning, disconnection is typically associated with problems where users neglect or isolate themselves from real-world responsibilities and interactions [19, 167]. This issue often occurs during the transition between virtual and real environments, where users prioritize their digital lives over real interactions [260], leading to a devaluation of real-world experiences [365]. Unfortunately, disconnection can lead to detachments, making it harder to differentiate between the physical and digital worlds [19], especially with prolonged interactions with NPCs—mimicking real-life identities [256]—which can cause confusion and disorientation [334].

CYBERBULLYING. It is a growing concern, reflecting aggressive and intentional acts carried out through virtual platforms. This form of bullying often overlaps with traditional bullying but is potentially exacerbated by the anonymity provided online [123, 283]. Cyberbullying in the meta-

verse involves persistent harassment, which can have severe psychological effects on victims due to the immersive and pervasive nature of virtual environments [123]. The issue is compounded by the ethical dilemmas posed by AI-driven content and interactions, which can sometimes unintentionally contribute to the spread of harmful behavior [338]. Addressing cyberbullying requires a comprehensive approach that includes technological, ethical, and social interventions to create safer virtual spaces.

ADDICTION. The rise of the metaverse has also raised significant concerns about addiction. This immersive environment can lead to excessive use, causing users to neglect real-world responsibilities and experience social isolation and mental health issues [327, 355]. The appeal of the metaverse often exacerbates feelings of loneliness and anxiety as some users become more comfortable in the virtual world, which in turn hinders their real-life social skills and relationships [167]. Based on this, virtual environment companies can exploit users' addictive behaviors through transactions and the sale of virtual goods, potentially leading to financial strain for those who cannot control their spending [334]. Addressing these interconnected issues requires a comprehensive approach, including responsible design practices by developers, mental health support for users, and public awareness campaigns to mitigate the negative impacts on individuals and society [360].

4.3.3 *RQ_3: What are the Current Technical Issues in Metaverse?*

In ***RQ_3***, our goal was to highlight the most critical technical issues that the metaverse needs to address. The findings, shown in Figure 4.4, categorize these issues into five key areas: *Environment Infrastructure*, *Privacy and Security*, *Interaction and Usability*, *Communication and Network*, and *Rendering and Visualization*. Each of these key areas includes multiple categories, which in turn may contain several subcategories. While these subcategories may appear to address similar topics, they are intended to highlight different dimensions and nuances within the broader category.

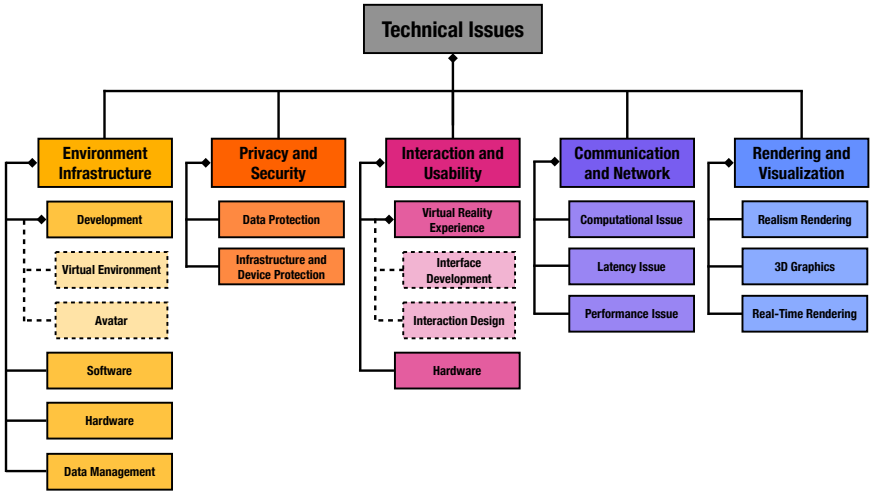


Figure 4.4: Technical Issues Taxonomy for the Metaverse – Each technical issue is represented using the *IBM Palette Library* for color blindness, with different opacity levels indicating the membership of sublevels within their parent categories. Multiple memberships within the same category are also represented using dashed lines.

As a result, these subcategories provide valuable insights into where research and the scientific community should focus their efforts to enhance the overall category. The following sections describe the specific categories identified in our work.

4.3.3.1 *Environment Infrastructure*

This category addresses the issues related to the infrastructure of the metaverse, including the need for robust and scalable hardware and software, efficient data storage and processing, and ensuring stable and high-speed connectivity to support seamless user experiences.

DEVELOPMENT. The development of the metaverse involves addressing several key issues, each of which underscores the need for advanced technologies. Generally, advanced voice synthesis is required for accurate attribute recognition and real-time speech generation [60], CNNs with anti-aliasing for biometric recognition [327], and dual exposure fusion

algorithms to improve low-light image quality [327]. These technologies are not just desirable, but essential for the evolution of the metaverse. Robust system architectures and load balancing are also essential [198], as well as software compatibility and standardization [66] and managing digital object manipulation complexity [93]. Advanced algorithms and realistic mobility models are needed for dynamic areas of interest [198]. Deep learning and data analytics enhance user interactions [81], while interoperability ensures seamless experiences [178]. Efficient navigation systems are crucial for functionality [279, 348]. In education, the metaverse needs engaging content, AI-driven virtual instructors, and standardized protocols for cybercampuses [282]. It also benefits from pedagogical integration for language learning [260] and real-time environment modifications to boost engagement [93]. However, as shown in Figure 4.4, the metaverse has developmental issues from the perspective of its representative elements, i.e., *Virtual Environment* and *Avatar*. On the one hand, avatar development needs accurate facial recognition and animation technologies to achieve realistic expressions [77, 256]. Realistic avatars demand natural facial expressions and mouth movements, but integrating real-world data into the metaverse involves advanced processing [10, 175]. Customization for non-gender identities is limited and often depends on third-party tools, including advanced voice modulation [130]. Avatar creation tools must adapt to various online contexts and personality nuances [365]. Additionally, creating visually and motion-accurate avatars is complex, with high-fidelity tracking being resource-intensive [252], particularly for full-body tracking, which results in a lack of diversity in body types and gestures [130]. NPCs need enhanced artificial intelligence to interact realistically [260]. On the other hand, the virtual environment development also presented issues that needed to be addressed. Achieving a high level of immersion requires advanced VR technologies, sophisticated graphics, and user-friendly interfaces [149]. The precise manipulation of 3D objects involves using hand gestures in a more dynamic way to select and edit vertices with pressing, pointing, and gripping actions that are sometimes hindered by

sensor inaccuracies and require careful consideration to ensure smooth user experiences [191]. Addressing issues such as color distortions and unrealistic textures in virtual environments and human body characteristics is also essential to achieving greater degrees of photo realism and immersion [352].

SOFTWARE. The development and maintenance of software infrastructure within the metaverse environment present several critical issues. The lack of standardized protocols and frameworks complicates the integration of various platforms, hindering seamless interaction and affecting user experience and asset sharing [111, 334]. Additionally, integration with existing educational tools and ensuring compatibility with a wide range of devices, particularly mobile technologies, is crucial for accessibility [282]. Ensuring interoperability across AR/MR technologies remains a significant issue [144], and blockchain integration for managing virtual content and handling high transaction volumes is essential [261, 350, 353]. These issues collectively lead to significant consequences, including the digital divide, where unequal access to technology reinforces social inequalities [243]. Innovative technologies integrating AI and blockchain bring both opportunities and issues [167], highlighting the need for sophisticated technology to create immersive experiences [352]. Addressing these software-related issues is vital for fostering a unified and accessible metaverse ecosystem, ensuring security and sustainability [149, 360].

HARDWARE. The development and immersive experience of the metaverse, especially for educational purposes, are significantly constrained by current hardware capabilities and infrastructure limitations. The technical infrastructure needed to support cybercampuses requires substantial investment in hardware, cost considerations, and advanced sensor technology to achieve the desired level of interactivity and immersive experiences [327]. Integrating head-mounted displays with hand tracking for VR and ensuring compatibility with mobile platforms for AR users is critical for synchronizing actions and interactions in real-time across

different user environments [81]. Additionally, in metaverse educational classes, there is a need for high-quality one-way cameras to capture full classroom settings, but the high cost associated with professional-grade equipment presents a barrier [248]. The substantial development costs and infrastructural challenges in supporting the data-intensive nature of the metaverse further complicate the deployment of these advanced technologies [364]. Consequently, the hardware requirements, including processing power, battery life, and display technologies, need significant advancements to meet the demands of the metaverse [26, 355]. High device costs also limit widespread adoption and accessibility, adding to the complexity of building an inclusive and comprehensive metaverse infrastructure [360].

DATA MANAGEMENT. In the metaverse, effective data management is a crucial technical issue involving many technologies, including Artificial Intelligence, Blockchain, and Cloud Computing. Addressing issues such as processing efficiency and managing large volumes of data is critical. Seamless experiences and real-time interactions depend on robust data processing capabilities [350]. Artificial Intelligence faces difficulties in delivering personalized experiences and conducting emotional analysis due to the need to manage and process vast amounts of data while also considering ethical implications [364]. These data management challenges are further complicated by the requirement for secure storage solutions, real-time data processing, and data integration from various sources [66, 334].

4.3.3.2 *Privacy and Security*

This category focuses on the technical issues related to protecting user data and ensuring secure interactions within the metaverse.

DATA PROTECTION. The dynamic nature of the metaverse should allow users to access multiple virtual worlds through a single platform. While this concept seems like science fiction, it is actually quite similar to how we understand the internet. Managing vast data depends on the virtual

world being accessed [26]. This data can be divided into two main categories: (1) *personal data* related to the physical person and (2) *personal data* related to the virtual person, which may or may not derive from the physical person. The first category includes information such as name, surname, and banking details; the second includes data related to the virtual person, such as avatar representation, including voice customization ensuring the user's physical gender and other characteristics with which the user identifies [60, 327] virtual assets such as customized 3D virtual scene or objects. Therefore, it is crucial to implement security techniques that focus on the privacy of virtual users, from authentication to the use of virtual components [7, 167, 360], preventing unauthorized access or misuse of user/avatar data within the metaverse [247, 338].

INFRASTRUCTURE AND DEVICE PROTECTION. Ensuring the security of the metaverse involves multiple critical aspects, focusing on building robust privacy systems and protecting devices. Firstly, wearable devices, which are expected to be primary access points for the metaverse, require secure key management and user authentication methods that are efficient and do not heavily tax their limited computational resources [338]. Secondly, network security is crucial for safeguarding data transmission and preventing unauthorized access. This requires comprehensive measures such as encryption and advanced firewalls to protect the vast network infrastructure [338]. Lastly, maintaining system integrity and stability is essential for user trust. This includes protecting against intellectual property theft and mitigating denial of service attacks through robust defense mechanisms [123]. Addressing these areas collectively ensures a secure and seamless metaverse experience.

4.3.3.3 *Interaction and Usability*

This category focuses on the issues related to enhancing user interaction and usability within the metaverse, including intuitive interface design, seamless navigation, and user-friendly experiences that cater to diverse user preferences and abilities.

VIRTUAL REALITY EXPERIENCE. It is crucial to allocate significant attention to the interaction design phase to create a seamless virtual reality experience in the metaverse. Indeed, as shown in Figure 4.4, this category can be split in *Interface Development*, and *Interaction Design* to have a unique experience that facilitate user interaction with the environment and with other users. Real-time interaction capabilities are crucial to prevent interruptions to ensure interactions that foster emotional engagement, providing a seamless user experience and a sense of control within the virtual environment [111, 334]. Moreover, balancing realism and usability adds another layer of complexity, as it is essential to create a realistic virtual environment while maintaining ease of navigation for effective interactions through head-mounted display [260]. For this reason, addressing VR motion sickness by optimizing rotational movements and angular velocities is paramount for ensuring user comfort and usability [322].

Then, creating intuitive and user-friendly interfaces across different platforms is essential for seamless user experiences. Managing immersive virtual environments with realistic details is crucial for achieving more immersiveness [111, 144, 191]. To enhance user interaction, systems must enable users to engage with digital content effectively, encouraging interaction and evoking emotions through well-integrated design elements [260, 279, 289]. Furthermore, these interfaces must be accessible and cohesive, seamlessly integrating multiple functionalities to provide a comprehensive and user-friendly experience [322].

HARDWARE. The metaverse is significantly dependent and related to hardware, which impacts user interaction and usability. Issues with device dependence and limitations hinder the overall experience. Current head-mounted displays (HMDs) suffer from problems such as poor display quality, limited field of view, and user discomfort, which restrict accessibility and versatility [144]. Moreover, integrating multisensory inputs, combining visual, auditory, tactile, and potentially olfactory stimuli, poses a considerable challenge in creating cohesive and immersive experiences [111]. The implementation of haptic interac-

tion further complicates usability in virtual environments. Developing software capable of interacting with virtual objects through touch and managing high refresh rates for effective haptic feedback is critical for enhancing user experience [342]. Additionally, ensuring high-quality visual and interactive experiences is essential for the effectiveness of immersive systems, as the type of camera used—i.e., professional vs. non-professional—significantly affects the overall quality of experiences such as tele-education [248]. Lastly, sensitivity profiles need to be implemented to adjust interaction parameters to counteract adverse effects caused by head movements and sensor limitations, thereby enhancing hand gestures' stability and accuracy [191].

4.3.3.4 *Communication and Network*

These issues concern metaverse communication infrastructure, requiring reliable connectivity, high bandwidth, and low latency for real-time interactions.

COMPUTATIONAL ISSUE. The computational issues within the metaverse are extensive and diverse. Creating high-quality 3D environments and integrating AI necessitates significant computational resources and advanced hardware [243, 350]. Using deep learning for dynamic interactions introduces additional complexity, requiring advanced computational capabilities to ensure seamless user experiences [248, 353]. Robust infrastructure and networking solutions are critical to accommodate the metaverse's high connectivity and data transfer requirements[249, 350]. Furthermore, integrating various communication methods —i.e., voice, text, gesture—and the wide spectrum of resources needed underscores the technical limitations involved [85, 260, 264]. Lastly, addressing the intricacies of human image synthesis, particularly in disentangling pose and appearance, is crucial for crafting realistic and immersive virtual experiences [352].

LATENCY ISSUE. Latency is a critical issue in the metaverse, significantly impacting the user experience and the effectiveness of XR (Extended Re-

ality) applications [59, 66, 74, 248, 252, 342]. Real-time XR streaming must handle device inputs efficiently to ensure a smooth and immersive user experience, which is essential for the effectiveness of XR applications and for achieving the high frame rates necessary for real-time interactions and immersive experiences [254]. Low latency is crucial to prevent delays that could disrupt interactions and cause discomfort, such as dizziness, due to delayed data transmission, necessitating extremely low latency to ensure a high-quality user experience [74, 254]. High-end end-to-end latency, particularly on web-based platforms, highlights the need for improved server-processing techniques and receiver-side optimizations to enhance the overall performance and reduce lag in the metaverse [78]. Ensuring low latency and addressing these technical issues are crucial to support the growing demand for high-quality, real-time virtual experiences in shared virtual spaces.

PERFORMANCE ISSUE. Performance issues in the metaverse are a significant concern, as highlighted by various studies [78, 118, 198, 338]. Ensuring scalability and consistent performance across dynamic user-generated content and variable user behavior is crucial. Linear increases in throughput, as more users join, can lead to scalability issues and increased on-device resource utilization. Maintaining network security is also essential to prevent threats and attacks on the vast network infrastructure supporting the metaverse. Integrating emerging technologies like blockchain and AI further complicates performance considerations, necessitating efficient handling of high transaction volumes. Addressing these issues requires optimizing infrastructure, implementing advanced software solutions, and ensuring network security to provide users with a seamless and immersive experience.

4.3.3.5 *Rendering and Visualization*

These issues involve metaverse rendering and visualization, requiring high-quality graphics, real-time rendering, and immersive visuals to boost engagement.

REALISM RENDERING. Realism rendering involves the process of creating virtual objects and avatars that closely resemble and behave like their real-world counterparts. This task can be critical due to the variability of environmental conditions, such as different lighting scenarios and indoor versus outdoor settings [144]. Additionally, avatars need to accurately represent physical and demographic characteristics, including skin tones, facial and emotional expressions, and body shapes [365]. Seamless integration of virtual objects with real environments is crucial for creating unique metaverse experiences [93, 342]. Accurate textures, shadows, and physical properties are vital for immersion but are complex to implement, affecting the overall metaverse experience.

3D GRAPHIC. Despite significant advancements in 3D graphics and computer vision, the metaverse and its graphical rendering still pose significant issues that could potentially impact the overall user experience and engagement quality. As a result, the metaverse is particularly prone to technical issues, such as glitches when creating and rendering complex virtual environments or objects with intricate details [59, 152, 202]. Additionally, there are instances of lag and slower rendering times, which are directly related to the communication and network issues discussed earlier.

REAL-TIME RENDERING. This subcategory, together with the two abovementioned, enhances the infrastructure to support seamless interactions among multiple users without lag or technical glitches. This involves addressing the complexity of rendering dynamic multi-user activities and interactions in these environments to ensure smooth and efficient performance [279]. Additionally, focusing on the technical aspects of real-time rendering and overall fidelity helps reduce discrepancies between visual perception and physical motion, significantly reducing motion sickness [322]. Furthermore, improving the rendering capabilities ensures that real-time collaborative modifications and synchronous visualization in shared virtual spaces are executed effectively [342].

4.4 DISCUSSION, IMPLICATIONS, AND FUTURE STEPS

As a first output of our study, the results allow to extend the theoretical metaverse classification proposed by Almoqbel et al. [8], enriching it with additional insights from our SMS. This is illustrated in Figure 4.5 and would serve as the foundation for the definition of metaverse engineering, offering a theoretical framework for understanding the metaverse from different perspectives and connecting them to the specific research communities in the field.

In particular, the left side depicts the aspects outlined in the related work section, specifically the elements pertaining to the definition of the metaverse provided by Almoqbel et al. [8], such as "*Activity*", and "*Technical Specification*" elements. Instead, the enhancement on the right side represents our contribution, namely the connection between the *Activity* and *Technical Specification* categories and the taxonomies presented in the results section. Our research has uncovered that the metaverse presents interconnected socio-technical issues. For instance, from a social perspective, particularly in the "*Interaction and Engagement*" category, we have emphasized the significance of avatar representation and perception in virtual interactions and environments and how these aspects impact social factors such as gender identity, privacy, mental health, and addiction. Concurrently, from the technical perspective, specifically in terms of "*Environment Infrastructure*," where we have highlighted the necessity for advanced facial recognition and animation technologies to capture natural expressions, including the potential for customization to support non-binary identities, both in physical appearance and voice. Thus social and technical issues are deeply interconnected. Addressing technical challenges — such as enhancing facial recognition — can lead to more realistic avatars, better support for gender identity representation, and, ultimately, improved social well-being.

However, the process is not straightforward. Despite improvements, the absence of regulations and norms of behavior, described as "*Social Norms and Ethics*" issues, could give rise to abuse and illegal activities

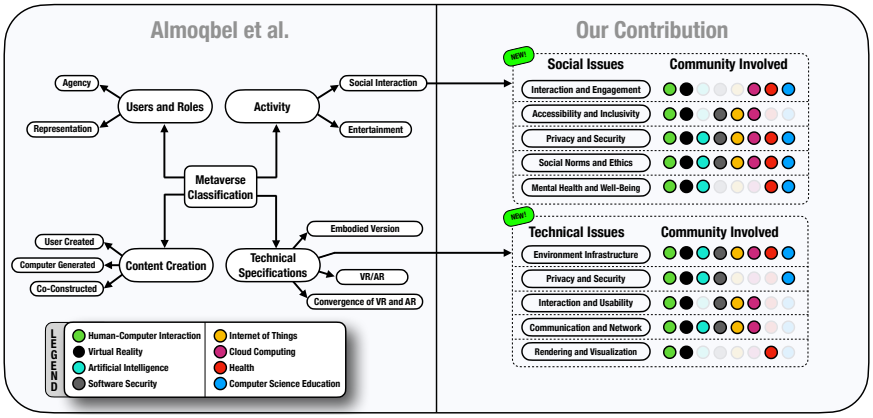


Figure 4.5: How our contribution with Social and Technical Issues advances the metaverse classification proposed by Almoqbel et al. [8]

such as cyberbullying, resulting in psychological problems in the physical and virtual world. It is therefore essential to address both technical and social aspects in a balanced way, ensuring that technical advancements contribute positively to social outcomes without creating unintended drawbacks. Achieving this balance requires the involvement of diverse expertise from multiple scientific communities, each bringing valuable perspectives. However, identifying the specific skills needed to effectively manage this interplay remains a complex challenge. To navigate this, we have partially drawn on the findings from $\mathbf{RQ}_1$, focusing on the research communities that have previously engaged with similar issues, thereby helping to identify which communities should be involved in managing the socio-technical relationship.

4.4.1 *Toward a Unified Metaverse Framework*

The metaverse remains a topic that presents opportunities across a wide range of fields, including business, healthcare, and entertainment. However, most of the current research and applications focus on educational environments that enhance learning experiences [123, 248, 360, 364] [229]. These experiences can range from virtual classrooms and interactive labs

to historical field trips, providing immersive learning opportunities that go beyond traditional methods.

Despite these opportunities, the current definition and understanding of the metaverse still lack essential improvements in its characteristics, particularly regarding the *interoperability*. As a result of this limitation, the metaverse still resembles isolated virtual reality applications and has not yet become the comprehensive digital environment envisioned by many; consequently, it still lacks the characteristics of a unified platform that integrates diverse contexts and functionalities. This fragmentation may explain the continued skepticism among researchers and practitioners.

To move beyond basic VR, the metaverse must address the interoperability issues, evolving into the next iteration of the Internet. Several studies cited in the taxonomy of technical issues have identified the interoperability issue as a critical concern. They emphasize that today's metaverse consists of separate, non-communicating virtual environments, which limits both user experience and overall development. Addressing these interoperability issues is essential to enable seamless transitions across virtual instances, allowing different applications, domains, and communities to converge. As shown in the previous section, both technical and social challenges affect multiple contexts and must be adapted accordingly. When viewed not as obstacles but as drivers of innovation, these challenges can guide the creation of a unified metaverse—open, collaborative, and inclusive. In this regard, remarkable advancements were made by Havele et al. [152], who provide a framework for realizing interoperability for a unified metaverse. They trace the evolution of virtual worlds, highlighting both advancements and the ongoing challenges that hinder the development of a cohesive virtual ecosystem. The authors emphasize the importance of interoperability, advocating for the adoption of the *Extensible 3D (X3D) standard*, which supports interactive 3D content across different platforms. By integrating with web standards such as HTML5 and WebGL, X3D enables seamless transitions between virtual worlds, ensuring users can move seamlessly across environments without losing

their identity or data. They also argue that, with current technology and open standards, a unified metaverse is both feasible and near.

However, X3D is not the only framework proposed in the literature. Other initiatives, such as glTF (GL Transmission Format), aim to provide a lightweight and efficient format for transmitting 3D models, widely used in real-time rendering applications and web-based environments. glTF is often referred to as the "JPEG of 3D" due to its focus on fast loading and runtime performance, making it suitable for immersive applications. Moreover, standards like OpenXR and WebXR have emerged to ensure cross-device compatibility for input and interaction, enabling a unified runtime interface across VR/AR headsets. It is worth noting that these are not the only unique frameworks studied in the literature; therefore, more systematic studies are needed to report the pros and cons of the interoperability framework.

Despite this opportunity, the unified metaverse requires software advancements from various perspectives. It must adopt and adapt the same core principles of software engineering: "*the establishment and the use of sound engineering principles to obtain economically developed software that is reliable and works efficiently on real machines*" [295].

The unified concept of the metaverse that we envision incorporates the key features outlined by Havele [152] as well as the foundational principles of software engineering [295].

Each metaverse instance—whether developed for education, entertainment, healthcare, or business—must be engineered to address domain-specific socio-technical challenges through dedicated research and development. A concrete example of this engineering effort involves utilizing blockchain technologies to securely manage and store data within each metaverse context. These independently developed instances can then be integrated into a broader interoperable ecosystem, such as the one enabled by the X3D framework.

In this vision, interoperability is not just a technical feature but a foundational design goal: by adopting a shared structure like X3D, individual metaverse instances can communicate and exchange data while preserv-

ing user identity and experience continuity. For example, users could seamlessly transition between different metaverse environments—such as from a healthcare metaverse to an educational one—without losing access to their personal data or virtual identity. This is made possible through the use of dedicated blockchains in each context, combined with a unifying blockchain infrastructure that governs data consistency, identity persistence, and avatar representation across the entire metaverse ecosystem [261]. Such an approach allows users to register once within the unified metaverse, create a core identity and personal avatar, and then either maintain or adapt these representations based on the specific needs of each domain, all while ensuring legal, ethical, and security standards are upheld.

4.4.2 *The Starting Point for Metaverse Engineering*

The Unified Metaverse Framework discussed above must integrate key theoretical foundations to support the development of Metaverse Engineering as a novel and rigorous research field. Based on our empirical findings and the identified entanglement between technical and social issues, it is essential to position this emerging discipline in relation to existing paradigms such as *Socio-Technical Systems Theory* (STST) [13], *Actor-Network Theory* (ANT) [171], and *Human-Centered Computing* (HCC) [165]. Each of these frameworks provides a complementary lens to understand the multifaceted nature of metaverse systems. STST emphasizes the co-constitution of technical infrastructures and social practices, offering valuable guidance for the design of collaborative and organizationally embedded virtual environments [13]. ANT, in contrast, draws attention to the heterogeneous networks of human and non-human actors—such as avatars, algorithms, interfaces, and spatial rules—whose interactions shape both the experience and the behavior within metaverse ecosystems [171]. Finally, HCC places the needs, values, and abilities of users at the center of the design process, promoting accessibility, ethical awareness, and value-sensitive design—dimensions that align closely with several of the socio-technical

concerns uncovered in our mapping study [165]. However, our intent is not to treat STST, ANT, or HCC as sufficient paradigms in themselves, but rather to build upon their strengths to establish Metaverse Engineering as a dedicated design- and problem-solving-oriented discipline. In our vision, a new research domain, called ***Metaverse Engineering***, actively synthesizes these theoretical contributions to tackle the unique challenges posed by immersive, entangled, and evolving systems. Drawing on the language of ANT, we consider each research community as a socio-technical actor, guided by both human-centered values and technological innovation.

In addition to these theoretical foundations, Metaverse Engineering draws on established applied domains such as *Software Engineering*, *Human-Computer Interaction*, and *Digital Experience Design*. However, it goes beyond merely integrating their methods or goals. More particularly, Human-Computer Interaction provides foundational knowledge in interface design, embodiment, and usability, but Metaverse Engineering requires going beyond traditional screen-based interactions to address presence, avatar-mediated communication, and the affective and ethical dimensions of persistent identity in virtual spaces. Similarly, while Software Engineering offers methods for requirements elicitation, architecture, and testing, these need to be rethought for systems that are co-produced by user communities, evolve in real-time, and implicate social norms, fairness, and governance. Digital Experience Design contributes to an understanding of immersion, engagement, and aesthetics, yet these are only a part of the broader value-sensitive and inclusive design challenges at stake in metaverse environments. So, we envision Metaverse Engineering as a novel engineering paradigm that synthesizes these contributions into a cohesive socio-technical perspective, capable of guiding both research and practice. Based on these conceptual and applied foundations, we provide a clear definition of Metaverse Engineering, clarifying its relationship with, and divergence from, existing research communities:

> *The **Metaverse Engineering** (ME) is an emerging interdisciplinary field concerned with the systematic requirements, design, development,*

> *and governance of immersive virtual environments. It builds upon and reorients principles from established domains such as Software Engineering, Human-Computer Interaction, Artificial Intelligence, Internet-of-Things, and related fields to address the socio-technical challenges posed by virtual, augmented, and mixed reality. ME aims to provide a unified framework for engineering metaverse systems that span several application contexts while ensuring ethical, inclusive, and sustainable user experiences.*

Such a new paradigm may even potentially evolve into a dedicated research field, inform interdisciplinary curricula, and inspire lifecycle models specifically tailored to the development and governance of immersive and socially embedded systems. In this sense, we may conceptualize ME along three complementary dimensions. First, as *an emerging research domain*, it integrates perspectives from engineering, human-computer interaction, and the social sciences to establish methods, tools, and evaluation frameworks that are attuned to the socio-technical complexities of the metaverse. Second, it has the potential to shape a *new curricular framework* that combines technical competencies with participatory design, ethics, identity management, and policy literacy, thereby equipping future professionals to navigate the distinct challenges of responsible metaverse development. Third, ME may support the definition of a *dedicated lifecycle model*, where socio-technical iteration is a core principle and values such as fairness, inclusion, and accountability are treated not as peripheral concerns but as foundational elements, integrated from requirements elicitation through to deployment and ongoing system governance, with explicit attention to macro-ethical and dual-use risks [128].

Following the ME definition, we emphasize the adaptation of software engineering principles within the metaverse. As a result, the metaverse engineering with software engineering principles leads to fundamental aspects: software engineering for the metaverse (SE4Metaverse) and the use of the metaverse for enhancing software engineering practices (Metaverse4SE). In our discussion, the primary focus is on the SE4Metaverse, which aims to use and adapt software engineering principles to create in-

dividual instances of VR worlds that can seamlessly integrate into a larger, unified metaverse. Our study can be seen as a first step toward adapting software engineering practices to the context of the metaverse, and more specifically, to the ME. The scientific method we used, i.e., a *Systematic Mapping Study*, plays a similar role to the early stages of software development: it acts like requirements elicitation. In software engineering, this means gathering needs, expectations, and constraints from stakeholders. In our case, the socio-technical issues we identified can be understood as Functional Requirements (FRs), and Non-Functional Requirements (NFRs). Depending on the context, these requirements will need to be analyzed, designed, implemented, and tested, following an engineering approach that considers both the technical side and the human side of virtual environments. FRs in ME define **what** a particular virtual world instance must accomplish. They outline the features, functions, and capabilities that the metaverse should offer users. In contrast, NFRs specify **how** the metaverse should behave, addressing key quality attributes such as performance, security, scalability, and usability, ensuring the system meets certain standards.

To illustrate this, we provide a non-exhaustive list of examples in the following that demonstrate how socio-technical challenges can serve as the basis for ME. Our focus is on functional requirements related to the technical category of *Environment Infrastructure*, which includes the creation of *Virtual Environments* and *Avatars*:

- **Virtual Environment FR1.** *In an educational context, students should be able to interact with virtual learning tools, manipulate virtual objects, and collaborate with peers.*
- **Virtual Environment FR2.** *The virtual environment should enable the addition or removal of digital resources, such as virtual boards or specific tools related to the subject matter.*
- **Virtual Environment FR3.** *The environment should offer accessibility features like speech-to-text and text-to-speech options, adjustable display settings, and intuitive navigation for users with disabilities.*

For avatars, FRs might include:

- **Avatar FR1.** *Avatars should feature facial recognition capabilities for an accurate representation of facial expressions, enabling users to perceive emotional cues, thus enhancing engagement and feedback.*
- **Avatar FR2.** *Users should be able to customize their avatars' facial features, body types, clothing, and accessories.*
- **Avatar FR3.** *Avatars should support flexible gender representation, allowing users to select non-binary or gender-fluid avatars, particularly in inclusive educational or social settings.*

Regarding NFRs, examples include:

- **NFR1.** *The environment should ensure secure communication, protect data, and comply with privacy regulations.*
- **NFR2.** *The environment must support various hardware (VR headsets, AR glasses, desktops) and software platforms, while integrating with educational tools like Learning Management Systems (LMS).*
- **NFR3.** *The environments should be designed with existing interoperable frameworks to ensure smooth transitions between different environments.*

However, the current lack of virtual environments specifically tailored to different fields limits the exploration of how the metaverse can be used for software engineering. Despite the potential to enhance collaboration, visualization, and simulation in software development, more research and specialized platforms are required to achieve effective integration between the metaverse and software engineering.

Further studies and experimentation will be crucial in clarifying how the metaverse can revolutionize software development practices. We envision that applying software engineering methods to metaverse development within a unified framework will lay the foundation needed to use the metaverse for advancing the software engineering field.

4.4.3 *The Metaverse Engineering Roadmap*

In this section, our goal is to leverage the findings from $\mathbf{RQ}_2$ and $\mathbf{RQ}_3$, in conjunction with the unified metaverse outline, to craft a roadmap with distinct phases for research and development in social and technical challenges. This roadmap will provide researchers with a solid foundation for letting the metaverse evolve while equipping them with the user's needs and addressing technical and social aspects and the required knowledge to build them.

4.4.3.1 *Phase 1: Defining Social and Technical Guidelines*

In this initial phase, clear social and technical guidelines will be established to shape the foundation of the metaverse. From a social perspective, there will be a strong focus on ensuring accessibility and inclusivity. This includes providing equitable representation for all users, particularly those with disabilities or from marginalized groups, and guaranteeing that the metaverse is a space where diverse identities can expand. Privacy and security protocols must also be prioritized, with measures to protect personal data, prevent identity theft, and secure the anonymity of users where necessary. Additionally, there must be a focus on mental health and well-being, with proactive measures to prevent addiction, isolation, and disconnection from real-life interactions.

On the technical side, this phase involves laying down the infrastructure to support these social priorities. Technologies that enable real-time rendering and seamless user interaction will be identified and refined. Furthermore, the network infrastructure must ensure that the platform can accommodate large numbers of users simultaneously without compromising on performance. This will involve ensuring low-latency connections, fast data processing, and a robust system architecture that can handle high user engagement in dynamic virtual environments.

4.4.3.2 *Phase 2: Technological Implementation*

In this phase, the focus will shift toward implementing the technologies that will drive interaction and engagement within the metaverse. One of the critical aspects of this is enhancing avatar representation and interaction. Sophisticated facial recognition and motion-capture technologies will be integrated to allow users to express themselves more naturally in the virtual space, making interactions feel more real and emotionally resonant. Improvements in real-time rendering will ensure that these interactions remain fluid and responsive, further enhancing the sense of immersion.

Simultaneously, security measures will be deployed to safeguard user data. Blockchain technology, for example, can decentralize the management of personal information, ensuring higher levels of data protection. Additionally, tools will be introduced to monitor for harmful behaviors, such as cyberbullying or abuse, and provide interventions where necessary. Systems to support mental well-being, including the monitoring of excessive use or signs of social isolation, will also be implemented to keep users safe and engaged in a healthy manner.

4.4.3.3 *Phase 3: Validation and Regulation*

Once the core technological infrastructure is in place, the metaverse will enter a phase of validation and regulation. Accessibility testing will be conducted to ensure that all features and functions are usable by individuals with disabilities. This will include examining how well avatar customization, user interfaces, and interaction systems cater to diverse needs. The goal here is to create a universally inclusive platform that empowers all users, regardless of physical or cognitive abilities, to participate fully. As part of the validation process, it is also crucial to test interoperability across metaverse instances. This includes verifying whether user identities, digital assets, and interaction protocols can persist and operate consistently across different platforms built on heterogeneous technologies. Interoperability validation ensures that the metaverse does not evolve as a set of isolated environments, but rather as a cohesive ecosystem capable of

supporting seamless transitions and cross-domain continuity. At the same time, this phase will involve developing ethical and regulatory frameworks for the metaverse. Legal experts, sociologists, and ethicists will work together to create a system of rules and norms that govern behavior within the platform. These regulations will help maintain respectful interactions, provide safeguards against abuse, and address legal and economic complexities that may arise in virtual spaces, such as intellectual property issues and the governance of virtual economies. In addition to standard validation activities, Phase 3 should also include a systematic assessment of macro-ethical and dual-use risks [128]. While traditional validation approaches in Software Engineering and Human-Computer Interaction emphasize usability, performance, and safety, metaverse systems introduce distinctive societal challenges. These include pervasive surveillance enabled by biometric and behavioral tracking, labor exploitation within virtual economies, the manipulation of public opinion through immersive misinformation, and the potential militarization or coercive misuse of immersive platforms. These risks clearly require the adoption of regulatory frameworks and design principles that account not only for technical failure modes but also for far-reaching societal impacts. To this end, we advocate for the integration of established ethical frameworks into the validation process. For instance, the *ACM Code of Ethics*[9] and the *IEEE Ethically Aligned Design*[10] offer a foundational basis for guiding ethical decision-making in the design and deployment of metaverse systems. Indeed, these frameworks emphasize principles such as accountability, non-maleficence, transparency, and the primacy of public good, providing a normative anchor for addressing both intended and unintended uses of immersive technologies. Incorporating these principles during Phase 3 ensures that ethical and dual-use concerns are not postponed to post-deployment remediation, but instead treated as first-class validation criteria integrated throughout the lifecycle of metaverse engineering.

[9] The ACM Code of Ethics: https://www.acm.org/code-of-ethics.

[10] The IEEE Ethically Aligned Design: https://standards.ieee.org/wp-content/uploads/import/documents/other/ead_v2.pdf.

4.4.3.4 *Phase 4: Continuous Improvement and Maintenance*

Lastly, this involves regularly reviewing and updating accessibility, inclusivity, privacy, and mental health policies based on user feedback and emerging social needs. On the technical side, infrastructure, real-time rendering, and network performance will be continually optimized to keep pace with advances and increasing user demand. Security measures, such as blockchain-based protections, will also be updated to counter new threats. Ethical and regulatory frameworks will adapt to evolving legal standards and societal expectations, while also remaining vigilant toward macro-ethical and dual-use risks such as surveillance, labor exploitation, or misuse for coercive purposes. This phase acts as a feedback loop, ensuring that improvements from Phases 1, 2, and 3 are consistently integrated, keeping the metaverse secure, inclusive, and up-to-date. In parallel, ongoing research will focus on the psychological and social impacts of the metaverse on its users. This will involve studying how users interact with the platform, identifying any new social or technical challenges that arise, and ensuring that the guidelines and systems in place can adapt to meet these emerging needs. By continuing to research and address these issues, the platform will remain responsive, safe, and engaging for its diverse user base.

4.5 THREATS TO VALIDITY

Threats to the validity of an SMS often stem from data extraction errors, incomplete studies due to search term or engine limits, and researcher bias in selection criteria. We identified and mitigated such threats in our study [182, 346].

INTERNAL VALIDITY Internal Validity threats concerns the ability to establish cause-effect relationships without interference from external factors [346]. Our study follows the systematic method by Kitchenham et al. [182], so threats are mainly linked to the data selection process described

in Section 4.2. To address them, we detailed the search terms, data sources, inclusion/exclusion criteria, and quality assessment to ensure replicability.

Search terms were derived from previous SLRs and primary studies. Given the metaverse's multidisciplinary nature, spanning VR, software engineering, and HCI, we employed the Delphi method to refine and validate the terminology with experts across these domains. While this process may involve some bias, the terms used were grounded in established literature, and expert input expanded but did not alter the core list.

We queried reputable databases, including the *ACM Digital Library*, *Scopus*, *IEEE Xplore*, *Web of Science*, and *SpringerLink*, ensuring comprehensive coverage. To mitigate researcher bias, each author independently applied the selection and quality criteria to ensure objectivity. Discrepancies were discussed and resolved in regular meetings.

CONSTRUCT VALIDITY Threats associated to construct validity concerns how accurately a study measures the concept it intends to assess [346]. Although we aimed to comprehensively define metaverse engineering through social and technical issues, some nuances may have been overlooked due to the evolving and multifaceted nature of the metaverse. It means that operational definitions might risk oversimplifying complex phenomena that are essential for a complete understanding. To mitigate this, we adopted an iterative categorization process, including continuous feedback and multiple validation cycles, allowing us to refine our categories and better reflect the intricacies of the domain. Still, we encourage future studies to triangulate our results and offer complementary perspectives.

Additionally, we used a card sorting method to develop our taxonomy. While structured, this method may introduce subjectivity, as different themes might emerge if conducted by different individuals or at different times. To reduce this risk, we iteratively refined the taxonomy by merging or splitting categories when necessary, devoting significant effort to ensuring its consistency and completeness.

CONCLUSION VALIDITY Threats to conclusion validity relates to the credibility of the study's findings [346]. To ensure reliability and minimize bias during data selection and extraction, the entire research process — outlined in Figure 4.1 — was carefully conducted and jointly reviewed by all authors. Disagreements were promptly resolved through consensus.

To strengthen the validity of our conclusions, we followed established guidelines from Kitchenham et al. [182] and the *ACM/SIGSOFT Empirical Standards*. These standards were especially relevant during the quality assessment phase, where we applied both qualitative and quantitative criteria to select studies from reputable academic databases.

EXTERNAL VALIDITY Threats to external validity refer to the extent to which findings can be generalized beyond the study context [346]. Our study did not include non-peer-reviewed articles or paywalled sources that were not accessible through institutional or open channels. The decision to exclude inaccessible articles was a result of budget constraints, despite our attempts to obtain them through alternative avenues. We recognize that these exclusions may compromise the comprehensiveness of our review, particularly in a rapidly evolving field like the metaverse.

We relied on a subset of established databases commonly used in humanities research. While relevant, this may have excluded interdisciplinary studies—especially from psychology and sociology—that are indexed elsewhere and crucial to socio-technical issues. Our focus on high-impact venues aimed to ensure quality but may have overlooked valuable, less visible work. Finally, restricting the review to English-language publications may introduce geographical bias.

5

TOWARD A SECURE EDUCATIONAL METAVERSE: A TALE OF BLOCKCHAIN DESIGN FOR EDUCATIONAL ENVIRONMENTS

This chapter builds upon the paper published at the *Euromicro Conference Series on Software Engineering and Advanced Applications* (SEAA) [101], where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the metaverse engineering perspective introduced in Chapter 4, this chapter focuses on blockchain as a relevant enabling technology to address trust, security, and integrity issues in educational metaverse environments.

5.1 INTRODUCTION

Over the last decades, and even more in the current pandemic times, there has been a growing interest in the provisioning of technological and pedagogical architectures to support the so-called *distance learning*, that is, an educational method through which learners attend lectures without the need of physically attend a school or a college [223]. Most of the recent advances have been made in terms of 2D information technologies [204, 215, 298], with notable examples such as GOOGLE MEET[1] and ZOOM,[2] just to name a few.

[1]The GOOGLE MEET platform: https://meet.google.com.
[2]The ZOOM platform: https://zoom.us/.

Those platforms have been crucial in pandemic times to guarantee continuity of training, research, and educational activities, other than allowing companies to stay on the market, and are still widely used worldwide [212, 309]. At the same time, their widespread adoption has sharpened and globalized new types of problems and challenges, especially in the educational domain [46, 51, 89]. Examples include disparities in technology upgrades, inadequate learning aids, insufficient knowledge of educational technologies, loss of social iterations and the psychological effects that follow [160].

The *metaverse* represents one of the most popular emerging technologies nowadays: this is based on the concept of having a persistent, virtual, three-dimensional environment where individuals may communicate, engage, and collaborate [255]. Researchers, practitioners, and companies are seeing in this new technology the potential to address most of the negative implications that social distancing may pose and, more importantly, a brand new communication revolution that may limit the short- and long-term social, interaction, psychological issues of 2D solutions [38, 243]. Education is a special use case: the metaverse would not limit itself to the presentation of an exact digital replication of the surrounding educational world, but can also empower it from various angles by offering new teaching tools, creating scenarios and realistic online learning experiences, and lowering physical, geographic, and financial barriers for students with disabilities and those from low socioeconomic status or from rural areas [201].

However, all that glitters is not gold. The potential of the educational metaverse strictly lies in the technologies that enable it. While at this early stage researchers contributed already to the conceptualization of the tools and technologies that would be required to make this metaverse real, there is still a lack of software engineering instruments and investigations that may inform how to actually design a metaverse that makes an effective use of the available tools and technologies [255].

In this paper, we aim at performing the first step toward understanding how to tailor existing technologies to address two key non-functional re-

quirements, namely software security and privacy, in the metaverse. We take the case of *blockchain* [33], i.e., a popular technology that enables secure computing by storing data in a distributed and decentralized manner, by investigating how it may be used to support education environments. To this end, we conduct a systematic literature review (SLR) to elicit the *goals* for which blockchains can be used within educational environments and how applications have been *designed* to include them. Our ultimate goal is to collect the current knowledge of blockchain within educational environments to provide insights into how blockchain may be further tailored in the context of an educational metaverse—this was required because of the lack of studies that explicitly focused on the relation between blockchain and metaverse.

From an initial candidate set of 413 articles, the systematic process leads to 20 primary studies that are further analyzed to address our research objectives. The results of our study show that blockchain has been employed to support 3 main educational tasks. More importantly, we identified how application designs change with respect to these educational tasks. Finally, those findings let us develop a conceptualization of a blockchain-based educational metaverse which we hope may serve as a basis for further research on the matter.

Structure of the paper. Section 5.2 overviews the design of our study, while the results are discussed in Section 5.3. Our conceptualization of a blockchain-based educational metaverse is presented in Section 5.4, with the limitations of our study discussed in Section 5.5.

5.2 RESEARCH METHOD

The *goal* of our study was to understand how the current blockchain-based applications can support educational environments, with the *purpose* of providing insights into how they may be tailored in the context of an educational metaverse. The *perspective* was of both researchers and practitioners: the former are interested in understanding how blockchains can support educational environments; the latter are interested in overview-

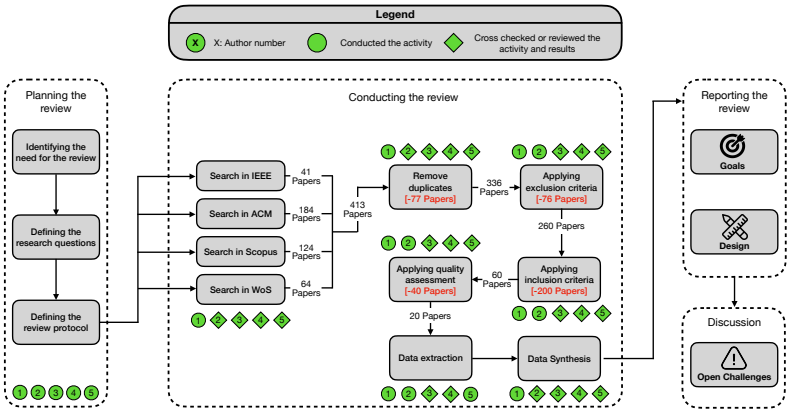


Figure 5.1: Overview of our research process.

ing the currently available solutions to possibly deploy them in practice. We conducted a SLR, i.e., a systematic approach aiming at collecting and synthesizing the body of knowledge on a specific matter [52]. We adopted the guidelines by Kitchenham et al. [183] and formulated two research questions (RQs) that drive the entire process.

> **RQ$_1$:** *What are the **goals** for which blockchains have been used within educational environments?*

With **RQ**$_1$ we were interested in analyzing the literature studies to understand the reasons the use of this technology in educational environments and, more importantly, the goals that blockchain aims to address.

> **RQ$_2$:** *How are applications **designed** in order to include blockchain for educational environments?*

RQ$_2$ aimed to highlight the choices about the design made when using blockchains within applications for educational environments and provide insights into the factors influencing their successful implementation.

Figure 5.1 overviews the main steps conducted to address our RQs, highlighting the SLR phases —reported in grey round squares and further elaborated in the next sections—along with the authors involved in each phase—a green circle indicates that the i-th author has been conducting the step, while a green rhombus indicates that the i-th author has been

reviewing the activities conducted. In terms of reporting, we followed the *ACM/SIGSOFT Empirical Standards*[3] and, in particular, the *"General Standard"* and *"Systematic Reviews"* guidelines.

5.2.1 *Search Strategy*

Our search strategy focused on search parameters to find the most pertinent terms to produce valuable results. First, we selected the research domain, analyzing primary or secondary studies terms, such as *Educational Environment* and *Blockchain technology*. Once the initial terms were obtained, we then derived a set of alternative words to get articles dealing with the same topic but using different spellings:

EDUCATIONAL ENVIRONMENT ("*educational environment*" OR "*remote learning*" OR "*distance learning*" OR "*online learning*" OR "*remote education*" OR "*distance education*").

BLOCKCHAIN TECHNOLOGY ("*blockchain technology*" OR "*blockchain*" OR "*block structure*" OR "*decentralized structure*").

Finally, we combined the above terms with the AND operator to aggregate the domain outcome, while synonyms were grouped using the OR operator, thus obtaining a ready-to-use query to increase the reliability of the obtained items:

Query: *(("blockchain technology" OR "blockchain" OR "block structure" OR "decentralized structure") AND ("educational environment" OR "remote learning" OR "distance learning" OR "online learning" OR "remote education" OR "distance education"))*

The obtained search query was run against four search engines, i.e., *IEEExplore*,[4] *ACM Digital Library*,[5] *Scopus*,[6] and *Web of Science*.[7] on De-

[3] The *ACM/SIGSOFT Empirical Standards*: https://github.com/acmsigsoft/EmpiricalStandards.

[4] *IEEExplore*: https://ieeexplore.ieee.org.

[5] *ACM Digital Library*: https://dl.acm.org.

[6] *Scopus*: https://www.scopus.com.

[7] *Web of Science*: https://www.webofscience.com

cember 14, 2022, obtaining 413 hits. As shown in Figure 5.1 41 of them came from *IEEEXplore*, 184 from *ACM Digital Library*, 124 from *Scopus*, and 64 from *Web of Science*. Afterwards, we removed duplicates, reducing the total number of papers to 336 (≃ 81% of the starting set).

5.2.2 *Article Selection Process*

Using exclusion and inclusion criteria, quality assessment, and data extraction are essential components of a systematic literature review [183] to answer the proposed RQs. Both exclusion and inclusion criteria have the same purpose i.e., to help ensure that only relevant studies are included by assessing each one. As for the exclusion criteria, a paper was discarded if at least one of the criteria was met:

- *it is not peer reviewed*;
- *it is not written in English*;
- *it is a poster o similar*;
- *it is not entirely available for free*.

A total of 76 papers matched one of the criteria and were discarded. The remaining 260 papers (≃ 63% of the starting set) were eligible for the next stage. An article was included if at least one of the following inclusion criteria were matched:

- *it includes the main **goal** of the blockchain in educational environments*;
- *it includes the educational blockchain application **design***.

At the end of this phase, 200 papers were discarded, and the remaining 60 papers (≃ 15% of the starting set) were included for the next step, i.e., the quality assessment, which is done to ensure that the primary studies actually contained reliable information to address the research questions of the study. In particular, we defined the following checklist:

- *Does the article clarify the goals that blockchain wants to address in educational environments?*
- *Does the article clearly and in detail describe educational blockchain application design?*

As one can expect, it was necessary to label the answers with "Yes" or "No". In addition, the paper's first author also found it necessary to consider an average case labeled "Partially". For measurement purpose, it was necessary to assign numbers. The following values were scored: "Yes" = 1; "Partially" = 0.5; "No" = 0. The final score of each primary study was obtained by summing the score defined for each quality assessment question. We classified the quality level into *'High'* ($score = 2$), *'Medium'* ($1.5 \leq score < 2$), and *'Low'* ($score < 1.5$). As a result, 20 papers received a score between *'High'* and *'Medium'* and were included in the final our SLR paper list, while the remaining 40 were discarded.

Next, the first two authors of the paper defined a data extraction form and jointly proceeded with the reading of the primary studies to elicit all relevant information required to address our RQs.

The data extraction process was constantly monitored by two senior researchers, who double-checked the activities performed to reduce inconsistencies. Then, the first two authors of the paper proceeded with synthesis of the extracted data, employing *thematic analysis* [49] to systematically analyze and identify common themes arising from the data. The research method was applied in an iterative manner and each step refined the themes emerged from the previous one. Also in this case, the process was double-checked by the other authors of the paper to avoid inconsistencies.

5.3 ANALYSIS OF THE RESULTS

Most of primary studies subject to our systematic synthesis were published between 2018 and 2022, with 80% of them being published between 2020

and 2022—hence confirming the acceleration brought by the COVID-19 pandemic.

5.3.1 ***RQ$_1$**: What are the goals for which blockchains have been used within educational environments?*

As for the goals for which blockchain has been employed within educational contexts, we were able to classify them under three main categories, which we discuss in the following.

APPLICATION. Blockchain has been proposed as a means to improve information sharing and distribution in platforms without the need for central control or ownership. Several studies [84, 114, 134, 176, 194] investigated the integration of blockchain in Massive Open Online Course (MOOC) platforms to enable stakeholders, such as students, faculty, and administrative staff, to upload lecture videos, engage in discussions, take notes, evaluate students, and evaluate courses. Additionally, Navya et al. [231] proposed using virtual coins to stimulate student participation in online classes, allowing them to use earned virtual currencies to pay fees or purchase other university resources.

DATA MANAGEMENT. The studies in [221, 349, 351] highlighted challenges that could negatively affect the quality of online courses due to the lack of security. The challenges stem from the uncontrolled data proliferation, inconsistent standards for student recognition, and difficulty in sharing resources. Blockchain technology can securely manage student data by decentralizing it over a peer-to-peer network instead of storing it on a centralized server, overcoming the mentioned challenges. Additionally, Zhuoya et al. [197] highlighted the security benefits of using blockchain, as it would enable the recognition of students through smart contracts, managing data such as courses passed, grades, and obtained certifications, facilitating the processes of verification and migration of students to other universities [14] and ensuring compliance with sensitive issues, such as fairness. Blockchain can also enable students to

perform transactions such as payment for reserved courses and sharing additional resources with other students.

SECURITY ASPECTS. Last but not least are security objectives such as (1) transparency, (2) efficiency, (3) privacy, (4) authenticity, and (5) accessibility [336, 343]. Transparency enables all stakeholders to access the data and verify learners' activities, [153]. Blockchain's smart contracts automate administrative processes and tasks without an intermediary like an academic office, thus ensuring efficiency [14]. Students can benefit from this technology in managing grades, exams, and notes and monitoring progress in sports disciplines [195]. Privacy, authenticity, and accessibility are essential to safeguard academic careers, and the data stored on the blockchain are immutable to prevent tampering by students or third parties [122, 133]. These security objectives must be ensured to maintain the integrity and reliability of student data.

RQ_1 – Summary of the results.

☛ The main goals of blockchain are to create ad-hoc applications for educational environments, ensuring proper data management and student privacy.

5.3.2 ***RQ_2**: How were applications designed to include blockchain for educational environments?*

As a foreword, Zheng et al. [363] define the blockchain in three types of systems: public, private, and consortium. Public blockchains are open to everyone, while private blockchains are available to restricted people. Consortium blockchains are a hybrid of the two. A key outcome of our study showed that although all blockchain types are widely spread and used, replicating an entire blockchain's development for general software systems is highly complex. In our research domain, each application that includes the use of blockchain is associated with a *blockchain protocol* that adapts the basic principles depending on the application's domain of use. On the one hand, our results show that the most used protocols in general

educational systems are those referred to as public blockchains (i.e., 6 articles report the use of the Ethereum protocol). On the other hand, specific educational systems are developed using private protocol blockchains (i.e., 4 articles use one among Hyperledge Fabric, MultiChain, and Ethereum Private Blockchain protocol). Lastly, multi-purpose educational applications use the consortium blockchain type with the same protocol as the private one (i.e., 2 articles use the Hyperledge Fabric protocol).

PUBLIC BLOCKCHAIN. In comparison to current educational platforms, those utilizing an Ethereum-based public blockchain are limited in functionality to managing student progress, saving grades, and academic multimedia data. These platforms employ smart contracts that can initiate a series of actions on the occurrence of predefined conditions. Different studies [14, 122, 221, 231, 265] have shown a similar architecture comprising three main layers: (1) Application Layer, (2) Communication Layer, and (3) Data Storage. The topmost layer contains the procedures for developing the graphical user interface. Therefore, the most used technologies refer to lightweight Spring Boot frameworks or React.js library for cross-platform development. The data storage layer allows smart contracts to be executed and saves data permanently in blocks. The middle layer acts as a communicator between the application layer and the storage layer. It contains all the procedures for developing smart contracts using the Go programming language, consensus algorithms to validate the inserted blocks, and Peer-to-Peer network protocols. As a matter of fact, the Ethereum protocol and architecture focus on smart contracts, which are to verbalize academic grades [14] and reward students who participate in classes [221] using cryptocurrencies [231]. As a final note, Kerr et al. [176] uses the same architecture but aims to replace current MOOC platforms and divides the storage layer into Infuria IPFS, Blockchain Ethereum, and MongoDB. Because of the large amount of memory requested for multimedia, files will be saved on IPFS, which returns a hash code on the Ethereum blockchain and acts as an index for future accesses. MongoDB, on the other hand, will collect student

analytics because of the high frequency of use of the platform and the large amount of data to be collected.

PRIVATE BLOCKCHAIN. Research studies employing private blockchain technologies utilize protocols like Hyperledger Fabric, Ethereum Private Blockchain, or MultiChain more frequently to perform extensive tasks than public blockchains. These private blockchain-based platforms usually follow a similar architecture to public blockchains, with a 3-layer architecture consisting of the Teaching Domain, Interaction Middleware, and Blockchain Infrastructure Domain, as observed in [80, 134, 195]. One of the primary motivations for employing private blockchains is to restrict access to resources only to recognized actors, such as students, faculty, institutions, and administrators, by establishing permissions for each of them [5, 134, 195]. However, Access and permissions management in private blockchains can be achieved by incorporating certain procedures in the platform architecture. For instance, with the Hyperledge Fabric protocol and a "*Certificate Authority*", valid credentials can be obtained to manage read and write permissions on the blockchain [134, 195]. Only users with permission recognized by the CA can access the resources. On the other hand, the Ethereum Private Blockchain protocol can use a relational database (MySQL) to manage user access and permissions [5]. In the former case, the change involves adding a CA procedure, which affects the data storage layer. In contrast, differences in the application and storage layers are required in the latter.

CONSORTIUM BLOCKCHAIN. As mentioned before, the consortium blockchain combines the features of public and private types while maintaining security and privacy requirements. It aims to provide a complete platform rather than one designed for specific purposes. As a result, the architecture of a consortium blockchain increase in complexity, as it needs to accommodate a wide range of functionalities and heterogeneous users. In a recent study [349], an 8-tier architecture using the Hyperledger Fabric protocol was proposed. The layers include (1) application tier, (2) learning systems and business abstraction tier, (3) cross-chain tier, (4) adaption tier, (5) contract tier, (6) security tier, (7)

storage tier, and (8) network tier. However, to simplify the design, the authors merged some layers into three main layers: (1) Trusted Open Learning Application, (2) Cross-Chain Layer, and (3) Blockchain Consortium. The Trusted Open Learning Application provides multi-purpose open learning applications such as credential sharing, student progress sharing, academic management, and intellectual property application management. The Cross-Chain Layer manages interactions between heterogeneous blockchains, including governance, task and permission management (via Certificate Authorities), and data adaptation through APIs. The Blockchain Consortium layer consists of the components that form a blockchain consortium network, including the structure of the blockchain, features for managing consensus in the network, and customization of smart contracts. While permission management is incorporated into the cross-chain layer in the architecture proposed in [349], another study [351] proposes a design that does not require permission management through Certificate Authorities and relational databases. The platform allows multiple universities on the network to share resources while guaranteeing intellectual property to all students.

In general, the design complexity and choice of blockchain type depend on the level of maturity of the applications to be developed for the educational domain. The lower level is suited for a public blockchain platform with limited functionalities that can address only a subset of educational objectives. In contrast, the middle level is better suited for private blockchains that require permission management since their access is restricted to authorized users. Consequently, private blockchains can support more diverse tasks than public blockchains. Finally, the highest level of application maturity is achieved through consortium blockchains, which encompass a complete set of software solutions for managing the entire university ecosystem, focusing on access management.

RQ_2 – Summary of the results.

☛ The type and complexity of a blockchain depend on the application's maturity. Public blockchains are limited to educational goals, while private blockchains have permission management and support more tasks. Consortium blockchains are designed for high-level applications like university management with access management features.

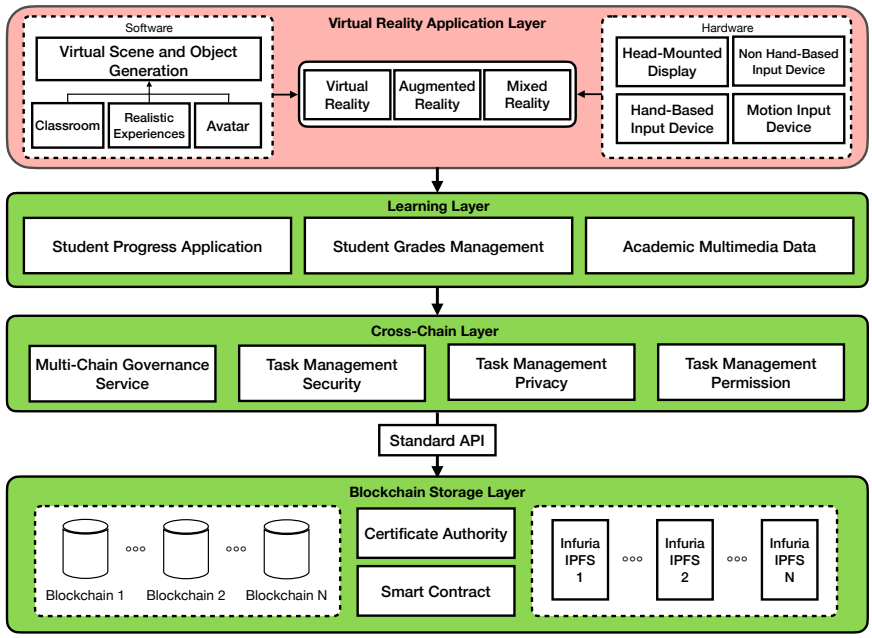


Figure 5.2: Proposed Application Design for Secure Educational Metaverse

5.4 TOWARD A SECURE EDUCATIONAL METAVERSE

The ultimate goal of our research was to understand how the blockchain technology can be exploited within the context of an educational metaverse. As such, we elaborate on our findings in an effort of providing insights into how the knowledge acquired through the systematic literature review can be tailored to account for the key aspects characterizing

the metaverse. Figure 5.2—also available in the online-appendix [100]—outlines a possible layout of a blockchain-based educational metaverse, which we designed based on the results of the study and use for the discussion.

In the first place, our findings demonstrate the rapid evolution of blockchain and its ability to facilitate various tasks and objectives. However, while blockchain seems promising, further investigation is required to determine how it can be adapted to the metaverse. In particular, the metaverse aims to create an immersive experience that bridges the physical and virtual worlds and encourages participation from both teachers and students. Integrating the blockchain technology into the metaverse is not a distant prospect, as it can be seamlessly incorporated into existing applications. The real advantage of the metaverse lies in its immersive potential, which requires further development of the application layer. The upper layer shown in Figure 5.2 represents the transformation from the application layer described in Section 5.3 to the virtual reality layer. In more detail, virtual reality can be enabled using software and hardware components to create virtual scenes, e.g., classrooms, realistic experiences and avatars. The latter empowers the immersive between the physical user and the avatar. Educational activities can be conducted using the *'Learning Layer'*, which contains multi-purpose open learning applications, including credential and student progress applications, academic management for student grades, and academic multimedia data, i.e., the tasks identified in the context of $\mathbf{RQ}_1$. Furthermore, the *'Cross-Chain Layer'* would represent a crucial software layer that enables interoperability between blockchain networks and the metaverse. Its modules provide the necessary governance, security, privacy, and permission features that ensure the smooth execution of cross-chain transactions [349]. Last but not least, it is worth noting that the blockchain layer focuses on several aspects. First, reference is made to the blockchain, in which different blockchains can be included to ensure access by multiple institutions or departments. Because of this heterogeneity of access, it is necessary to establish read and write permissions on the blockchains using a Certificate Authority

[349]. In addition, to ensure the management and use of multimedia data, an Infura IPFS must be associated with each blockchain. The use of such a resource is motivated by the fact that the blockchain cannot hold extensive data. Therefore, multimedia data will be saved on IPFS, generating a hash code to be kept on the blockchain. This hash code will be used as an index to retrieve the file [176]. It is essential to emphasize that each layer of the proposed design has been specifically tailored based on the outcomes acquired from $\mathbf{RQ}_2$. As a concluding remark, moving from the application layer to the virtual reality layer would address the limitations of existing applications, such as the lack of control over students' attention during classes and the prevention of unethical behavior during knowledge verification. However, creating realistic virtual experiences remains challenging due to the development complexity and the number of experiences required for each subject of study.

› **Take Away Message 1.** While the current blockchain technology is sufficiently advanced to be integrated within an educational metaverse, it should be adapted to take the immersive nature of metaverse into account—this requires further development of applications and interaction between virtual reality and blockchains. The proposed layout of a blockchain-based educational metaverse may serve as a conceptual basis to enable additional research on the matter.

5.5 THREATS TO VALIDITY

Some aspects might have biased the conclusions drawn in our systematic literature review. In the following, we discuss the major threats to validity and how we mitigated them.

Literature selection. A critical challenge of any systematic work is the identification of a complete set of primary studies. We approached the search process by adhering to the guidelines by Kitchenham et al. [183], who defined a set of standard steps to ensure the completeness of the information retrieved. It is worth remarking that the search has been applied

to multiple search engines, in an effort of collecting the largest possible amount of resources to further elaborate. Of course, we are aware that the reliance on the guidelines does not necessarily maximize the recall of the search process, yet it makes us confident of the procedures applied. Our future research agenda includes additional investigations into the matter that may corroborate the findings of our study. In addition, we released all the data employed in the study [100] to allow further researchers to replicate our work and possibly extend it with additional insights.

Literature analysis and synthesis. Upon completion of the search process, we proceeded with the systematic investigation of the resources identified. We applied a number of exclusion and inclusion criteria to make sure to identify the most appropriate set of primary studies that could address our research questions. Perhaps more importantly, we also applied a quality assessment of the resources retrieved in an effort of ensuring the soundness of the primary studies with respect to the quality of information required to address our objectives. These steps have been manually conducted: we acknowledge risks connected to subjectiveness and/or human error. To mitigate those potential issues, we defined a formal collaboration structure. On the one hand, the two first authors of the paper constantly collaborated during the steps of the systematic process, opening discussions and solving disagreements whenever needed. On the other hand, the other authors of the paper were involved in one-hour meetings every week: these meetings had the goal to double-check the entire process conducted by the first authors and provide further advice on the next steps to conduct. Such a formal structure made us confident of the conclusions drawn in our work.

6

BREAKING BARRIERS IN THE METAVERSE: A COMPREHENSIVE EXPLORATION OF ACCESSIBILITY FOR USERS WITH DISABILITIES

This chapter builds upon the paper published at the *Workshop on Artificial Intelligence with and for Learning Sciences: Past, Present, and Future Horizons* (WAILS) [108], where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the metaverse engineering perspective outlined in Chapter 4, this chapter shifts the attention toward accessibility, emphasizing inclusion as a fundamental design dimension of educational metaverse environments.

6.1 INTRODUCTION

The metaverse has emerged as a promising domain for enhancing human engagement experiences in modern society, characterized by deep interconnectivity and digital integration. This three-dimensional virtual environment provides a large plethora of possibilities across entertainment, education, work, and social interaction, redefining conventional perceptions of digital reality. The educational setting appears to be a valuable scenario for leveraging the metaverse, as it could offer a digital environment enhanced by analytical tools and technologies capable of monitoring not only the academic progress, but also the social and psychological situation of students. For example, previous work has argued that Artificial Intelligence (AI), which is one of the main driver technologies of the metaverse,

could play a crucial role in reducing accessibility barriers for students with disabilities. [38] However, despite the hype it is currently subject to, the metaverse still presents some issues; in fact, this paradigm shift has shed light on the accessibility and inclusivity challenges faced by individuals with disabilities in educational environment [229], highlighting the need for customized AI tools to address inclusivity challenges [38].

In this paper, we aim to identify the set of challenges that people with disabilities face when trying to access the metaverse, with the corresponding solutions currently available and envisioned at the state of the art. To do this, we perform a Systematic Literature Review (SLR) to gather information on the current landscape of accessibility in the metaverse, ultimately distilling practical take-away messages that we believe can drive further research. Moreover, our finding could leverage AI tools, enhancing the overall metaverse experience for everyone.

6.2 RESEARCH DESIGN

This study *aims* to identify the set of challenges that people with disabilities face when trying to access the metaverse with the corresponding solutions currently available and envisioned at the state of the art, with the *purpose* to highlight the difficulties that people with disabilities experience while accessing the metaverse. The *perspective* is from both researchers and practitioners: the former are interested in understanding whether the metaverse can support people with disabilities, and which measures could be taken into account to increase physical and social inclusion; the latter are interested in finding potential solutions to make the metaverse an inclusive place, enabling easy use of it. Furthermore, we believe that the results of this study may offer valuable insights for AI-powered monitoring and support of users in the metaverse.

Given our goal, we performed a Systematic Literature Review, i.e., a meticulous approach that involves various steps to gather, analyze, and report knowledge about the subject under examination. Following the

guidelines proposed by Kitchenham [181], we formulated two research questions driving our work:

> **RQ$_1$:** *What are the main challenges faced by individuals with disabilities when trying to access the metaverse?*

The primary objective of **RQ**$_1$ is to gain insight into the barriers people with disabilities encounter in the metaverse. This knowledge is essential to empower them, influence policy changes, and advance technology for more comprehensive virtual interactions. Furthermore, it raises public consciousness about the importance of digital accessibility.

> **RQ$_2$:** *What measures can be taken to enhance accessibility for individuals with disabilities, enabling their active engagement in the metaverse?*

With our **RQ**$_2$, we aimed to explore effective measures that an educational metaverse could implement to address the accessibility challenges identified. It aimed to offer meaningful perspectives on how individuals with disabilities can be integrated into this cutting-edge technology.

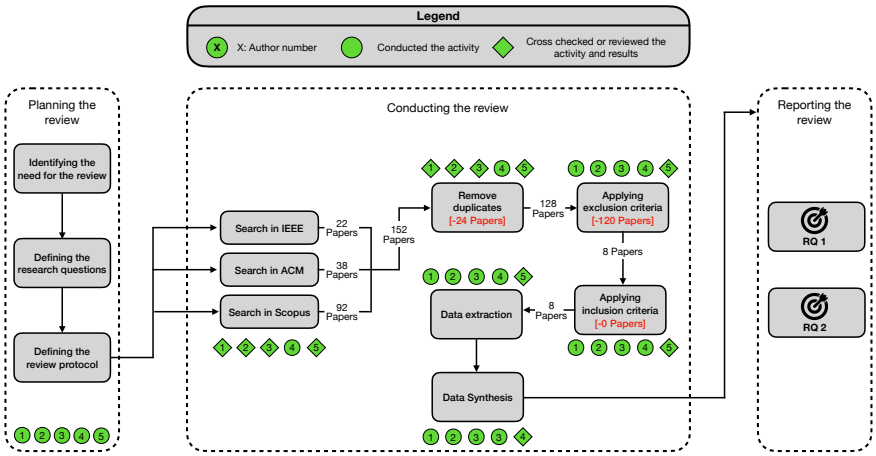
The main steps we employed to tackle the RQs mentioned earlier are outlined in Figure 6.1, where we depicted the various stages of the SLR process using grey round squares, which are elaborated upon in the subsequent section. We indicated the authors responsible for each phase using green circles. Additionally, we used green rhombuses to denote the authors who reviewed the completed activity. More information was provided in the online appendix of this paper [107]. As a final remark, we report the results by following the "*Systematic Review*" guidelines depicted in the *ACM/SIGSOFT Empirical Standards*[1].

6.2.1 *Search Strategy*

Initially, we meticulously analyzed and selected the most relevant research domains encompassing primary and secondary studies, including but not limited to *Metaverse* and *Disabilities*. It is important to note that our research only focused on the topic of metaverse, excluding virtual reality

[1] https://github.com/acmsigsoft/EmpiricalStandards

Figure 6.1: Research Process Overview.



due to the large number of results. This choice allows for a more focused accessibility examination within the unique and evolving metaverse concept.

After expanded the scope of the study, we enlarged our search by formulating a comprehensive list of synonyms to capture articles on the same topic but with other spellings. To develop a well-defined research query, we used the AND operator to combine the mentioned domains and the OR operator to combine the synonyms. As a result of this phase, we generated the following query:

Query: *"Metaverse" AND ("disability" OR "physical disability" OR "disabled people" OR "accessibility" OR "inclusion")*

The query was run on June 14th, 2023 against the three of the most known research engine, namely *IEEE Xplore*[2], *Scopus*[3], and *ACM Digital Library*[4], obtaining 152 primary studies.

[2] https://ieeexplore.ieee.org
[3] https://www.scopus.com
[4] https://dl.acm.org

6.2.2 *Article Selection Process*

After acquiring articles, we conducted an additional analysis to remove 24 duplicate entries that were identified from multiple data sources. To confirm the validity of our study, we strictly applied the exclusion and inclusion criteria outlined by Kitchenham et al. [181]. These criteria were designed to ensure that only the relevant articles addressing the research questions were considered. We removed any article that met at least one of the following exclusion criteria: (1) not peer-reviewed, (2) not related to metaverse accessibility, (3) not written in English, and (4) full text not available for free.

At the end of this phase, 120 papers were discarded, and the remaining 8 papers were considered suitable for further evaluation under the inclusion criteria. The papers that fulfilled at least one of the following inclusion criteria were considered eligible and moved on to the next evaluation phase: (1) articles describing challenges related to accessing the metaverse from people with disabilities, and (2) articles reporting measures to improve the inclusion of people with disabilities in the metaverse.

Following this phase, we have integrated all the examined articles into our study. However, when the number of available studies is limited, conducting a quality assessment may not provide significant insights, which is the case here. As a result, we decided to analyze the available content directly instead of engaging in a potentially less informative quality assessment. For this reason, the authors defined a data extraction form and read the primary studies together to gather relevant information to address the research questions. The data extraction process was constantly monitored by a senior researcher. After this, the last step regards the data synthesis of the extracted data, applying the *thematic analysis* [49] method to analyze and identify common themes arising from the text. The process followed an iterative approach, where each step aimed to refine previously emerged themes. Also in this case, the process was monitored by the senior researcher.

Table 6.1: Papers participating in the Data Extraction Process.

Ref	Authors	Title	RQ_1	RQ_2
[83]	Choi and Ka	Empirical Evaluation of Metaverse Accessibility for People Who Use Alternative Input/Output Methods	☑	
[113]	Dudley et al.	Inclusive Immersion: A Review of Efforts to Improve Accessibility in Virtual Reality, Augmented Reality and the Metaverse		☑
[136]	Gerling and Spiel	A Critical Examination of Virtual Reality Technology in the Context of the Minority Body	☑	
[145]	Hadi Mogavi et al.	Envisioning an Inclusive Metaverse: Student Perspectives on Accessible and Empowering Metaverse-Enabled Learning		☑
[172]	Kanza et al.	Geospatial Accessibility and Inclusion by Combining Contextual Filters, the Metaverse and Ambient Intelligence		☑
[218]	Meena et al.	Advancing Education through Metaverse: Components, Applications, Challenges, Case Studies and Open Issues		☑
[258]	Parker et al.	Towards an Inclusive and Accessible Metaverse		☑
[301]	Seigneur and Choukou	How Should Metaverse Augment Humans with Disabilities?	☑	☑

6.3 RESULTS

Table 6.1 provides an overview of the eight papers which we finally considered in the Data Extraction process, pointing out the research question(s) they allowed us to answer. In the following, we elaborate on the relevant data extracted from the analysed literature, providing insights on the state of the art on metaverse accessibility, and distil practical takeaway messages that we believe can be meaningful for the communities of researchers and practitioners on the matter.

6.3.1 *RQ_1: On the Challenges Faced by People with Disabilities when Trying to Access the Metaverse*

Our first research question drove us to assess what are the main challenges faced by individuals with disabilities when trying to access the metaverse.

We extracted data from three primary studies [83, 136, 301], gathering information on the current limitations of existing metaverse platforms, which lead to accessibility challenges for people with disabilities. We identified five main families of challenges, both related to the intrinsic immersivity of the metaverse, and coming from a sub-optimal implementation of the platform.

Lack of Alternative Textual Descriptions. A significant accessibility barrier in the current implementations of the metaverse consists of the lack of alternative textual descriptions for content and functionalities. Such limitation undermines comprehension for individuals with visual impairments. In fact, such individuals often depend on assistive technologies to navigate digital spaces, and without comprehensive descriptions, they are left at a disadvantage, and are prevented from enjoying the metaverse experience.

Lack of Appropriate Markups. As in the real world people with disabilities rely on markups to orient themselves and perceive the space they are living in, proper markups play a fundamental role in enabling assistive technologies to operate effectively within the metaverse as well. Such markups are essential for people with disabilities to navigate and interact with the virtual world; without them, they face significant challenges in orienting themselves and engaging meaningfully in the digital realm.

Orientation and Mobility Issues. This family of challenges is the most thoroughly discussed in the current literature, since it directly arises from the metaverse intrinsically being based on the immersive experience of mobility in the digital realm. In fact, interacting with components like virtual reality controllers often requires precise actions, such as pressing small buttons, or performing specific arm, hand, and finger gestures. This presents challenges for individuals with disabilities who may not be able to perform these actions in the same way or to the same extent as the technology expects. For example, individuals with motor limitations may face difficulties operating VR controllers, and those with spinal cord injuries may struggle to wear headsets, which are quite heavy. Furthermore, people who use crutches or wheelchairs may find it difficult or even impossible to

use VR controllers available at the state of the art, since VR technologies often require full-body engagement.

Inadequate User Interface. Inadequacies in the user interface lacking proper feedback further complicate the participation in the metaverse for individuals with sensory or motor impairments, as it can hinder their understanding of available platform functionalities and operations. For instance, if a specific arm is required for mid-air pointing and selection, it can pose difficulties for individuals who prefer to use their stronger or potentially different arm. Similarly, actions that demand a combination of speed and precision can be problematic for individuals with tremors.

Avatar Customization. A further issue faced by individuals with disabilities when accessing the metaverse is related to avatar customization. Upon entering the metaverse, users have the option to choose their avatar's appearance, customizing various aspects such as facial features, hair colour, clothing, and accessories. Consequently, users with disabilities should have the opportunity to decide whether or not to represent their disability, for example, by choosing to depict their avatar in a wheelchair.

☞ **Answer to RQ$_1$.** The main kinds of challenges faced by people with disabilities who are interested in enjoying the metaverse experience are related to lack of alternative textual descriptions and appropriate markups, orientation and mobility issues, inadequate user interface, and avatar customization. Some of the challenges are due to the intrinsic nature of the metaverse, e.g., moving in the Virtual Reality, others are caused by sub-optimal implementation choices, e.g., inadequate feedback provided by the user interface.

Although the metaverse is currently subject to massive hype coming from both industries and enthusiastic people, it is not free from issues that undermine the experience of individuals with disabilities. This raises the need for practitioners involved in the design and development of metaverse platforms to pay particular attention to accessibility and inclusivity, to avoid letting people out from this novel realm.

Takeaway Message 1. There is the need for stakeholders involved in the creation of metaverse realms to acknowledge current accessibility issues and correct them to grant all people to enjoy the experience independently from their disabilities.

6.3.2 *RQ_2: On the Countermeasures to Allow People with Disabilities to Enjoy the Metaverse*

After gathering information on the open issues and challenges experienced by people with disabilities when trying to access and interact within the metaverse, our second research question encouraged us to look for possible solutions to deal with such problems and guarantee accessibility to all individuals. A number of six papers contributed to answering such research question [113, 145, 172, 218, 258, 301], reporting accessibility proposals related to three disabilities, i.e., motor, visual, and auditory impairments.

Motor Disabilities. The family of orientation and mobility issues is the one that mostly concerns people with motor disabilities. To overcome such difficulties, a number of solutions have been proposed in the literature, aiming at helping individuals interact within the metaverse realm. Some examples include (1) a pen-like controller enabling input through wrist movement, (2) gaze- or voice-based command interfaces which do not require a direct match between physical movements and virtual ones, and (3) non-invasive biosensors to detect eye movements and facial expressions, enabling alternative modes of interaction.

Visual Disabilities. People with visual impairments necessitate audio- and tactile-based interfaces to gain an enjoyable experience in the metaverse. The literature suggested the use of creative solutions to enable a proper interaction, such as (1) tactile gloves improving object perception, (2) *canetrollers*, i.e., controllers mimicking the experience of using a white cane in virtual reality, which in turn need the enhancing of markups in the digital realm to provide acoustic feedback to users, and (3) toolkits to ma-

nipulate the surrounding environment, such as magnification, brightness and contrast adjustment, and object recognition.

Auditory Disabilities. Orientation issues mainly impact people with auditory disabilities, who may experience difficulties in perceiving the direction of sound in the digital realm. To overcome such struggle, the literature proposed a system which is capable of identifying three-dimensional sounds and translating them into vibrations indicating the direction of the sound source. Vibration motors are positioned inside the user's ears, and the frequency of vibrations varies between the left and right ears to denote the origin of the sound from different directions; in this way, the difference perceived within the two ears enables users to accurately recognize the direction of the sound.

Answer to RQ_2. Accessibility of the metaverse can be improved by intervening in the underlying technologies, such as virtual reality. Examples of solutions encompass alternative input methods, strengthening of markers, and tactile and acoustic feedback.

Although a number of solutions have been proposed to assist people with physical disabilities, further effort is still needed to allow individuals with other kinds of impairments to enjoy the experience in the metaverse.

Takeaway Message 2. Further solutions are needed to aid people with other kinds of cognitive disabilities, such as learning disorders, communication impairments and difficulties in social interaction.

7

SENEM: A SOFTWARE ENGINEERING-ENABLED EDUCATIONAL METAVERSE

This chapter builds upon the paper published at the *Information and Software Technology* (IST) [274], where the author of this thesis was the second contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the metaverse engineering perspective established in Chapter 4, this chapter applies its theoretical foundations by developing SENEM as a first concrete prototype of an educational metaverse.

7.1 INTRODUCTION

Nowadays, the interest in the vast field of the metaverse has been steadily growing and is starting to find its place in various contexts and applications. A metaverse is a highly immersive three-dimensional digital world where users interact in real-time with the environment and others through their avatars, i.e., digital representations of the users [290]. The rapid technological advances, the increasing digitization of numerous daily activities, ranging from work to entertainment, and, notably, the impact of the COVID-19 pandemic that led to the need for digital solutions have all contributed to the significant surge in research interest in this field [276]. Indeed, recently, researchers started to design and develop metaverse for a plethora of tasks, ranging from entertainment to software development, passing through medical simulations and education contexts.

One of the most challenging use cases of the metaverse is education, where it may support educators and learners from many points of view.

First, the remote nature of the metaverse could break down physical barriers between individuals, allowing geographically dispersed people to communicate and study together [38], letting individuals in less affluent living conditions to receive a good education. In addition, classrooms could benefit from students' diverse backgrounds by engaging in more interesting discussions [34]. Lastly, implementing artificial intelligence (AI) and visualization tools in the metaverse can further improve communication and collaboration, break down cultural and language barriers, and engage students with immersive instruments such as simulations and historical event reconstructions [34, 293].

Although there are various potentials for using the metaverse in educational settings, its limitations still impede its development and widespread adoption. The metaverse itself is a complex structure that needs to incorporate aspects across diverse fields [193], and this complexity becomes more and more evident when considering the educational context. Moreover, despite the possibility for the metaverse to offer immersive learning experiences and the large adoption of virtual technologies for education [184, 242], there is still a lack of investigations in the field, specifically an insufficiency of studies of optimal design for educational metaverse that aims to support educators and learners effectively. In this regard, one emerging primary issue is the lack of guidance on the specific functional requirements that an educational metaverse should possess. Indeed, when potential implementers of this technology do not have a clear set of criteria or capabilities to aim for, it can lead to inconsistent user experiences, limited effectiveness in educational outcomes, and ultimately, hesitation among educational institutions to adopt this innovative technology. These specific gaps in research outline our research problem, which points out **the lack of guidance on the specific functional requirements that an educational metaverse should enable**, which impacts the wider adoption of this technology in society.

This paper contributes to overcoming the limitations above through two main steps. First, we elicit and catalog a list of requirements following an engineering-focused approach. We conducted a literature survey

followed by semi-structured interviews to validate our requirements list further. Second, we implement these requirements within an open-source metaverse platform named SENEM, i.e., Software Engineering-eNabled Educational Metaverse, tailored for remote educational and collaborative activities. We envisioned the tool as a platform that will be instrumental in defining further studies and tools. Lastly, we empirically validate SENEM to evaluate its learnability, efficiency, and user satisfaction.

Our findings are encouraging and represent a foundational starting point for future research, which can build both on top of the list of elicited requirements and the implemented platform. We believe that our work makes a series of solid contributions, specifically:

- a set of functional requirements *device-agnostic*—i.e., general requirements that are independent of the implementation device—that an educational metaverse should implement, elicited with a literature survey, followed by semi-structured interviews;
- the implementation of a new metaverse platform, coined SENEM, that addresses the requirements identified;
- a platform's evaluation through a Rapid Iterative Testing and Evaluation research approach to assess its usability and usefulness.

The paper is organized as follows. Section 7.2 introduces the research questions of the study. Section 7.3 reports the research design of the literature survey process and the achieved results, i.e., the set of requirements. Furthermore, it describes the methodology for the interview study and the final set of refined requirements. Section 7.4 presents the prototype developed starting from the finding of the first research step. It describes the main characteristics and how each requirement has been mapped into a functionality of the tool. Section 7.5 reports the research design and the results of the final experiment operationalized to evaluate the usability of the prototype.

7.2 RESEARCH METHODOLOGY

The *goal* of the study was to identify and validate a set of functional requirements for the development of a dedicated educational metaverse through a software engineering approach. The final *purpose* was to establish a foundational suite of features imperative for the well design and efficacy of educational metaverses. The study involves two *perspectives*: researchers and practitioners. On the one hand, researchers are interested in comprehensively understanding functional requirements in the educational field; they could also expand the user's needs using the metaverse and enhance its features within the educational context. On the other hand, practitioners are interested in developing educational tools that are founded on well-designed guidelines and principles in order to ensure a plethora of quality aspects within a highly interactive environment.

7.2.1 *Research Questions and Method*

Our paper is structured around the following main goal:

> **◎ Research's Main Goal**
>
> *Define a comprehensive list of functional requirements for an educational metaverse, designing and developing the requirements within a novel and engaging prototype utilizing virtual reality technologies. Ultimately, it is essential to thoroughly assess the platform, focusing on usability parameters such as learnability, efficiency, and satisfaction.*

To reach the aforementioned goal, we identified two research questions that guided our research design.

> **❓ RQ_1**—What are the functional requirements that an educational metaverse should fulfill to let educators and learners reach their objectives?

The first research question aimed at identifying a set of starting requirements for an educational metaverse. We were interested in identifying functional requirements independent of the type of technology or device on which the metaverse can be implemented. We addressed the first research question ($\mathbf{RQ}_1$) by means of two research methods. In the first place, we conducted a *literature survey* to extract the currently available scientific body of knowledge to extract an initial set of requirements using a traditional technique [241]. Afterward, we operationalized a *semi-structured interview* with seven researchers and Ph.D. students with mixed backgrounds and levels of experience in the field to validate the initial set of requirements and extend it. On the one hand, the *literature survey* approach allowed us to synthesize the current knowledge on the matter. On the other hand, the *semi-structured interviews* enabled a deeper and more robust analysis of the desirable characteristics of an educational metaverse.

After obtaining the set of requirements for the educational metaverse, we then designed and developed a prototype based on such requirements. We aimed to evaluate the tool from a usability perspective and obtain ulterior insights from a practical operationalization of our findings. For doing so, we formulated the second research question.

> ❓ **$\mathbf{RQ}_2$**—To what extent can an educational metaverse prototype empowered by software engineering satisfy the usability requirements of learners and educators concerning social and educational aspects?

To address the second research question ($\mathbf{RQ}_2$), we adopt the *Rapid Iterative Testing and Evaluation* (RITE) research method [216, 217]. Through RITE, we evaluated and improved the tool's usability with 28 participants, resulting in a final platform—publicly available in our online appendix [271]—that can be used by other researchers to conduct further studies in the field. Participants were asked to complete a questionnaire to assess the prototype's usability, focusing on well-known metrics [168], i.e., *learnability*, *efficiency*, and *satisfaction* [87, 235]. The strategy was to incrementally enhance the usability of the prototype, achieving a stable

version through a systematic process. This also involved refining the initial requirements in a continuous quality improvement cycle, ensuring the prototype's evolution towards significant quality improvement in functionality and user experience urging an integrative, multimodal approach to enrich usability evaluation through ongoing iterative methods [208].

Figure 7.1 outlines the three steps employed to answer the proposed research questions. In particular, the first step—highlighted in blue—focuses on eliciting and validating requirements to provide a software prototype for educators and learners to perform specific educational activities addressing $\mathbf{RQ}_1$. In the second step, we utilize the requirements gathered in the first step to design and develop an educational metaverse, identifying actors and scenarios to be used. Thus, the third step—highlighted in yellow—employs the tool developed in the previous step to validate its usability with 28 participants, addressing the $\mathbf{RQ}_2$. The aforementioned three steps have been described in Section 7.3, 7.4, and 7.5, thereby providing a comprehensive understanding of the research methodology.

7.2.2 *Ethical Considerations*

Since our study involved human participants, let us discuss some of the ethical considerations that guided all the phases of the study. At our university, studies involving human participants do not require approval from an Ethical Review Board yet. Nevertheless, the interview and survey design took into account numerous ethical and privacy concerns. Below, we outline the precautions we have taken to ensure full compliance with ethical considerations:

- All activities related to interviews and surveys were entirely anonymous. We recorded no identifying information of the involved participants.
- We made it clear to participants that they could withdraw their survey submission at any time and that no information entered up to that point would be tracked.

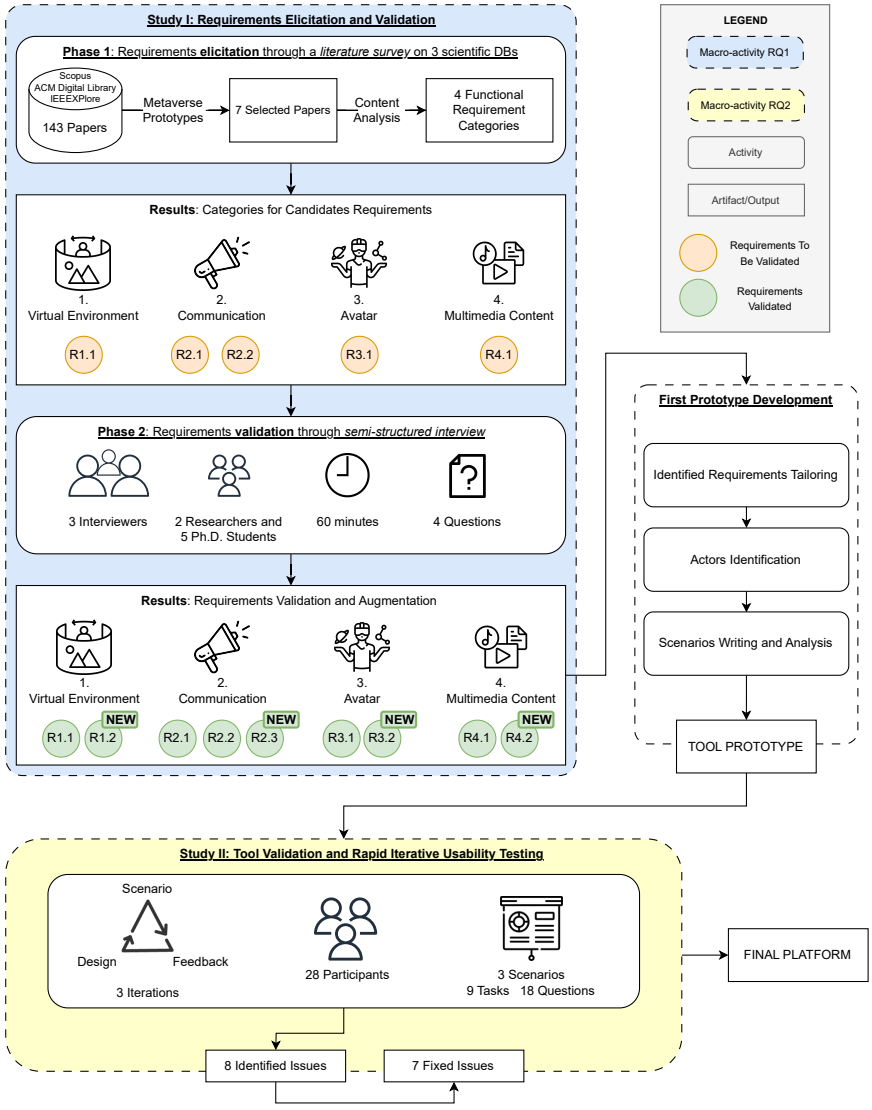


Figure 7.1: Overview of the research method.

- Before conducting an interview, we obtained explicit consent from each participant to record the session.
- Gender was the only sensitive personal data required in the tool's evaluation survey, which was collected for statistical purposes. However, it was an open-ended question, and participants were entirely free not to specify it.
- Access to the tool did not require any sensitive data. Participants were free to enter any name they wished and had complete freedom in customizing the appearance of their avatars.

These measures were all agreed upon and explicitly communicated by the authors of the paper. All of them were made clear to the participants before any surveys or interviews for our research were conducted.

7.3 STUDY I: REQUIREMENTS ELICITATION AND VALIDATION

In this section, we report the research method used to answer $\mathbf{RQ}_1$, i.e., the requirements elicitation and validation for an educational metaverse. Specifically, we report the design and results for the literature survey and interview; since these methods are consecutive—i.e., the second depends on the results of the first—we decided to discuss them in the order of execution.

7.3.1 *Literature Survey*

As a first step to address $\mathbf{RQ}_1$ we conducted a literature survey to collect the educational metaverse requirements that the research community has already identified in previous research. This step allowed us to have an initial set of requirements to extend and validate during the second step (i.e., the interviews). To conduct the literature survey, we followed the guidelines by Kitchenham and Charters [183], as detailed in the following sections.

7.3.1.1 *Design*

In the context of our literature survey, we performed three activities. First, we built a search string for identifying relevant literature; then, we collected the literature and checked if it was related to our objectives; in the end, we extracted knowledge to answer our RQ_1.

Starting from the first research question, we highlighted the main terms for our research. When defining the search string, we followed the well-established guidelines by Kitchenham and Charters [183] to ensure the completeness of the article collection phase.

Indeed, we were interested in obtaining the requirements for a "*virtual environment*" to conduct "*educational activities*", leading to **metaverse** and **educational environment** as target domains. At this point, we derived a set of alternative spellings for broadening the scope of our research as follows:

METAVERSE ("*metaverse*").

EDUCATIONAL ENVIRONMENT ("*distance learning*" OR "*online learning*" OR "*distance education*").

In constructing the query, the disjunction of synonyms was achieved by utilizing OR operators, whereas an AND operator established the conjunction of the target domain. This approach enables the query to be used effectively across different online data sources. The keywords of the second part of the strings focus mainly on the remote learning modality. This choice was motivated by two main reasons: (1) the surge in publications on the metaverse indeed started in the (post-)COVID-19 period, i.e., after 2020, when there was a growing need to devise digital solutions to continue remote education [276]; (2) literature advocated the role of the metaverse as a tool to support geographically distributed teaching since such distributed learning provides the opportunity for more people—facing various issues—to continue learning [22] and also shows outstanding commercial advantages [99].

General Search String

((“metaverse”) AND (“distance learning” OR “online learning” OR “distance education”))

We ran the search string against three well-known research engines, i.e., *Scopus*, *IEEEXplorer*, and *ACM Digital Library*, reporting 143 documents in total. Upon conducting a comprehensive review of the collected literature, we examined and chose papers pertaining to educational metaverse prototypes. This approach has allowed us to identify the most relevant and informative research papers, which have been subsequently selected for an in-depth analysis. The initial step in extracting data involves a *qualitative content analysis* [72], whereby researchers carefully examine the relevant data to extract meaning and concepts. This process entails two essential phases: (1) iterative development of a codebook and (2) application of the codes to the raw data. In the present study, the researchers who conducted the data extraction also developed the codebook, while the primary author applied the codes to the raw text. The data were sufficiently clear, and we did not require additional software tools during this phase. We report an example of how the first and second authors applied the data analysis procedure, passing from raw data to codes:

RAW DATA: “*The VoRtex prototype contains a virtual environment classroom with 3D material that supports learning. The virtual environment classroom contains a table, chairs, projectors, a video and presentation panel, and a virtual agent that assists the avatars during lectures. [...] The users can communicate using the chat or voice systems.*”

CODES: *Virtual environment; using 3D learning materials; communication systems; avatar representation.*

All codes were extracted using an inductive approach from raw data. We analyzed the codes and their frequency to extract categories and functional requirements. However, it is important to emphasize that in cases of disagreement, we confidently engaged in discussions to resolve. Additionally, in an effort to minimize subjectivity in non-explicit requirements,

the third author of the paper provided invaluable assistance in resolving any conflicts that may arise. As a final remark, the entire process was subject to continuous supervision by two senior researchers who diligently double-checked the activities performed to mitigate any inconsistencies that crept in.

7.3.1.2 *Analysis of the Results*

In our research, we conducted a thorough literature survey to identify the candidate requirements for developing a prototype metaverse tailored to educational purposes. In the following, we reported on the relevant literature obtained during our survey process. Then, we presented the identified requirements divided into categories extracted during our analysis.

COLLECTED LITERATURE ANALYSIS Table 7.1 summarizes the papers collected from the literature analysis.

EXTRACTED REQUIREMENTS In the field of education, prototypes are built using different technologies and serve various purposes. In addition, research has emphasized the significance of active learning in virtual classrooms. This approach prioritizes learners' engagement in activities, allowing them to actively participate in these activities rather than relying on passive learning methods such as lectures or teacher-led instruction. This stimulates learners to collaborate, participate in group activities, and engage in discussions, increasing teamwork, decision-making, and communication skills [234]. These recommendations have inspired the design of our tool and, therefore, implement an active learning environment. On top of this active learning environment, we identified several unique characteristics to be considered in an educational metaverse. Their shared attributes help us to determine the needs categories that should be integrated into our prototype as candidate requirements. The following list describes the obtained categories and the relative requirements found:

VIRTUAL ENVIRONMENT It is imperative to emphasize the importance of virtual environments as a fundamental element that distinguishes

Table 7.1: Summary of the Collected Literature

Reference	Description
Duan et al. [112]	A metaverse prototype developed with the primary aim of allowing new learners to explore the campus and create shareable digital content. Hence, the focus is on building a **virtual environment** that closely replicates the physical environment, including classrooms, rooms, and offices, where users can move freely. Additionally, users can **communicate** with one another and establish social and collaborative relationships through voice or text chat.
Jovanovic et al. [170]	VoRtex, a Unity-based platform allowing multi-user interactions in a 3D **virtual environment**. With VoRtex, online classes can be conducted using **avatars** to interact with other users and access **multimedia contents**, such as teaching materials. The virtual classroom is designed to resemble a real-life classroom with desks, chairs, and projectors. Moreover, avatar's **communication** is allowed through the use of text chats that support speech-to-text, making it easier for users to complete writing tasks.
Shen et al. [304]	A prototype called V-Classroom that uses Internet of Things (IoT) devices such as sensors and high-performance cameras to convert physical university classrooms into 3D **digital environments**. V-Classroom does not use avatars to represent learners: they are automatically inserted into the virtual classroom with no possibility to explore the environment.
Sin et al. [307]	An educational metaverse based on a system of nodes. Each node represents an academic course and allows for **multimedia content** sharing. However, although the proposed prototype encourages exploration, the nodes only provide access to new environments without emphasizing user interactions.
Ng et al. [234]	A virtual platform to enrich learners' educational experiences. It allows users, even if not represented by an avatar, to explore and observe **virtual environments** with a 360-degree view of the entire developed environment. Moreover, exploration and observation were enhanced by connecting and **communicating** with other users to exchange information according to specific requirements.
Song et al. [314]	The Learningverse, a metaverse platform which is based on three key concepts: (1) the interaction in the platform through an **avatar**, which is customizable within the platform itself; (2) a 3D **virtual environment** in which users can **communicate** and cooperate to learn with many 3D objects and different **multimedia content**, such as images, videos, or text resources; (3) a peer-to-peer network to allow users to connect via Internet.
Schaf et al. [296]	The 3D AutoSysLab, a metaverse platform prototype, to assist students in hands-on electrical engineering lab sessions. The prototype presents a Mixed Reality system that integrates a 3D **virtual environment** and physical objects for the lab session. Users are represented by their **avatar**, and they must **communicate** and cooperate to complete the assigned task. The learning material is shown in the virtual world as **multimedia content**, such as images or slides.

a metaverse from a traditional 2D platform, as pointed out by Mystakidis [229]. These environments facilitate user autonomy in exploring and navigating virtual settings. Creating such environments entails replicating familiar areas on a university campus, such as classrooms with desks and chairs. Users can interact with these elements to attend lectures or explore non-educational spaces.

R1.1 *The system should allow users to explore all virtual environments. Exploration consists of interacting with objects, rotating the view, zooming in on components of interest, and walking.*

COMMUNICATION Virtual learning environments should not only function as a means for learners to enhance their skills but also include features that facilitate efficient communication. Such communication should occur in both directions, among learners and among learners and instructors, and should be complemented by two separate modes: text chat and voice chat. Those methods will empower users to effectively exchange and deliberate on educational matters versatilely.

R2.1 *The system should allow users to facilitate communication by allowing them to use a voice channel.*

R2.2 *The system should allow users to facilitate communication by allowing them to use a text channel.*

AVATAR Within the metaverse, avatars play a crucial role in crafting a digital identity and encouraging social connections in the virtual realm. They empower users to undertake, communicate, socialize, and participate in various activities tailored to their tastes, whether rooted in reality or imagination. As such, avatars are essential for personalization and interaction within the metaverse.

R3.1 *The system should allow users to have a digital replication of themselves to attend a large number of activities.*

MULTIMEDIA CONTENT The effective management and representation of digital content plays a crucial role in the success of a metaverse.

This allows users to easily create, share, and consume content. This functionality has added significance in an educational metaverse as it offers access to various educational resources, such as images, videos, presentations, audio, and interactive media. The availability of such content enhances the educational potential of the metaverse.

R4.1 *The system should allow users to projector and share educational multimedia resources.*

7.3.2 *Interview*

Our second investigation consisted of an interview study. Specifically, we conducted *semi-structured interviews* [159]; they combine specific questions (for studying the main topic to be covered by the research) and open-ended questions (to elicit unexpected types of information). The conduction of an interview holds significant importance for two fundamental reasons: (1) to validate the requirements that have already been established in the literature, thereby adding valuable contribution to the existing body of knowledge, and (2) to elicit various perspectives from educators based on their positive and negative experiences during the COVID-19 pandemic, but also to have their vision about the field.

7.3.2.1 *Design*

By following the guidelines by Hove and Anda [159], we crafted a semi-structured interview with straightforward and accessible questions for our participants. For the interview, we decided to utilize an online format via ZOOM[1] as our communication tool. This choice was made due to its ability to record the meeting without the file expiring and its automatic transcription feature. However, as technical issues may arise, we had three interviewers present. Our primary interviewer was the first author, with the second and third authors manually transcribing concepts and offering support throughout the interview. It is worth noting that all participants

[1] Zoom: https://www.zoom.us

present during the meeting were duly informed of the recording that was to take place and provided explicit consent.

The semi-structured interview consisted of three parts. It began with an introduction and ice-breaker where participants shared their research interests and demographic details to provide context on their career backgrounds. Then, the first author then outlined the study's goals and explained key metaverse concepts like interaction techniques and educational technologies, necessary because of the novelty of the topic. After confirming participant comfort, the main interview began with questions divided into four categories: virtual environment, communication, avatar, and multimedia content, as detailed in a previous section on candidate requirements.

All data collected were combined and handled in accordance with data regulations, which specified that information would be used just for research purposes (more details about the questions can be found in our online appendix [271]). Participants were informed of these policies to ensure transparency and clarity throughout the process. After completing all interviews, the first and second authors collected the text, comparing the automatic and manual transcriptions. Then, they conducted a quality assessment phase to evaluate the overall data quality for the content analysis phase.

7.3.2.2 *Participants*

Our study required participants with a certain level of proficiency in educational settings. We have defined specific criteria for each participant, including high skill and expertise in software engineering, human-computer interaction, and computer science education. To meet these requirements, we have chosen *convenience sampling*, a non-probabilistic approach that selects participants based on proximity, availability, and willingness to participate [146].

Our sample consisted of 2 highly experienced senior researchers and 5 Ph.D. students enthusiastic to participate in the study. The motivation behind the decision to recruit both faculty and students was that only by

combining feedback from both was it possible to capture all the facets needed to achieve our goal. We carefully selected diverse participants, including 4 male and 3 female participants. Senior researchers have dedicated over 20 years to research and academia. Indeed, their areas of expertise range from software engineering, focusing on application design and usability engineering, to computer science education. The Ph.D. students' research topics are equally impressive and cover a broad range of software engineering domains, including software engineering for accessibility, software engineering education and training, and human and social aspects of software engineering.

7.3.2.3 *Procedures*

To initiate the process, we utilized a scheduling tool to arrange individual interviews with our 7 participants. We decided to conduct each interview individually to allow each participant to freely discuss their point of view. As a first step, we obtained permission from each interviewee to record the entire session. Once this permission has been explicitly obtained, we connected to the ZOOM platform with the participant. Each participant's interview lasted for 60 minutes. The first part of the available time was used to break the ice with the interviewee and provide a useful informational overview of the topic. Then, one by one, questions were posed to the interviewee, who was free to discuss openly, guided by the interviewers. The call was recorded, but at the same time, the interviewers took note of the key points highlighted from the perspective of each of the interviewees. At the end of the discussion, the interviewee was allowed to add any final comments, after which the interview was terminated.

7.3.2.4 *Analysis of the Results*

All the semi-structured interviews confirmed that the candidate requirements obtained through the comprehensive literature survey were suitable for inclusion in an educational metaverse. However, the contribution of 7 respondents in each candidate requirements category was even more significant, as further reported in the following.

VIRTUAL ENVIRONMENT When participants were asked to envision an educational virtual environment, it became clear that greater freedom to explore could ignite curiosity and facilitate learning, enabling learners to pursue their interests independently. Furthermore, participant P4 provided an insightful perspective: "*During the COVID-19 pandemic, I attended several meetings on Zoom, each with a different name and password. An educational metaverse should provide the same structure, with scalable rooms with passwords and the ability to facilitate multiple simultaneous sessions to foster interaction and social relationships between learners and educators.*". Considering this, we have added a scalable room system requirement to the criteria for virtual environments:

R1.2 *The system should allow users to create simultaneous sessions that are protected by a password.*

COMMUNICATION All 7 participants confirmed during the interview that communication in a metaverse should incorporate textual and vocal techniques. However, an exciting reflection emerges from the interview with P1, who states: "*Utilizing both methods is crucial since the textual technique allows for retaining important information, whereas the vocal approach promotes social interaction and enhances communication efficiency. Moreover, the vocal approach creates a sense of presence akin to physically being with another individual. Additionally, we should include nonverbal interactions such as facial expressions and gestures to enhance the immersive experience and perception of presence.*". The authors have unanimously recognized this view as one of the most relevant, as it is intrinsically linked to the closest definition of a metaverse. However, it should be noted that the accurate representation of facial expressions in a metaverse is still a challenge. To overcome this limitation, the feature of "Emotes", which consist of predefined facial expressions or body movements activated at the user's discretion, was introduced:

R2.3 *The system should allow users to interact using non-verbal interaction, represented by "emotes".*

AVATAR Regarding the creation of avatars, i.e., digital representations of users within the metaverse, all participants agreed on their relevance for facilitating interactions. However, when we asked what main aspects should characterize it, P3 pointed out,"*I think you should not classify features as more or less important. Everyone might have different opinions about it. From my point of view, I would like to have the ability to customize my avatar according to my preferences. In real life, I can decide how to comb my hair, what to wear according to my mood, and add any accessories. This flexibility could also include users with disabilities.*". This comment stressed the importance of allowing users to customize their avatar from two perspectives: (1) physical characteristics, such as skin, lip, and eye color; (2) personal characteristics, including hairstyle, clothing, and accessories:

R3.2 *The system should allow users to customize their avatars based on physical and personal characteristics.*

MULTIMEDIA CONTENT Finally, participants were asked to share their preferences for multimedia content in an educational metaverse. Participants emphasized the importance of projecting and presenting slides or images for educational purposes. Moreover, the interview with P2 highlighted a key point: "*In my lectures, slides are essential to illustrate my talk and provide references to students about what I am explaining. However, using a whiteboard, I always try to change the use of slides with practical examples*". Based on this observation, it was decided to include the virtual whiteboard as an additional multimedia requirement:

R4.2 *The system should allow users to interact with a whiteboard, sharing all the content with other users.*

Summary of the Requirements Elicitation Study (RQ_1)

The requirements obtained during our literature survey (Section 7.3.1) were validated by the answers provided by the participants of our interview study (Section 7.3.2); moreover, the last study also corrob-

orated the requirements with new ones. The overall set of elicited requirements is reported and described in Table 7.2 .

7.4 SENEM: A NOVEL SOFTWARE ENGINEERING-ENABLED EDUCATIONAL METAVERSE

In this section, we describe the tool developed according to the requirements elicited in the first phase of the study (Section 7.3), while in the next Section 7.5 we present the evaluation of and improvement strategy for the tool. We decided to report in the following order because of the impossibility of understanding the evaluation experiment without having an overall idea of the tool composition and function.

The developed platform is publicly available on its GitHub repository.[2] The repository contains both the Unity3D project with the source code and the already built application for Windows and MacOS.

7.4.1 *Requirements Implementation*

In the following, we describe how the requirements identified in the first phase of the study (see Table 7.2) have been concretely implemented into the metaverse platform. Figure 7.2 shows an overview of the tool architecture and event flow—better discussed in Section 7.4.3—focusing on which component implements the identified requirements.

REQUIREMENTS OF VIRTUAL ENVIRONMENT Such a category refers to requirements to provide users with an environment to facilitate user autonomy in exploring and navigating virtual settings.

- *Scalable rooms system.* The platform offers real-time connection with other users as a critical feature. This connection has been implemented through a *room system*, allowing users to choose whom

[2] SENEM Github Repository: https://github.com/vipenti/SENEM_Metaverse

Table 7.2: Summary of the Functional Requirements for Study I

Category	Functional Requirement	Source
Virtual Environment	R1.1: *The system should allow users to explore all virtual environments. Exploration consists of interacting with objects, rotating the view, zooming in on components of interest, and walking.*	Literature Survey
	R1.2: *The system should allow users to create simultaneous sessions that are protected by a password.*	Interview
Communication	R2.1: *The system should allow users to facilitate communication by allowing them to use a voice channel.*	Literature Survey
	R2.2: *The system should allow users to facilitate communication by allowing them to use a text channel.*	Literature Survey
	R2.3: *The system should allow users to interact using non-verbal interaction, represented by "emotes".*	Interview
Avatar	R3.1: *The system should allow users to have a digital replication of themselves to attend a large number of activities.*	Literature Survey
	R3.2: *The system should allow users to customize their avatars based on physical and personal characteristics.*	Interview
Multimedia Content	R4.1: *The system should allow users to project and share educational resources.*	Literature Survey
	R4.2: *The system should allow users to interact with a whiteboard, sharing all the content with other users.*	Interview

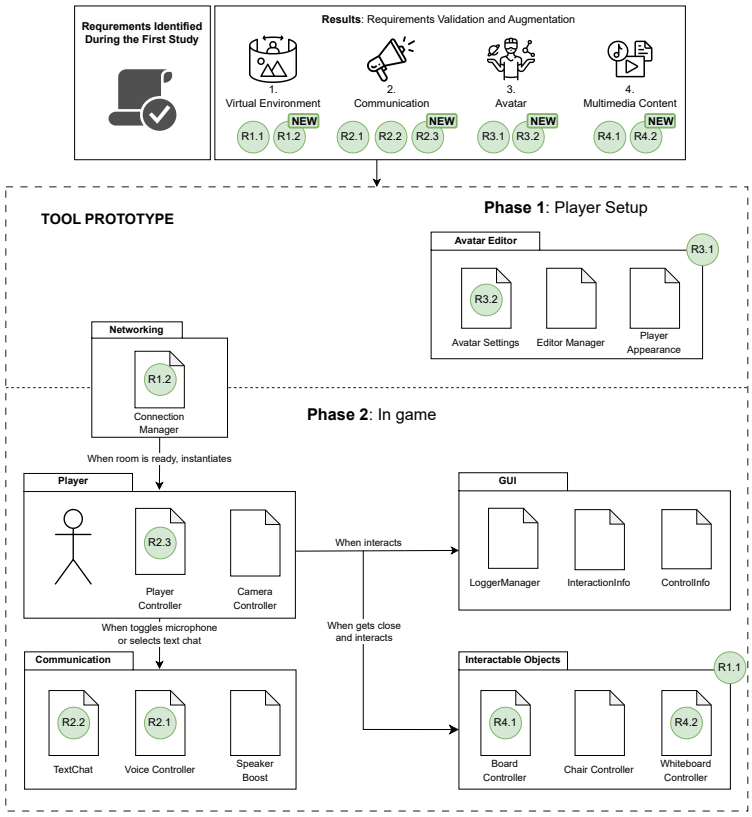


Figure 7.2: Overview of the prototype and requirements.

to connect with. The first user intending to connect will create the room, providing it with a password, and then share this information with the other interested people. They can use it to connect to the room and initiate real-time interaction with other users. When each user disconnects from the room and it becomes empty, it is automatically deleted.

- *Free three-dimensional exploration.* Interaction with the platform occurs freely, exploring the 3D environment through one's avatar. Users can walk, sit, and interact freely with various objects in the scene. They can rotate their view and adjust the zoom level of their perspective as well.

REQUIREMENTS OF COMMUNICATION Such a category refers to requirements to provide users with tools and methods for communicating with each other easily.

- *Voice communication.* Users can engage in real-time communication with each other through voice chat. Using their microphones and voices, they can make their avatars speak and hear others as in genuine verbal communication. The voice chat is also equipped with proximity and three-dimensionality features, allowing the tone of voice to vary based on the distance and position of the interlocutor.
- *Text communication.* Users can communicate through text chat, which is readily available and visible in the platform's user interface. Such a chat always displays the last ten sent messages on the screen. Additionally, users can review the entire chat history after the session, through a log file stored locally on their device—as notified upon accessing the virtual classroom.
- *Non-verbal interactions.* Users can use some gestures to interact with each other non-verbally. Avatars are equipped with communication animations, such as waving, clapping, or raising a hand. All users in the virtual classroom are notified when one of these actions is performed to decrease the likelihood of missing actions not directly seen by the avatar.

REQUIREMENTS OF AVATAR Such a category refers to the possibility of users creating an avatar.

- *Avatar's customization.* Users can customize the avatar's appearance through which they interact with the platform. The tool provides a dedicated editor to modify various avatar elements, including skin, hair, eyes, and more.

REQUIREMENTS OF MULTIMEDIA CONTENT Such a category refers to requirements to provide users with tools to easily create, share, and consume content.

- *Projection and presentation of multimedia content*. Users can broadcast multimedia content in the virtual classroom through the available projector. Educational materials like slides or images can be uploaded and displayed during the platform's runtime. Users can control the content shown on the projector and make it visible to everyone else.

- *Interaction with the whiteboard.* Users can write on the whiteboard inside the classroom using their keyboard. One user at a time can approach the whiteboard and start writing, and what they write will be visible to everyone, supporting interaction and communication.

7.4.2 *Actors of the system*

This section introduces the actors that can be found in the platform and what distinguishes them from each other. The functionalities accessible to each user vary slightly depending on their role in the virtual classroom. Such a division is not clear-cut within the environment, but it will be used to better describe potential interactions within the tool.

The *room owner* is the first user intending to connect, thus creating the room and setting its password. This user also has the complete chat and access log on their device. All other users connecting to the room are *attendees* and can interact with each other and use all the communication methods. If the room owner crashes or disconnects, the second user who joined takes over their role to prevent the entire room from being deleted. The new room owner has access to the room's log from when they assumed the role. When a user approaches the projector, they can take on the role of *presenter* and control the displayed content. There can be only one presenter at a time, and the role is passed when a new user approaches and interacts with the projector.

7.4.3 *Architecture*

In the following section, we describe the architecture behind the tool and the event-based system that governs user interaction with the platform. The application was developed with the UNITY3D game engine, which shaped its architecture into three core components: (1) the game scene, (2) game objects, and (3) assets. The game scene forms a 3D virtual environment where all elements are integrated and interactions take place. It includes the virtual classroom scene, which houses most application logic, and the character editing scene. Game objects, such as avatars and GUI elements like buttons and text fields, consist of scripts, meshes, and textures that determine their functionality and appearance. Assets cover all resources used in the scene like sounds and animations.

The application operates on an *event-based* logic, where functions are triggered by specific events rather than a central management system. This involves code scripts attached to each component, activated by respective events. The code scripts can be logically organized into clusters that represent different functionalities of the platform. User interaction with the app is split into a setup phase, where users create avatars, and an in-game phase that starts when entering a room, with functions executing based on user actions. Throughout, networking features run continuously to manage user interactions and room dynamics.

7.4.4 *Graphical User Interface (GUI)*

In this section we illustrate the different screens the user encounters and the commands through which they can interact with the environment.

Figure 7.3 displays the interface of the tool's startup screen. When users open the application, they encounter the main elements shown in the green squares. The enumerated components are explained below.

1. The form with login information: In the first text input area, the user enters the name that will be displayed to others in the classroom, and in the second, the password of the room they want to join.

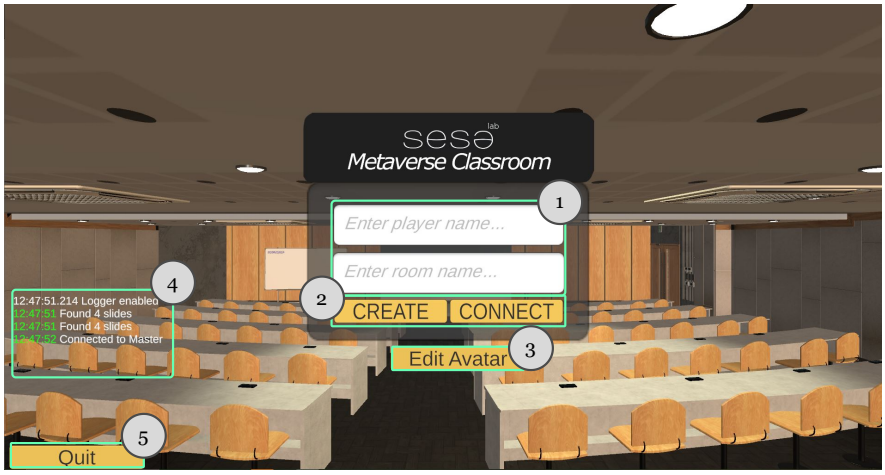


Figure 7.3: Starting screen of the tool.

2. *Create* or *Connect* to room buttons: If a user is the first to connect, after entering the data, they will press the *Create* button to create the room. Otherwise, they will press *Connect*. In both cases, if this operation is successful, the user will have access to the virtual classroom.

3. The *Edit Avatar* button: This will take the user to the avatar creation screen.

4. The logger: It displays information about the application's status. If the log shows "Connected to Master," the server connection was successful, and the user can create and access rooms.

5. The *Quit* button: It allows to exit the application.

When the *Edit Avatar* button is pressed, the user is redirected to the avatar editing screen. In such a screen (see Figure 7.4), the user can customize their avatar's appearance, which will then represent how other users see them within the virtual classroom. The enumerated components are explained below.

1. Editing window: The interface through which the user customizes their avatar's appearance. It is divided into sections, each control-



Figure 7.4: Avatar editing screen.

ling the color and shape of one of the customizable components: uniform, skin, lips, eyes, hair, beard, eyebrows, and accessories.

2. Avatar preview: The model that shows real-time changes to the appearance made through the editing window. It can be rotated and zoomed in to inspect it thoroughly.

3. *Load Game* button: It allows to save the changes and return to the application's initial screen.

4. Info label: It informs users of the commands to control the model during the editing session.

Upon entering a room, users find themselves in a 3D virtual environment, viewing the virtual classroom and other users in real-time from a first-person perspective, with the avatar's camera positioned at head level. The interface, shown in Figure 7.5, includes the following components:

1. The virtual environment and other users: Users see each other's avatars and names, observe real-time movements, and hear voice chats, with the intensity varying by distance.



Figure 7.5: Virtual classroom's interface.

2. Text chat: Displays the last ten messages along with the sender's name and timestamp. A text input field allows for sending new messages.

3. *Leave* button: It returns the user to the platform's initial screen.

4. Info label: Displays contextual information, such as whether the user is near the stage or a chair, and whether these are occupied or available

5. Voice chat info: Shows the detected input device and microphone's status—i.e., *muted* or *unmuted*.

6. Command info and *Options* button: Provides quick command info and access to settings for microphone sensitivity, resolution, and ambient sound adjustments.

Within the virtual environment, users can interact with various elements to access different features provided by the tool. Figure 7.6 displays the following elements that users can interact with, namely: (1) the whiteboard, where they can write as an editable text area shared by all users in the room; (2) desks and chairs where users can sit and observe, as well as interact

with the presenter; (3) the stage and projector, where the presenter can display and control slides for other users to see, and view them themselves while speaking, thanks to the synchronized display in front of the projector.

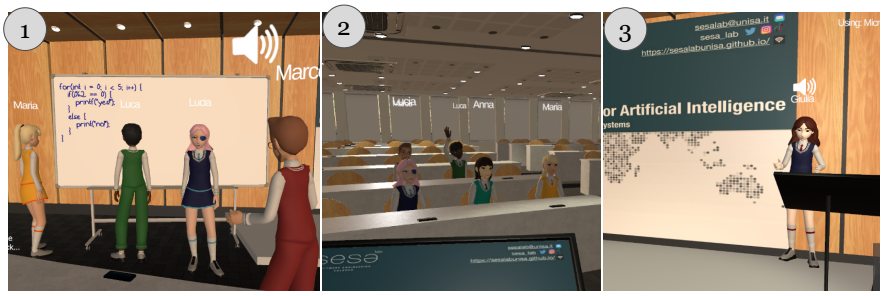


Figure 7.6: Users interacting with the virtual environment.

7.5 STUDY II: SENEM VALIDATION WITH RAPID ITERATIVE TESTING AND EVALUATION (RITE)

In this section we describe the method used to address **RQ**$_2$, i.e., to evaluate the tool's usability and improving it until its final version. In particular, we first present an overview of the *Rapid Iterative Testing and Evaluation (RITE)* [216, 217] approach. Then, we describe the tailored version of RITE for our study.

7.5.1 *The RITE Methodology*

RITE was first introduced by Medlock et al. [216, 217] in video game development. Specifically, the approach was used to identify and fix issues—from a usability point of view—of the tutorial of Age of Empires II.[3] Concretely, RITE consists of evaluating a tool's usability through an iterative approach, where each iteration consists of (1) testing the tool with a set of potential users and (2) modifying the tool according to par-

[3]Age of Empires II (HD) official website (accessed on September 2023): https://www.ageofempires.com

ticipants' feedback [216, 217]. The decision of what to fix or ulteriorly test is in charge of the research team, and the process should end when the product reaches enough quality.

7.5.2 *The RITE Evaluation*

We applied RITE to evaluate the usability of our tool and its functionalities. Specifically, we represented usability in terms of three well-known aspects [87, 235]:

- *Learnability*, i.e., the measure that represents how easy it is for users to learn how to use the tool.
- *Efficiency*, i.e., the trade-off between the resource used—expressed in terms of completion time, mental, and communication effort—and accuracy and completeness with which the users achieve their goals.
- *Satisfaction*, i.e., the user's satisfaction when using a tool in a specific context.

The choice of opting for these metrics rather than alternative ones, e.g., the System Usability Scale [55], was mainly driven by our willingness to use metrics that might have assessed SENEM under multiple perspectives, such as learnability, efficiency, and satisfaction. Indeed, the metrics by Nielsen [235] and by Constantine and Lockwood [87] allow to consider a broader spectrum of variables, hence providing insights that might have better reflected the overall experience of users interacting with SENEM. Furthermore, these metrics have been largely recognized in the field of usability assessment [168]. In the following, we present the experiment design for evaluating the above-mentioned aspects as well as the obtained results and implications.

7.5.2.1 *Experiment and Survey Design*

Our evaluation consisted of the execution of 9 tasks described—described below—using our platform by a set of participants.

T1 Creating an avatar using the built-in editor

T2 Performing the login in the application

T3 Using the projector and associated tools to share and present slides

T4 Sitting on chairs in the room

T5 Communicating performing an avatar's emote

T6 Communicating using the built-in voice system

T7 Communicating using the built-in textual chat

T8 Writing something on the whiteboard

T9 Writing something on the notes' tablet

The same tasks—or a subset—were executed at each iteration to identify and fix issues, and we selected the tasks to test all the platform functionalities. Such process continued until (1) no more critical issues were identified, i.e., issues preventing users from performing tasks, and (2) the participants agreed that the tool's usability was good. To evaluate the outcome of each iteration, we relied on surveys—administered to the participants after each test—and findings obtained during the iteration execution.

EXPERIMENT DESIGN According to the RITE approach guidelines, we evaluated the tool through a set of tasks encompassing real-world use scenarios. The first one consisted of a *Remote seminar*: a group of individuals was asked to attend a seminar in the metaverse. In particular, one of the participants was the speaker researcher, while the others were the attendees, composed by both students and other researchers. In the second one, a group of students was asked to deliver an *exam* project's presentation

in the metaverse. This time students involved in the evaluation played the presenter role in turn and the teacher participated as an attendee. Last but not least, participants were asked to collaborate to perform a *group activity* in the metaverse. In particular, each group of students had to access the virtual classroom and find a space to work alone, sharing the available resources—i.e., the projector and the whiteboard. It is important to highlight that all the described scenarios were real tasks that had to be performed, i.e., in a completely real context rather than a simulation.

From a practical point of view, a set of participants were recruited for each iteration to participate in the scenario activity. Before the execution date, the authors contacted the participants and helped them set up the platform on their workstations. This allowed us to identify potential compatibility problems and rapidly fix them. Before the execution, all the participants were asked to start the platform and enter the session room. The participants were physically dispersed, i.e., they participated in the experiment remotely, while the authors distributed themselves in order to provide help if some problems—also technical—arose.

During each iteration, the authors of the paper participated in the experiment. Following RITE, we recorded all interesting data and issues identified during the experiment, as well as participants' feedback, and analyzed them afterward.

SURVEY DESIGN After each iteration, using Google Forms—we administered an anonymized survey to the participants in order to (1) evaluate their experience, (2) evaluate the tool's usability, and (3) collect follow-up feedback. Details about the administered questions are in Table 7.3.

The survey is structured into four sections. The first section gathers demographic data such as gender, role, and years of experience of the participants. For students, 'years of experience' refers to years of academic study. The survey is anonymous and does not require identifying information. At the end of this section, participants are asked if they acted as a presenter, using presentation tools, or as an attendee, observing others' presentations without using these specific features. Depending on their response,

Table 7.3: Follow-up survey questions.

ID	Question	Type	Metric
Q1	What gender do you identify with?	Open-ended question	Demographic
Q2	What is your academic role?	{Student, Researcher}	Demographic
Q3	How many years of experience do you have?	Numeric	Demographic
Q4	Were you a presenter or a listener?	{Presenter, Listener}	-
Q5	How satisfied are you with the overall usability of the tool?	Likert scale of five points from *Very dissatisfied* to *Very satisfied*	Satisfaction
Q6	How easily did you learn to use the tool for your presentation?	Likert scale of five points from *Very difficult* to *Very easy*	Learnability
Q7	How would you rate the presentation modality provided by the tool?	Likert scale of five points from *Very bad* to *Very good*	Efficiency
Q8	How easy is it to control your presentation and avatar during the exposition?	Likert scale of five points from *Very difficult* to *Very easy*	Learnability
Q9	How easy is it to interact with your listeners and answer their questions?	Likert scale of five points from *Very difficult* to *Very easy*	Efficiency
Q10	How would you rate the quality of communication channels?	Likert scale of five points from *Very bad* to *Very good*	Satisfaction
Q11	How likely are you to use this tool compared to online communication platforms (e.g., Teams, Zoom, Meets...) to give your presentations?	Likert scale of five points from *Not at all likely* to *Very much likely*	Satisfaction
Q12	How engaged did you feel while experiencing the presentation?	Likert scale of five points from *Not engaged at all* to *Very engaged*	Satisfaction
Q13	How easily did you learn to control and position your avatar?	Likert scale of five points from *Very difficultly* to *Very easily*	Learnability
Q14	How satisfied were you with the interaction capabilities with the presenter and other participants during the presentation?	Likert scale of five points from *Not satisfied at all* to *Very satisfied*	Satisfaction
Q15	How well were you able to view and read the presentation?	Likert scale of five points from *Very difficult to see and read* to *Very easy to see and read*	Efficiency
Q16	How well were you able to listen to the presenter?	Likert scale of five points from *Very difficult to listen* to *Very easy to listen*	Efficiency
Q17	How likely are you to use this tool compared to online communication platforms (e.g., Teams, Zoom, Meets...) to attend presentations and seminars?	Likert scale of five points from *Not at all likely* to *Very much likely*	Satisfaction
Q18	Please share any additional feedback or suggestions you have regarding the tool's features, usability, or any improvements you would like to see.	Open-ended question (optional)	Learnability, Efficiency, Satisfaction

participants are directed to the second section if they were presenters, or to the third section if they were attendees. The second section, once completed, also leads to the third section. These sections feature closed-ended questions designed to measure the usability of the tool through metrics such as satisfaction, learnability, and efficiency, with responses recorded on a 5-point Likert scale, with 1 representing the lowest and 5 the highest. The fourth section includes an optional open-ended question to gather additional feedback, report bugs, and suggest improvements, made optional to avoid collecting uninformative responses.

Regarding the results analysis, we used descriptive statistics/plots for the closed-ended questions of the surveys, while content analysis [72] for extracting potential ideas from the open-ended feedback.

The selection of survey questions was a result of a collaborative effort. Such an activity was conducted during three meetings, each involving researchers with at least three years of experience in survey design and survey-based research. Each question underwent thorough discussion in these meetings until a consensus was reached. Subsequently, the initial survey design was validated through a pilot study involving three researchers who were neither involved in the tool's development nor the experiments. Adhering to the guidelines outlined by Flanigan et al. [127], a deliberate decision was made to maintain anonymity in the survey, ensuring that the influence of the authors on respondents' answers was minimized. At the end of this process, the survey was created using Google Forms[4] , and the completion time was estimated to be ca 10 minutes.

7.5.2.2 *Participants*

Regarding the recruitment of participants, in the beginning, we adopted *convenience sampling*, i.e., a non-probability sampling method where the sample is taken from a group of people easy to contact [146]. We decided to adopt such a strategy because of the availability of participants from our university. However, we were aware that such a strategy is known to provide results that are not highly generalizable [23, 146]. For this reason,

[4] Google Forms website: https://www.google.com/forms/about/

we identified a series of base criteria that the participants should meet (described in the following). Moreover, we plan to perform replications of the validation experiment in order to strengthen our results.

Following the RITE approach guidelines [216, 217], we defined some fundamental criteria that each participant had to meet. Specifically, we were looking for students and researchers with experience in human-computer interaction. Our choice was motivated by the aim of obtaining feedback supported by a theoretical knowledge foundation. These participants needed to be affiliated with the academic context for which the tool was intended, and they had to be individuals capable of genuinely representing users who would use the platform. Among these, we selected individuals with knowledge or experience about the metaverse to obtain opinions informed by other experiences. We did not define more stringent criteria to avoid bias in our results and tried to keep our set of participants as heterogeneous as possible.

In the end, 28 participants were recruited, comprising 5 researchers and 23 students of the master's and Ph.D. programs. As previously specified, each was already meant to participate in the activities later scheduled within the metaverse. Consequently, students for each activity were selected from the pool of participants available, aiming to align with the criteria mentioned before. 13 participants participated in the first activity (*remote seminar*), 5 participants in the second (*exam presentation*), and 10 participants in the third activity (*group activity*).

7.5.2.3 *Procedure*

We followed the same procedure for each of the three iterations performed with RITE. In the preparation phase, participants received the platform prototype to install on their devices at least 24 hours prior. This addressed technical issues beforehand, ensured everyone's participation, and gathered initial installation feedback. Organizers assisted in resolving any problems, and no issues preventing individual participation were encountered in any of the three iterations.

Participants and organizers were physically present at the university for the experiment setup. Participants were divided into small groups, ranging from 1 to 3 individuals, and they were physically separated to enable remote communication. Within each group, individuals were positioned far apart in the room to restrict communication to the platform. This ensured a controlled environment and organizer presence to guide participants. During the third iteration's group activity, participants in the same group collaborated within the platform despite being in different rooms.

The experiment began with an organizer accessing the platform first and creating a room password for all participants to connect. After participants created their avatars and accessed the platform, 10 minutes of free exploration allowed for connectivity checks and interface familiarization. Organizers then explained activity guidelines, e.g., project presentation methods or collaborative task instructions. Each activity lasted 45 minutes, during which platform behavior and technical issues were observed. Subsequent iterations addressed previously highlighted problems. The activity concluded after 45 minutes, followed by a 10-minute evaluation survey. Upon completing the survey, the session ended, and participants left the experiment location.

7.5.2.4 *Analysis of the Results*

The usability evaluation concluded after three iterations when the tool reached an acceptable state, and no issues were encountered that prevented the correct completion of the tasks and activities. As mentioned above, the activities carried out during the iterations were: (1) the *remote seminar*, with 13 participants, marking the first real test of the platform with multiple users connected in a single room; (2) the *exam presentation*, in which a group of 4 students presented their exam project to a professor using the platform, resulting in a total of 5 participants; (3) the *group activity*, during which three groups of three students each and a teacher connected to the platform to collaborate on a project, for a total of 10 participants.

Table 7.4 shows the issues encountered at each iteration and the implemented solutions. By the end of the third iteration, the platform was fully functional, allowing for more subjective feedback beyond technical or usability aspects. Data from all iterations were summarized in a graph showed in Figure 7.7, which depicts the changes in the mean—on the left—and in the standard deviation—on the right. In al phases, it can be observed an increase in average responses and a decrease in standard deviation, indicating more consistent positive feedback. This trend was also reflected in the declining number of issues reported, showed in Figure 7.8. showcasing the effectiveness of immediate solutions applied after each iteration under the RITE method. In conclusion, the RITE method has been a valuable approach to refining the usability of the developed tool. While room for further enhancements remains, the platform's overall usability reached an acceptable level, prompting the conclusion of the evaluative iterations. The collected feedback will continue to inform future developments and refinements.

Summary of the RITE Evaluation (RQ_2)

The RITE evaluation successfully contributed to improving the platform's usability. At the end of the third iteration, all three metrics considered—i.e., efficiency, learnability, and satisfaction—showed significant improvement, and the number of issues encountered had decreased considerably from the beginning of the experiment.

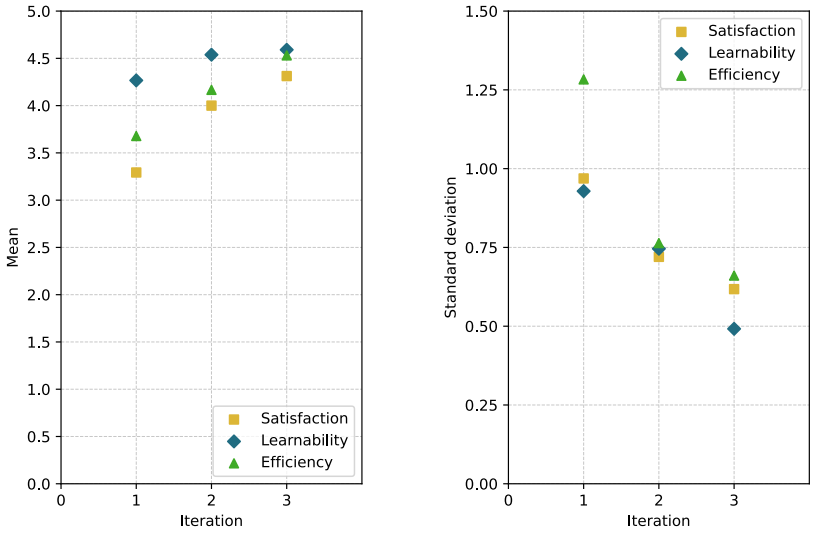
7.6 LIMITATIONS

The work has some limitations, which can be identified both in the requirements-gathering phase and due to the prototype nature of the developed tool and the constrained context in which it was developed and tested. In the following, we identify the main limitations and explain how they were addressed to improve the research.

Literature Selection and Analysis. We performed a *literature survey* to identify educational metaverse requirements from previous research.

Table 7.4: Emerged issues and implemented solutions during the experiment.

ID	Name	Description	Iteration	Solution
I1	Synchronization bug	When a new user accessed the platform, they began controlling an avatar that wasn't theirs due to poor synchronization among network objects.	1	We improved the synchronization logic between clients and how the platform handles new accesses.
I2	Bad visibility	The visibility of the slides from the farthest seats was poor, and the names of other avatars sitting in front covered parts of the presentation.	1	We added the option to zoom the camera, allowing users to zoom in or out at any time. We also added the option to temporarily hide other users' names above avatars to avoid visibility issues.
I3	Animation lag	The animation synchronization was slow and laggy, causing many avatars to appear standing even though they were actually seated.	1	We improved the animation trigger mechanism, preventing avatars from standing when they should be sitting.
I4	Bad tablet interaction	The interaction with the tablet for taking notes was found to be not very usable or useful.	1	We removed the note-taking functionality on the tablet available to each user.
I5	Lack of interaction	Users requested more non-verbal interactions, such as applause at the end of a presentation.	1	We added the ability to applaud and wave with the hand through one's avatar.
I6	Low voice volume	Users found it difficult to hear each other using voice chat unless they were very close.	2	We increased the overall voice chat volume and slightly reduced the spatial audio blending.
I7	No chat history	The history of the text chat was lost, and there was no way to read previous messages beyond the ten displayed on the screen.	2	We implemented a text chat log feature that saves all messages on the user's device, accessible even after the session ends.
I8	Limited choice in avatar customization	Users requested a greater variety of cosmetics during the avatar customization phase.	3	*We plan to address this feedback in future developments.*



(a) Mean (b) Standard deviation

Figure 7.7: Mean and SD of survey answers across iterations.

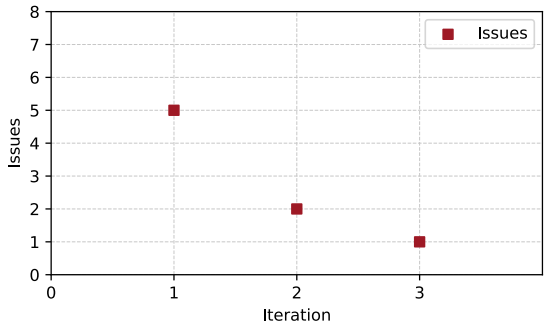


Figure 7.8: Number of found issues across iterations.

However, this approach shows the critical challenge of determining the complete set of primary studies. It is worth remarking that the research process reported in 7.3.1.1 has been applied following the guidelines provided by Kitchenham et al. [183], who defined a set of steps to collect the most significant amount of resources and to elaborate the results.

An additional limitation could arise from literature analysis, as the identified requirement categories may need to be more accurate. We tried to mitigate this risk by not confining everything to a single analysis session, but organizing multiple meetings and discussions. Multiple authors of this work focused on different aspects of the requirements to ensure each category received proper attention and to mitigate the risk of incorrect requirement extraction. In other words, applying these steps makes us confident of the process used. Our future research agenda includes a more thorough systematic search, including additional search engines and applying more rigorous selection criteria to the primary studies.

Semi-Structured Interview. Requirements validation and augmentation were obtained by performing *semi-structured interviews* with 7 participants selected through a *convenience sampling*. Despite this, they have the characteristics described in 7.3.2.2—i.e., they have a certain level of proficiency in the educational setting, including high expertise in different domains close to software engineering, human-computer interaction, and computer science education—the results could be limited to the participants own perspective and opinion. Our future research agenda includes a focus on generalizing the obtained findings and assessing the transferability of the results to a broader population of both learners and educators. Moreover, we faced a significant limitation concerning the design of the interview. To ensure the accuracy and comprehensiveness of the information gathered, we adhered to the recommendations provided by Hove and Anda [159] while formulating our questions. Furthermore, we conducted a pilot study involving four learners who identified certain biases and imperfections we addressed before performing the reported interviews.

Set of Requirements. Our set of requirements shows some limitations. Indeed, while our requirements aim to provide a broad set applicable to

various platforms and devices, they do not specifically cover all the aspects of the metaverse, specifically the ones concerning the more immersive technologies—e.g., VR headsets and haptic feedback devices, widely considered in metaverse applications. The requirements resulting from our literature survey and interviews cover more generic and traditional aspects of metaverse platforms. While it ensures greater accessibility and applicability across standard technology platforms, this choice results in the underrepresentation of immersive technologies' unique capabilities and experiences, which could impact user engagement and realism in the metaverse. Furthermore, the focus of the extracted requirements is more concentrated on a remote education modalities, not currently allowing their effective application in face-to-face contexts. In our future work, we will seek to address these gaps, extending our framework to incorporate more requirements that allow the full potential of immersive technologies to be exploited and different teaching contexts.

Tool Development. Concerning the developed tool, it still exists as a small-scale prototype, which can be further developed to become a more comprehensive platform from both an educational and academic perspective, as well as a true metaverse. Furthermore, to keep the project completely open source, the server technologies used have limited capacity, preventing the loading and synchronization of the application once it is built. Currently, it is only possible to load and display multimedia content before building the executable. Furthermore, the tool currently lacks the feature for taking notes via a tablet. This feature was initially included but was later removed during the tool evaluation because it was deemed not very user-friendly in its implementation. As a result, participants in educational activities had to compromise their immersive experience and resort to external tools for note-taking. As a final concern, the limitation that emerged during the last iteration of the RITE —i.e., to increase the avatar customization options—will be addressed to improve and promote inclusivity within the platform.

8

COLLECTING AND IMPLEMENTING ETHICAL GUIDELINES FOR EMOTION RECOGNITION IN AN EDUCATIONAL METAVERSE

This chapter builds upon the paper published at the *International Workshop on User-Centered Practices of Knowledge Discovery in Educational Data* (UKDE) [104], where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the metaverse engineering perspective introduced in Chapter 4 and operationalized through SENEM in Chapter 7, this chapter investigates emotion recognition as an advanced capability for educational metaverse environments, while also reflecting on the ethical issues raised by its adoption.

8.1 INTRODUCTION

The metaverse, originally envisioned in Neal Stephenson's 1992 novel *"Snow Crash"* [317], has evolved into a tangible reality, stemming from the realms of Extended Reality (XR) and Virtual Reality (VR). It offers an immersive experience, described in contemporary literature as a three-dimensional virtual world where users freely explore and interact through customizable digital personas known as avatars [290]. Characterized by features such as persistent activities, experiential realism, interoperability, and scalability, the metaverse facilitates synchronous and real-time interactions among thousands, or even millions, of users simultaneously [369].

Among the multiple use cases of the metaverse, education represents a key application domain. On the one hand, the increasing diffusion of this technology has been favored by the COVID-19 pandemic [276], which enforced the identification of alternative means to let learners and educators interact. On the other hand, the innate immersive and interactive properties present new educational opportunities, transcending traditional constraints such as physical and language barriers, thus fostering a more equitable learning environment [190]. Indeed, the metaverse has the potential to facilitate experiential learning through immersive simulations and virtual experiments, enhances collaboration among students and educators, and supports personalized learning experiences tailored to individual student needs [190].

Nonetheless, all that glitters is not gold. Despite the many advantages offered by the use of metaverse for education, there are still open educational challenges that may limit the widespread diffusion of the technology. In the context of this paper, we focus on *emotional isolation*, that is, the feeling of disconnection or loneliness from others on an emotional level, which may negatively impact learners' motivation and participation [97].

Machine learning represents a potential instrument for identifying emotional isolation states within an educational metaverse: by analyzing patterns in user interactions and expressions, emotion recognition systems can detect signs of emotional isolation, enabling educators to intervene and provide necessary support to learners [97]. However, the introduction of these systems within an educational metaverse raises significant ethical challenges: indeed, the use of data collected from users' emotional expressions and interactions may present dilemmas regarding consent, privacy, and the potential for unintended consequences such as algorithmic bias or discrimination.

This paper proposes an initial step toward the deployment of ethical emotion recognition systems within an educational metaverse. We first provide a literature review of the ethical considerations surrounding the deployment of emotion recognition technology within educational metaverses. Building upon our findings, we report on our experience with imple-

menting the most critical ethical consideration, namely the *protection of privacy* within SENEM [273], an existing educational metaverse platform available in literature. More particularly, we provide the implementation steps for privacy guidelines into SENEM and outline future directions to raise awareness on additional ethical areas, e.g., accountability, to consider and integrate new technology, i.e., Blockchain, for strengthening data protection.

8.2 SENEM: A SOFTWARE ENGINEERING-ENABLED EDUCATIONAL METAVERSE

This section discusses the SENEM platform and its features [273], exploring its relevance to our work. Indeed, to achieve concrete results, we have leveraged this existing contribution to tangibly implement the literature review findings to enhance the educational metaverse. In particular, we extend this platform with a new feature able to implement emotion recognition that implements the ethical guidelines we have identified.

Pentangelo et al. [273] developed the Software Engineering-eNabled Educational Metaverse (SENEM), shown in Figure 8.1. The work represents a valuable advancement of the state of the art that links educational metaverse and software engineering due to the two main contributions obtained from the research. As a first contribution, the authors conducted an initial literature survey to identify the main elements to consider when creating a virtual educational environment. They then validated these requirements by consulting with experienced educators and learners, gaining valuable insights and perspectives on each requirement. Their work revealed that a substantial amount of literature focused on four primary macro-categories: (1) Virtual Environment, (2) Communication, (3) Avatar, and (4) Multimedia Content. As a second contribution, they implemented the elicited requirements into a working prototype as shown in Figure 8.1—i.e., SENEM—which exhibits all the features identified in the first step of their research, and described below.

Virtual Environment. Users explore and interact with the platform in a 3D virtual environment resembling a real classroom. They can freely move in such an environment by walking with their avatar and interacting with different objects—e.g., chairs, a projector, a whiteboard—rotating the view and zooming in on components of interest. The system also allows the creation of simultaneous sessions protected by a password.

Communication. Users can communicate with one another through different channels. They can use voice chat via a microphone or type messages into text chat. Moreover, they can perform non-verbal interactions through the emotes of their avatars—e.g., waving, raising a hand, or clapping.

Avatar. Users can choose their representation in the metaverse through a customizable avatar. The platform presents an editor where users can choose the aspect of their avatar based on physical and personal characteristics, such as skin tone, hair, clothes, eyes, and more.

Multimedia Content. The platform has a projector on which users can upload and share multimedia resources, supporting educational and collaborative activities. Moreover, users can write and share textual content with one another via an interactive whiteboard.



Figure 8.1: The SENEM Metaverse.

Despite its potential, the SENEM platform is currently limited to primary functional requirements and lacks emotion recognition features. The metaverse's complexity allows for the integration of various technologies to enhance user immersion and engagement. This platform will enable us

to implement our findings into SENEM by incorporating emotion detection and recognition, ensuring these enhancements align with established ethical guidelines.

8.3 COLLECTING AND IMPLEMENTING ETHICAL GUIDELINES FOR EMOTION RECOGNITION

The *goal* of the study was to combine emotional recognition technology with a unique use case in the metaverse: education. The *purpose* was to gain insights into managing sensitive information, ensuring the protection of privacy concerning the emotions of both learners and educators within a complex digital system like the metaverse.

To obtain a comprehensive understanding of the ethical considerations encompassing emotional recognition technology, we performed a literature review. The entire process was driven by the following research question (RQ):

> **RQ_1: What *ethical considerations* and *guidelines* must be taken into account to ensure the secure deployment of *emotional recognition* technology in an *educational metaverse*?**

RQ_1 first aims to gather current knowledge on ethical considerations related to emotional recognition. Secondly, the gathered information is used to enhance an already existing open-source platform for the educational metaverse, namely SENEM [273]. For clarity, Section 8.3.1 outlines the process for collecting papers through a literature review and presenting the obtained results, while Section 8.3.2 delves into the application in practice to include emotional recognition tasks in the SENEM platform, considering one of the ethical aspects identified namely, the protection of privacy.

8.3.1 *Collecting Ethical Guidelines for Emotion Recognition*

This section discusses the research method used to address $\mathbf{RQ_1}$. Our focus is on describing the design and outcomes of the literature review conducted to identify the body of knowledge on ethical emotional recognition.

8.3.1.1 *Design*

We followed a structured approach consisting of three primary steps. First and foremost, we created a research string derived from a set of carefully selected keywords to search for papers on ethical emotion recognition in an online digital library. Next, we collected and evaluated the knowledge obtained to ensure its relevance to our research objective. Finally, we extracted valuable insights to answer our research question. To ensure the completeness of our collection phase, we used well-established guidelines by Kitchenham et al. [183] and identified the main terms for our purpose based on our research question. To find an exhaustive list of terms, we focused on three specific domains retrieved from the research question: *emotional recognition*, *ethical guidelines*, and *education*. By exploring these domains, we identified a set of synonyms to broaden the scope of our study. The complete list is provided below:

- **Emotional Recognition**: ("*emotional recognition*", "*emotional detection*", "*affective computing*")
- **Ethical Guidelines**: ("*ethics*", "*ethical*", "*ethical guidelines*", "*ethical considerations*")
- **Education**: ("*education*")

In formulating the query, the domains were isolated by applying the AND operator, while the synonyms of each domain were connected through the OR operator. The following box shows the used search string.

General String

((“*emotional recognition*” *OR* “*emotional detection*” *OR* “*affective computing*”) *AND* (“*ethics*” *OR* “*ethical*” *OR* “*ethical guidelines*” *OR* “*ethical considerations*”) *AND* (“*education*”))

To search for relevant literature, we ran the search string on *IEEE Xplore*[1], a well-known research engine. The output of this search consisted of 16 papers. We selected four that focused on ethical emotional recognition and analyzed them in depth. To extract data, we used a *qualitative content analysis* technique [72], which involves carefully examining the relevant data to extract meaning and concepts. This process has two crucial phases: (1) iterative development of a codebook and (2) application of the codes to the raw data. In this study, the researchers who extracted the data also developed the codebook, while the primary author applied the codes to the raw text. The data was clear enough, so we did not use any additional software tools for this phase.

It is important to note that two experienced researcher authors constantly monitored and refined the entire process, meticulously reviewing all aspects, from the development of the research strings to the content analysis process. Their invaluable assistance ensured the resolution of any conflicts of data subjectivity.

8.3.1.2 *Analysis of the Results*

The analysis revealed a range of essential ethical guidelines for applying emotion recognition technologies in educational and research settings. These guidelines underscore the critical ethical considerations essential for employment emotion recognition, especially in the educational context.

When it comes to using emotion recognition technologies in educational and research settings, multiple ethical guidelines and considerations need to be taken into account. One of the most critical aspects of these guidelines is the **protection of privacy**, informed consent, and ethi-

[1] https://ieeexplore.ieee.org/Xplore/home.jsp

cal compliance. Participants need to be properly informed and give their consent for their data to be used, and measures must be in place to ensure secure data management and protection of participant information [31, 32, 196, 294]. **Transparency**, **accountability**, and adherence to **legal and ethical standards** are also crucial, as are interdisciplinary ethical approval and robust data integrity measures [31, 196]. The studies also stress the importance of addressing **biases** and ensuring **fairness** and representation in the application of these technologies, promoting an inclusive and nondiscriminatory approach [196, 294]. Additionally, emotional safety, participant comfort, and potential **psychological impacts** of technology use must be managed properly, with a focus on mitigating negative emotional experiences and fostering a supportive and safe research environment [32, 196]. These guidelines advocate for a multidisciplinary approach to ethical issues, integrating insights from computer science and psychology to develop comprehensive standards that adhere to the self-respect and rights of all individuals involved [31].

8.3.2 *Implementing Protection of Privacy for Emotion Recognition*

The first step for implementing facial emotion recognition is to use a well-structured dataset that contains face images. Canal et al. [63] already provides a literature review describing the most used and available datasets that can be used for emotion recognition. One of them is *Facial Expression Recognition 2013* (FER-2013) [141], composed of 35.887 images labeled in seven expressions: happiness, sadness, disgust, fear, surprise, and anger. We developed a Convolutional Neural Network (CNN) that can recognize emotions by analyzing grayscale images with dimensions of 48x48 pixels. The network architecture includes two convolutional layers, each with 32 and 64 filters and ReLU activations, for capturing visual features, followed by a max pooling layer to down-sample the image dimensions and dropout layers to prevent overfitting. After this first step, the model repeats this pattern with additional convolutional layers with 128 filters each to enhance detail detection. Finally, the network includes a flattened layer and

two dense layers, with the final layer using softmax activation to classify images into one of seven emotion categories. To optimize learning, we used the Adam optimizer and categorical cross-entropy loss.

It is worth noting that the model was initially pre-trained using a basic CNN through the Keras library, with data divided into 80% for training and 20% for testing. To optimize the model's settings, we employed Random Search, a method that helps find the best combination of parameters within the model by trying out various possibilities. The model with the best combination of parameters was directly added to SENEM. We then take great care to ensure the most critical ethical concern identified by the literature: the protection of privacy. Indeed, the platform must respect user privacy and provide a safe environment for emotion analysis. Users are informed about why and how the emotion recognition feature is used. The information gathered is only for the teacher and does not affect students' grades. It helps the teacher adapt their teaching methods based on a general report of the class's emotions, which aims to make learning more effective. Users are informed that the webcam needs to be used to get real-time data about their facial expressions, but this data is not saved or stored to protect their privacy. Users can choose whether or not they want to use this facial recognition technology. If they decide not to use it, they can still attend the class, but their emotions will not be analyzed or shown to the teacher. Access to the SENEM platform does not require users to log in or register, which keeps their identities private. However, not knowing the exact identity of those who agreed to have their emotions analyzed or being unable to see each student's emotions might make the information less accurate. However, other aspects extracted from the literature review, such as transparency, bias and fairness, and psychological impacts, need more effort in future studies.

8.4 DISCUSSION AND FUTURE DIRECTION

Outlining ethical guidelines that can assist both participants and researchers in conducting experiments and scientific activities more clearly

and safely is of crucial importance [20]. In this regard, a significant point of discussion is the discrepancy between the two most common types of guidelines proposed by research, namely purely theoretical guidelines and technical guidelines that support actual implementation activities. On the one hand, theoretical guidelines emphasize the importance of following a process that carefully adheres to ethical norms in tasks involving the collection of sensitive data, such as emotion recognition, ensuring these data are managed and stored transparently and securely; on the other hand, there is a need to complement them with actual technical guidelines that specify technologies and methodologies to make the former concretely implementable.

In the specific context of the metaverse, blockchain technology appears to be particularly promising in supporting researchers and developers in the challenge of concretely implementing an ethical, secure, and transparent process in collecting user data [368]. The blockchain is a distributed ledger technology that provides a secure and transparent record of transactions. Blockchain technology has numerous applications in the metaverse, primarily related to the storing and exchanging of data among users. For these reasons, the very nature of blockchain seems well-suited to the technical implementation of the ethical guidelines provided in our study [132, 329].

Given these motivations, a crucial future step in developing our work will be to complete and enhance the implementation of the ethical guidelines identified using specific technologies to support this task. A concrete example is provided by Di Dario et al. [101], who have constructed a comprehensive theoretical framework for including blockchain technologies in the metaverse. Leveraging this practical framework alongside ethical guidelines will lead to a complete, secure, and ethical process for collecting and analyzing user data for emotion detection, thereby enhancing the features of SENEM in this area in a significant and ethical-aware manner.

PART III

ENGINEERING AND EMPIRICAL EVALUATION OF EDUCATIONAL METAVERSE

9

ACCELERATING 3D SCENE DEVELOPMENT FOR THE METAVERSE: LESSONS FROM PHOTOGRAMMETRY AND MANUAL MODELING

This chapter builds upon the paper published at the *International Conference on Intelligent Metaverse Technologies and Applications* (iMeta) [267], where the author of this thesis was the second contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the theoretical foundations established in Part II, this chapter opens the engineering and empirical path of the thesis by examining practical approaches for accelerating 3D scene development in metaverse environments.

9.1 INTRODUCTION

In recent years, interest in the expansive domain of the metaverse has been steadily increasing, finding its relevance across diverse contexts and applications [193]. The metaverse is an immersive three-dimensional digital environment where users interact in real-time with both the surroundings and other users via their avatars, which serve as their digital proxies [290, 317]. This surge in interest has been fueled by rapid technological advancements, the growing digitization of various daily activities—from work to entertainment—and the significant impact of the COVID-19 pandemic, which underscored the necessity for digital solutions [193, 276]. Consequently, researchers have begun designing and developing metaverses for

various purposes, including entertainment [237], software development [124], medical simulations [185], and educational applications [112].

The development of high-quality 3D models is crucial for the metaverse, as these models form the foundational elements of the virtual environments and objects that users interact with. The degree of immersivity—the extent to which users feel present within the digital world—relies heavily on the realism and intricacy of these 3D models, allowing a fluid social interaction with other avatars [240, 262]. Detailed and lifelike models contribute to a more engaging and believable experience, allowing users to interact with the virtual space in ways that mimic real-world interactions. However, developing such 3D models and the scenes they compose for integration into virtual worlds like the metaverse is a complex task [64, 65, 207]. One of the primary challenges is achieving the high levels of detail and realism needed to enhance immersivity [369], which demands substantial computational resources and time. Moreover, many professional tools (e.g., Blender and Autodesk) are difficult to learn and use due to their numerous functionalities [65, 207]. Additionally, creating these 3D models requires specialized skills that take time to acquire [65]. Despite the support of these tools, the considerable effort involved in developing 3D models and scenes often results in outcomes that lack realism and quality.

Given the previously mentioned difficulties, various solutions have been proposed to automate the process of creating 3D models and scenes. Specifically, research has focused on utilizing tools, such as Artificial Intelligence (AI), to generate scenes and models from textual descriptions. Many of these approaches involve using AI to identify and position pre-existing models in a scene based on a textual description [138, 211]. However, these methods do not create models from scratch; they find models similar to the users' requests. In response to this limitation, recent advancements have led to the development of techniques—like **photogrammetry**—based on object recognition and Computer Vision (CV) modeling through pictures of the actual object to model [27, 64]. These new approaches aim to enhance the automation of 3D model creation, potentially generating models that are more accurate and tailored to the specific needs. Nevertheless, the

research in such a field is still in its early stage, and no clear methodology or process has yet been proposed or evaluated for the automatic creation and insertion of 3D scenes into the metaverse.

This work aims to contribute to the body of knowledge on the use of computer vision techinques, specifically photogrammetry, for 3D scene reconstruction for the metaverse. More in detail, the objective is to conduct a comparative analysis of two approaches to scene creation: manual and photogrammetry-based. The goal is to evaluate the effectiveness of the automated computer vision-based approach—leveraged using the Polycam tool [277]—in supporting the development of metaverse environments. In addition, this work seeks to provide useful lesson learned based on the results of our experiment to assist professionals in deciding whether and in which scenarios to rely on such automated techniques. All the material produced by our experiment is made available at our online appendix [268].

9.2 EXPERIMENT DESIGN

This research aims to conduct a comparative analysis of two distinct methodologies for constructing 3D environments intended for integration within the metaverse: a predominantly manual approach and a semi-automated technique supported by CV. Our ultimate goal is to develop comprehensive guidelines detailing (1) the optimal conditions for deploying each method and (2) the effective utilization of automated processes in 3D virtual environment creation.

To reach our objective, we executed an empirical study to compare the above-mentioned techniques by replicating a real-world indoor setting in three dimensions. The experiment required us to recreate the same indoor environment using two approaches: the first through manual modeling and texturing of each element and the second via computer vision technologies, notably leveraging the Polycam [277] software to transform 2D photographs into 3D models. The choice of Polycam was guided by its ability to demonstrate efficiency and user-friendliness as a photogram-

metry application, capable of generating digital casts with a good balance between accuracy and processing speed compared to its competitors [58]. Moreover, Polycam is an open-access tool, downloadable by all users on their smartphones, which can therefore easily promote greater approachability in 3D scene reconstruction. Afterwards, we employed a suite of metrics specifically tailored for assessing 3D models to evaluate the results from both methodologies.

9.2.1 *The Two Techniques*

In this study, we focused on evaluating two distinct techniques for a common task: reconstructing a real-world scene within a 3D virtual environment.

- **Manual technique:** The first method, termed the "manual," involves a traditional approach where scene elements are crafted and textured manually utilizing Blender [41], a widely used open-source 3D modeling software [325, 331]. This choice was motivated by Blender's accessibility and substantial community support. Specifically, this process involved directly modeling all elements from the real scene within the software to create accurate 3D representations and associated materials for integration into the virtual environment.

- **Photogrammetry technique:** The second method, referred to as "Photogrammetry technique" leverages the Polycam [277] software to generate 3D models from photographs of the environment intended for reproduction. This approach begins with photographing the target environment, followed by using Polycam to create both the models and materials. These components were then imported into Blender, where they were assembled to reconstruct the scene.

9.2.2 *Experiment Procedure*

The experimental activity central to our study involved the digital reconstruction of a real-world scene within a 3D environment, specifically a living room owned by one of the study's authors (depicted in Figure 9.1, Picture A), using the two methodologies described earlier. The decision to replicate the living room was driven by two primary factors: (1) in line with Dionisio's emphasis on realism as a vital attribute of the metaverse [369], we aimed to recreate a commonplace yet intricate environment that is familiar in everyday human life; (2) having complete access and control over the physical space allowed us to adjust the complexity of the scene by modifying its elements as needed. The objective of this reconstruction was to produce a textured, functional 3D replica of the living room, where "functional" implies that the model is capable of being rendered and navigated in real time.

Prior to initiating the experimentation, a preliminary feasibility analysis was performed through a pilot study in a kitchen environment facilitated by one of the co-authors. The primary objective of this pilot study was to equip the research team with detailed knowledge of the tools and methodologies involved. Additionally, this initial exploration helped refine the experimental procedures for the main study, which are detailed in the subsequent section of this document.

In terms of procedure, concretely, the authors first organized the living room to contain some objects to make it seem as accurate as possible. Specifically, the set of objects consisted of: sofa, lamp, curtains, painting, coffee table with plant, radiator, air conditioner, fireplace with decorations, wall-mounted wardrobe with TV, potted plant, and remote control. As a second step, one of the co-authors (hereafter referred to as the *experimenter*) took pictures of the room; such were used as references for creating the living room using the two techniques and computing metrics (described in the continuation of the paper). After this, the experimenter used both techniques—starting from the manual one—to create the living

room models and imported them into Blender. The entire process required multiple sessions of two hour each conducted on consecutive days.

The decision to assign the experimental tasks to a specific author was strategic rather than arbitrary. This author possesses considerable expertise in 3D modeling, acquired through formal education—completing both an introductory and an advanced course at a university—and personal projects. Engaging this author as a reference point enabled us to evaluate our methodology through a case study that closely mirrors a real-world scenario.

As a result of the above-mentioned procedure, two distinct 3D representations of the same living room scene were created within Blender. This approach allowed us to leverage Blender's capabilities to initially collect metrics related to model complexity and detail. Following the modeling phase, both scenes were exported to Unity3D, a robust game development platform, to assess their functionality. This step was crucial for evaluating how well each model performed in a dynamic environment, particularly focusing on real-time rendering capabilities and interactive potential. The functionality assessment in Unity3D helped determine the practicality of each modeling approach in creating realistic, immersive, and interactive 3D environments suitable for applications such as virtual reality experiences and simulations in the metaverse.

9.2.3 *Metrics for Evaluation*

In evaluating the two modeling techniques used in our study, we applied a set of metrics designed to capture both the time investment and quality of the resulting 3D scenes. The primary metric was the duration required to create each scene using the manual and photogrammetry techniques. This measurement provided insights into the actual time savings offered by each method, allowing us to weigh these against the quality of the final 3D models produced. Moreover, in terms of quality, we used three additional metrics:

NUMBER OF POLYGONS — This metric quantifies the complexity of the 3D models. A higher number of polygons—i.e., the number of triangular faces composing the mesh—generally indicates a more detailed model, which could enhance realism but might also affect performance, especially in real-time applications [48]. This measure is relevant for the study because the number of polygons is closely related to the functionality of the scene and its operability in real-time—a crucial feature of the metaverse [369]. Indeed, each polygon requires computational time to determine how it should be rendered on screen, including texture rendering and lighting operations [48]. Therefore, a higher number implies a greater need for hardware and software resources to run the simulation smoothly with the created scene. To compute this metrics, we compared the results obtained from the two techniques regarding *number of triangles*. It is important to specify that the experimenter did not receive any directives regarding the number of polygons to achieve during manual modeling and that the common goal of both techniques was to obtain a result as visually close to the real reference as possible.

STRUCTURAL SIMILARITY INDEX (SSIM) — This metric was first proposed by Wang et al. [340] and is based on the idea of measuring the quality of a 3D model by confronting it with the original object. We used the SSI to compare the visual similarity between the original photographs of the living room and the resulting 3D models. Specifically, the SSIM extracts three features from two images for comparison, i.e., luminance, contrast, and structure. This index helped us assess how accurately each technique managed to capture the real-world appearance and textures in the virtual environment. The metric ranges from -1 to 1, where -1 indicates maximum dissimilarity and 1 indicates maximum similarity.

The SSIM was calculated as follow: by taking three photos of the real room from three different angles, ensuring that all objects were captured in at least one image, we generated three renders from the same angles for each scene. We attempted to precisely match the angle of each real photo in the renders of the 3D scenes as if we were taking the same photo

inside the virtual room. Subsequently, for each render, we calculated the SSIM with the corresponding real image. We chose this methodology for calculating the metric on the entire room scene rather than individual models because we were interested in evaluating the realism of the room as a whole, rather than the realism of individual models.

GPU USAGE — The GPU usage percentage for running the real-time simulation of the produced scenes. This measurement is useful for determining the functionality and operability of the results in actual metaverse contexts, i.e., 3D environments rendered in real-time that can be freely explored by the user [290, 369].
To measure this, we exported the two generated scenes to Unity3D, a graphics engine particularly used for metaverse applications [112, 274]. We set up the two scenes and positioned a player with a first-person view that could be freely controlled using a mouse and keyboard. We ran the simulation for 5 minutes on three different machines, each with a different model of NVIDIA GPU, with varying computing power: an NVIDIA GeForce RTX 3060, an NVIDIA GeForce MX130, and an NVIDIA GeForce GT 730. During the simulation, we measured the average GPU usage and average frames-per-second (FPS) in each session.

By employing the above-mentioned metrics, we aimed to comprehensively assess the balance between time efficiency and quality in the creation of 3D environments, facilitating a deeper understanding of the trade-offs involved in choosing between manual and photogrammetry modeling techniques.

9.2.4 *Threats to Validity*

One significant threat in this experiment stems from the dependency on a single participant's skill level and familiarity with the modeling tools used, namely Blender and Polycam. This reliance raises concerns about the reproducibility of the experiment since the results may be different from those of another individual with different levels of expertise. For ex-

ample, if the participant is more proficient with Blender than Polycam, the results might be inherently biased in favor of manual modeling over photogrammetry generation. Furthermore, consistency in task execution is crucial. The same co-author conducted all modeling tasks under both techniques, which could introduce personal bias or variability in the application of each method. Such factors could skew the comparative analysis, favoring one method due to subjective preferences or familiarity rather than objective performance. Nevertheless, since the objective of this paper is to present and explore an automated method rather than undoubtedly assessing its superiority, we judged this choice as a good compromise in this part of the research.

The study is potentially compromised by its limited generalizability. The experimental design involves reconstructing a specific indoor environment—a living room—using two distinct methodologies. While informative, the results might not generalize to other types of environments, such as outdoor scenes or different architectural styles. This limitation restricts the applicability of the study's conclusions to similar settings and might not hold true for varied scenarios. Moreover, because the experiment utilizes particular software tools, the findings are somewhat tied to the capabilities and limitations of these tools at the time of the study. Technological advancements or different software choices could yield different outcomes, affecting the broader applicability of the results.

A potential limitation lies in whether the metrics used comprehensively capture the intended constructs. The study employs metrics such as the time taken, number of polygons, SSIM, and GPU usage to evaluate the quality and efficiency of the modeling techniques. However, these metrics may only partially encompass all relevant aspects of practical utility, such as the user experience in interactive applications or the computational performance in real-time rendering scenarios. For instance, a model with fewer polygons might be less realistic, thus offering a poor user experience despite higher performance or lower computational demand. Therefore, relying solely on these metrics might not provide a complete picture of each method's effectiveness and practicality.

9.3 ANALYSIS OF THE RESULTS

The experiment's output consisted of two scenes resembling the indoor environment used as a reference, one for each technique. All the produced material is available in our online appendix [268]. Figure 9.1 shows a comparison of the models for the same object with the two techniques.

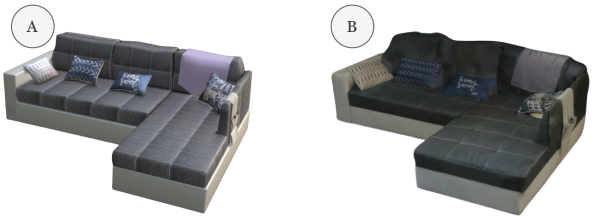


Figure 9.1: Visual result of the two models resembling the sofa; A for the manual technique and B for the photogrammetry one.

Regarding the manual technique, each model was created manually in Blender, using photos of the room as a visual reference. Such photos were also used for the creation of the textures. The time for completing the scene, from accessing the room to take the photos to the completion of the 3D project, was **10 hours and 30 minutes**. This required five work sessions, each of two consecutive hours.

Regarding the photogrammetry technique, each model was generated by Polycam using its smartphone application. From 50 to 150 images were taken from all possible angles for each model. Subsequently, Blender was used only to compose the final scene. The time for completion, measured from scanning the room to finishing the 3D project, was **2 hours and 40 minutes**. This means that, in the context of our study, the photogrammetry technique reduced the time by nearly fourfold compared to the manual technique.

The first evaluation of the models was the polygon count for each, i.e., the number of triangular faces composing the mesh. This is pertinent as the polygon count directly influences the scene's functionality and real-time operability, which is a critical aspect of the metaverse [369].

The total number of polygons obtained from the manual technique was **56,113**, while the number obtained by the photogrammetry one was **470,902**. Each model's polygon number is shown in Table 9.1. In this case, the difference between the two techniques is evident, as the photogrammetry technique has a total number of triangles that is more than eight times greater than that of the manual technique. However, more information can be obtained by visually examining the mesh topology, i.e., the arrangement of vertices on the surface. Figure 9.2 shows the two topologies for the sofa model. The differences between the two results lie primarily in the complexity and density of the polygons. The meshes resulting from manual modeling operations are simpler and cleaner but capture fewer details of the real objects' shape. The meshes derived from Polycam scanning, faithfully structured from images of the actual objects, captured much finer details, resulting in significantly higher polygonal complexity. Moreover, the meshes derived from the photogrammetry technique are not entirely complete, as the sides that could not be photographed are missing.

Table 9.1: Objects' number of triangles for each technique.

Model	**Triangles Manual**	**Triangles Photogrammetry**
Sofa	2,433	37,339
Lamp	1,758	23,468
Coffee Table	2,162	62,304
Radiator	2,392	59,467
Painting	2,450	3,291
Air Cond.	96	34,211
Curtain	1,210	30,800
Potted Plant	14,780	10,000
Fireplace	4,160	142,237
Wardrobe	15,430	35,155
Remote control	9,242	32,630
Total	**56,113**	**470,902**

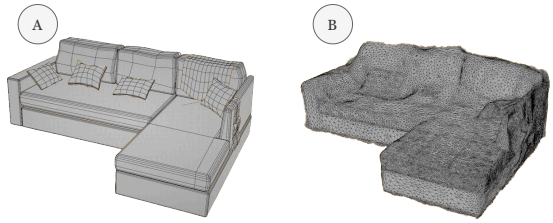


Figure 9.2: Topology of the two models resembling the sofa; A for the manual technique and B for the photogrammetry one.

Following the preliminary analysis of the obtained models, we were interested in gaining more accurate insights regarding the realism and verisimilitude of the models compared to the actual reference scene. Therefore, we calculated the SSIM [340]. Figure 9.3 shows an example set of images from the same angle for the metric calculation.



Figure 9.3: Three images from the same angle for the SSIM calculation. A shows the image taken in the real scene, B the render of the scene created with the manual technique, and C the render of the scene created with the photogrammetry technique.

The SSIM values obtained for each angle are summarized in Table 9.2. Additionally, Figure 9.4 shows the heatmap generated for Angle 1 for both techniques. For all three angles, although slightly, the results indicate a greater similarity between the real images and the results from the photogrammetry technique. Despite the manual technique's results being visually cleaner and featuring complete object meshes with a lower polygon count, the SSIM results regarding similarity to the real environment are interesting. This suggests that despite the technical inaccuracies and scanning limitations of some elements of the room, the CV results contribute to a more realistic outcome, as it can reproduce both models that closely match the real object's proportions and more realistic textures.

Table 9.2: SSIM values for each technique.

Picture Angle	SSIM Manual	SSIM Photogrammetry
Angle 1	0.7009	0.72
Angle 2	0.696	0.7439
Angle 3	0.6037	0.6892

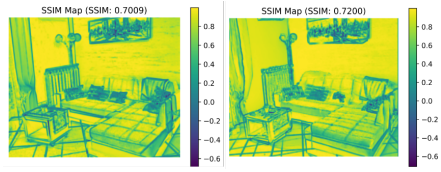


Figure 9.4: Heatmaps resulting from the SSIM calculation for Angle 1. Left: manual technique. Right: photogrammetry technique.

As the final step in evaluating the results of the two simulations, we were interested in assessing the functionality of the generated scenes in a real-time, freely navigable context. Therefore, we exported both scenes to Unity3D, a graphics engine particularly used for metaverse applications [112, 274].

Table 9.3: Measurement results of Unity3D simulations.

GPU	Mean GPU usage Manual	Mean GPU usage Photogrammetry
RTX 3060	34.4%	38.6%
MX130	86%	99%
GT 730	99%	99%
GPU	**Mean FPS Manual**	**Mean FPS Photogrammetry**
RTX 3060	60	60
MX130	28	27
GT 730	24	25

Table 9.3 presents the measurement results for each of the GPUs. The results of the simulations did not show significant differences in GPU usage between the two techniques. In fact, the main difference was in the performance of one GPU compared to another, rather than significant

variations between the scenes generated by the two techniques. The only notable variation was with the NVIDIA GeForce MX130, which reached its capacity limit only with the CV-generated scene, although it also showed high usage for the manual scene. However, this result is encouraging from the perspective of using auto-generation techniques for metaverse scenes: the latest GPU models can adequately handle even a significant difference in the number of polygons between two scenes, opening up possibilities for using CV-generated models, despite their complexity, in real-time rendered applications.

Summary of the results

The photogrammetry technique recreated the scene in 2 hours and 40 minutes, compared to 10 hours and 30 minutes manually. However, the auto-generated models had eight times more triangles. SSIM showed slightly higher similarity for CV-generated renders with the real environment across all three angles. Real-time simulation in Unity3D showed no significant differences in hardware resource usage between the two scenes.

9.4 DISCUSSION AND IMPLICATIONS

The experiment results offer insights into the current automation level in 3D scene generation for the metaverse using photogrammetry. This section discusses the strengths and weaknesses of each technique and shares lessons learned for quickly creating functional 3D scenes based on our findings.

9.4.1 *Techniques' Comparison*

As a first consideration, comparing the two techniques reveals that neither is superior in all aspects. Currently, two discussion points can be addressed: (1) the photogrammetry technique has significant advantages and can already be used today for creating realistic and functional metaverses; (2)

this technique still has notable inaccuracies and technical limitations that require manual expertise to achieve the desired goal. To address this, we provide an overview of the strengths and weaknesses of each method.

MANUAL TECHNIQUE — Manually producing a 3D model using dedicated software such as Blender, refining its topology, and obtaining a complete and clean mesh is the best approach when designing 3D environments that need to be renderable in real-time and run on various devices with different hardware components and computing power. To date, the efficiency achieved by a model created and refined manually by an expert has yet to be surpassed by 3D model auto-generation techniques. However, choosing solely this approach when developing a vast, detailed, and realistic environment like the metaverse increases production costs and time, since the manual technique for a single scene took significantly longer compared to auto-generation with Polycam. When extending these results to larger and more complex environments, such timeframes can become unsustainable, highlighting the current need to integrate automation techniques to make the expansive and comprehensive concept of the metaverse a reality.

PHOTOGRAMMETRY TECHNIQUE — Using a 3D model auto-generation tool based on computer vision algorithms like Polycam allowed us to achieve tangible results in significantly less time. Although this characteristic represents the most obvious advantage, it is not the only one observed: the similarity to the real environment was also more faithful, as indicated by the SSIM calculation. An important strength of this technique, when aiming for realistic and credible scenes, is that it maps real objects on a 1:1 scale, effectively scanning them. The level of detail it captures is greater and more refined than a manually generated model based solely on 2D photo references. Another significant strength is the auto-generation of textures, which are also faithfully extracted and created from the real object. However, using this technique alone to fully develop a real-time renderable 3D environment is not yet feasible. The first evident limitation is the excessive polygonal complexity of the resulting models. Although this did not pose a real problem during the Unity

simulation, this excessive numerical difference in polygons compared to manually obtained models can be a limitation when scaling up to larger and more complex environments. A second major limitation is that the models are incomplete and have significant inaccuracies and distortions in many areas. While this technique produced visually excellent results for small and detailed objects that could be easily photographed from many distinct points, it was weak and imprecise for large objects with simpler geometric shapes, where it was impossible to obtain a complete scan. The resulting object appears incomplete and highly deformed for some objects, such as the wall-mounted cabinet, the air conditioner, or the lamp. Such considerations suggest that the technique can easily support the creation of 3D scenes for the metaverse, but we are still far from being able to rely entirely on photogrammetry technologies.

9.4.2 *Lessons Learned for Development of 3D Metaverse Scenes*

Following the comparative analysis of the two techniques, we state our lessons learned and suggestions on how to combine them to obtain the best of both worlds specifically within the context of Metaverse scene development.

- First, *the use of a photogrammetry tool can be particularly useful for initial scanning of the overall structure and proportions of objects to be refined later*. This can solve the problem of obtaining accurate proportions of the actual object and overcome the limitations of having only 2D references when using a manual technique. **In the context of the Metaverse, this allows for rapid creation of large-scale, immersive environments that mirror real-world proportions accurately, enhancing user immersion and interaction.**

- Second, *manual modeling techniques are more efficient for objects with simple geometry*. For objects with very simple geometry that can easily be reduced to primitive 3D shapes, such as rectangular cabinets, various cylindrical objects, or, in general, objects with very

simple lines, there is hardly any reason to rely on their 3D scanning. **This efficiency is crucial in the Metaverse where performance optimization is necessary to maintain real-time rendering and interaction speeds, providing a smoother user experience.**

- ☛ Third, *Photogrammetry techniques are particularly useful for generating models of small objects with a high level of detail.* Complementing the previous lesson learned, small objects with a high level of detail—such as the potted plant and the decorative items on the mantelpiece in the generated scene—are particularly suitable for being scanned and generated by photogrammetry algorithms rather than being completely developed manually. **In the Metaverse, these detailed objects contribute significantly to the realism and aesthetic appeal of the virtual environment, which is essential for user engagement and satisfaction.**

- ☛ Last, *integrating models generated by both techniques can be a valid way to balance level of detail and performance.* To obtain real-time 3D scenes that adequately balance performance with the level of detail and realism achieved, a good strategy is to combine models and outcomes from both techniques. **In the Metaverse, this balance is critical as it ensures that scenes are both visually compelling and performant, avoiding latency issues and enhancing the overall user experience.**

In summary, the photogrammetry offers significant advantages for constructing 3D environments. While it can not yet fully replace human expertise, our insights can help make creating 3D scenes for the metaverse more efficient.

9.5 FUTURE WORK

The results obtained from this study can be extended from various perspectives for future work. First, our findings were derived from a single type

of environment; in this regard, repeating the experiment in diverse settings could enhance the generalizability of the results. Additionally, deeper insights could be provided by including individuals with varying levels of expertise. Finally, further exploration could involve applying different software and devices for both techniques, broadening the applicability and robustness of the results. All the above-mentioned points are part of our future agenda.

10

TOWARDS AI-POWERED AUTOMATIC 3D SCENE GENERATION FOR THE METAVERSE: A COMPARATIVE ANALYSIS OF MANUAL AND PHOTOGRAMMETRY TECHNIQUES

This chapter builds upon the paper submitted at the *Cluster Computing* [270], where the author of this thesis was the second contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Extending the discussion presented in the Chapter 9, this chapter investigates how artificial intelligence can support the generation of 3D assets, further advancing scalable approaches to metaverse construction.

10.1 INTRODUCTION

In recent years, the concept of the metaverse has evolved from a science fiction term [317] to a tangible and rapidly developing reality. Commonly defined as a persistent, immersive 3D environment where users can interact with digital content and each other in real time [290], the metaverse has attracted growing interest across multiple research domains—including education, simulation, and social interaction [121, 255, 335, 360]. Its potential lies in enabling realistic, immersive experiences within controlled and customizable virtual environments.

At the core of metaverse applications are realistic and immersive 3D scenes—i.e., virtual environments that resemble credible settings and allow users to explore, navigate, and interact freely within them [255, 369].

Such environments are composed of a set of diverse 3D models, which represent an object as a set of vertices in a three-dimensional space; when these vertices are connected through edges and faces and properly textured, they form the shape and appearance of the intended object [147]. Achieving a realistic and credible 3D object inherently involves a trade-off: the more complex and detailed a model is, the more visually realistic it becomes and the better it captures fine-grained characteristics; however, such complexity, mainly related to the number of polygons composing the object and the texture size, also demands greater computational resources to ensure smooth rendering in real-time applications [147, 344]. Consequently, 3D content creators must constantly balance visual fidelity with performance optimization, adjusting the detail level to meet aesthetic and technical requirements.

For the reasons mentioned above, creating 3D scenes that are both visually appealing and high-performing in real-time can be particularly challenging. Moreover, the creation of 3D models generally demands advanced technical and artistic competencies, which require substantial time and experience to acquire [65, 207]. Such skills are not typically widespread within software development environments. This represents a significant barrier to the development and diffusion of the metaverse, as it discourages practitioners from engaging in the design and implementation of custom virtual environments. As a result, there is a frequent reliance on pre-made assets, which constrains both creativity and opportunities for personalization [65]. The demanding expertise required for 3D modeling, combined with the growing need for readily available 3D assets to experiment with realistic virtual scenes, has opened the space for research efforts aimed at supporting professionals and researchers in the generation and integration of 3D models within metaverse environments.

Artificial Intelligence (AI) has emerged as a promising means to mitigate these challenges. In particular, recent advancements have introduced novel approaches that leverage AI to automate and accelerate the 3D content creation process, thereby reducing the reliance on specialized expertise. One such approach is **photogrammetry**, which involves captur-

ing multiple photographs or videos of a real-world object or environment from various angles and algorithmically reconstructing a 3D model that replicates the original geometry and texture [27, 64]. Photogrammetry technologies mainly follow two approaches: (1) Multi-View Stereo (MVS), which reconstructs 3D geometry by matching features across overlapping images [337], and (2) Neural Radiance Fields (NeRF), which uses neural networks to generate photorealistic views by learning the color and density of points in space [220, 286]. Building upon these technologies, some tools have been proposed to make them accessible to a broader audience, including Polycam [278], which leverages MVS-based pipelines, and LumaAI [209], which implements a NeRF-based approach. These tools hold great value as they wrap complex computational pipelines within user-friendly interfaces, enabling even users with limited 3D modeling or AI expertise to create realistic digital assets with minimal effort.

Despite the growing availability of tools that leverage photogrammetry for 3D reconstruction, their adoption has not yet become standard practice in the development of virtual environments. A key limitation lies in the uncertainty regarding the quality and usability of the generated outputs—particularly in terms of balance between visual complexity and rendering performance, which is critical in real-time applications [135, 344]. Although prior research has investigated the use of photogrammetry to reconstruct complex environments and avatars [2, 139, 281], **there is a lack of empirical studies evaluating whether the photogrammetry resulting assets are ready for practical use in metaverse applications**. Specifically, there is limited understanding of whether such tools can effectively *democratize* 3D scene creation, enabling users without prior modeling expertise to produce usable virtual environments.

This study aims to contribute to the body of knowledge in the field of automated 3D asset creation by providing practical insight into the use of photogrammetry-based tools to create visually appealing and functionally optimized 3D scenes for the metaverse. In our previous conference paper [266], we conducted a first comparative experiment in which the same indoor scene was recreated both manually and using the Polycam

tool. In this study, we present an extension of our conference contribution: we build on our preliminary results and expand the scope to enhance the robustness and generalizability of the findings.

◎ Goal of the study

Conduct a comparative experiment involving a manual modeling technique and photogrammetry-based tools to assess the usability of such tools for creating realistic and functional 3D scenes for the metaverse.

Specifically, we reconstructed a total of three scenes and a broader comparison, not only between manual and automated approaches, but also between two photogrammetry-based tools based on different underlying technologies—Polycam based on MVS and LumaAI based on NeRF, respectively. The reconstructed scenes were then evaluated using a set of quantitative metrics, each capturing a key dimension relevant to 3D scene creation for metaverse applications. These included: completion time (technique efficiency), polygon count (model complexity), Structural Similarity Index (SSIM) (visual realism), GPU usage and average FPS (real-time performance), and Hausdorff distance between corresponding models generated by Polycam and LumaAI (geometric divergence across tools).

Our results provide three main contributions. First, it presents a comparative evaluation of manual modeling and two photogrammetry-based approaches for the creation of 3D scenes tailored to metaverse applications. Second, it highlights the primary trade-offs observed among visual quality, modeling time, and real-time performance across the different reconstruction techniques. Finally, it offers empirically grounded insights intended to support both practitioners and researchers in selecting the most suitable modeling approach based on specific project requirements and application contexts.

The paper is structured as follows. Section **??** provides a theoretical background and the work related to our study. Section 10.2 reports in detail the experiment design and procedure that we followed. Section 10.3

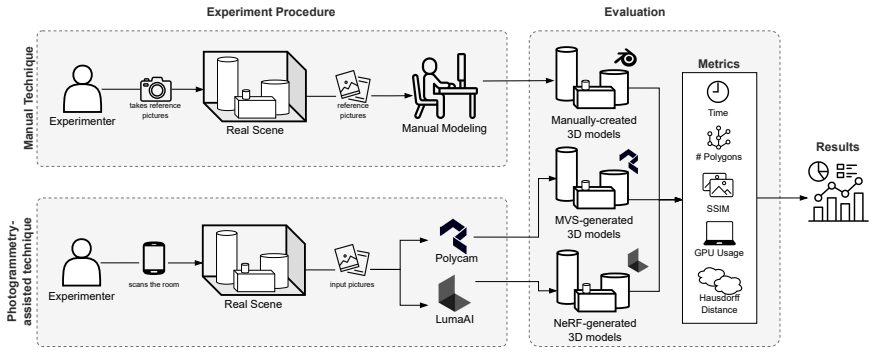


Figure 10.1: Overview of the experiment's procedure and evaluation

outlines the obtained results based on the computed evaluation metrics. Section 10.4 provides the discussion points from our results and some practical empirical guidelines. Finally, Section 10.5 draws the conclusion and future research directions.

10.2 EXPERIMENT DESIGN

To achieve our goal, we designed and conducted a comparative experiment involving two different techniques for 3D scene creation: manual modeling and photogrammetry-assisted modeling using freely accessible tools. The objective was to investigate the extent to which automated techniques for generating realistic 3D models can be effectively used to recreate virtual environments for the metaverse. Additionally, the experiment compares two photogrammetry tools—Polycam, which relies on MVS reconstruction, and LumaAI, which employs Neural Radiance the deep learning-based NeRF. Figure 10.1 summarizes the overall experiment's design and procedure.

1. First, we selected three scenes representing typical life scenarios and took photos of the objects inside them (for the manual modelling) and scanned them using a camera (for the photogrammetry-based approach). Our choice was guided by the emphasis of placed by Dionisio et al. [369] on realism, social presence, and interactiv-

ity as defining characteristics of the metaverse. Based on this, we chose typical environments that metaverse developers may wish to incorporate into their platforms: a domestic indoor environment (Scene Ⓐ—a living room), a working environment (Scene Ⓑ—an office), and a social environment (Scene Ⓒ—a meeting hall). Each scene comprised multiple objects varying in size, shape, and texture.

2. Then, one of the authors—with expertise in 3D modeling and texturing, hereafter referred to as the "experimenter"—was designated as the main participant responsible for creating all scenes using manual and photogrammetry-assisted techniques.[1]

3. Lastly, the generated 3D models were integrated into scenes designed to resemble metaverse environments. A set of evaluation metrics (described in Section 10.2.3) was computed, and the results were compared across the different setups to derive insights and formulate preliminary guidelines for practitioners.

10.2.1 *Employed Techniques*

In this study, we employed two major techniques to conduct the same task of obtaining a 3D representation of a real scene. The second technique will be divided into the use of two different tools, obtaining a total of three representations for each scene.

- **Manual Modeling**. This technique involves manually modeling each object by defining its geometry through the manipulation of vertices, edges, and faces within a 3D modeling environment. The process is eventually completed with a texturing process to resemble the real materials of the actual objects. We adopted Blender[2] for this

[1] The manual creation for Scene Ⓐ and its reconstruction with Polycam has been leveraged from the results of our preliminary experiment [266]. We integrated and completed such results with its LumaAI reconstruction and the computation of the new metrics. Scene Ⓑ and Scene Ⓒ were modeled and reconstructed from scratch, and the experimenter ensured to follow the same manual workflow previously used for Scene Ⓐ.

[2] https://www.blender.org/

purpose, as it is a widely accessible open-source tool with extensive documentation and community support. For each scene, the experimenter reconstructed all the objects from scratch, creating and applying textures through the material node system and relying on photographic references of the real-world counterparts.

- **Photogrammetry**. This technique utilizes photogrammetry-based mobile tools to scan real-world objects using a smartphone camera and automatically generate 3D reconstructions. Two applications, each based on a distinct reconstruction algorithm, were selected to explore the usability of such tools in different contexts. Both tools are freely available and compatible with standard mobile devices, making them accessible options for metaverse developers without specialized hardware or advanced 3D modeling expertise.

    - **Polycam**. This tool reconstructs 3D models by processing a series of overlapping images of a real-world object or environment captured from different angles using a mobile device. It uses an MVS pipeline [337], which first extracts features from each image and matches them across views to estimate the relative positions of the camera. Then, it triangulates the matched features to generate a dense point cloud, which is then converted into a mesh. Textures are generated by projecting the original photos onto the mesh surface, resulting in a photorealistic appearance. The entire process is automated and optimized for mobile performance [278].

    - **LumaAI**. This tool leverages NeRF-based models for the reconstruction [220]. Unlike traditional photogrammetry, which relies on geometry-based triangulation, NeRF uses a neural network to learn the volumetric radiance field of a scene from a set of 2D images taken from different viewpoints. The network learns how light behaves within a scene, mapping each 3D point and viewing direction to a corresponding color and density value. This approach enables detailed and photorealistic

reconstructions, which are particularly effective for capturing complex lighting and surface properties.

Both tools were selected because they allow 3D reconstruction using a mobile phone and can process the same input data—photos or videos of real-world objects. However, each tool relies on a different underlying reconstruction technique. This setup enables a direct comparison of the output quality and usability, allowing us to investigate whether and how the reconstruction method affects the final results and to identify any significant differences between the two approaches.

10.2.2 *Experiment Procedure*

To guide the experiment's design, we conducted a pilot study. One co-author tested the procedure in an indoor environment, which was not part of the three planned scenes for the experiment (a domestic kitchen), before conducting the main experiment. The aim was to gain hands-on familiarity with the selected tools and modeling techniques and identify potential challenges in their use. This preliminary exploration also served to fine-tune the experimental procedures, which were then applied consistently in the main study, as described in the following section.

The experiment's procedure began with setting up the scene. The authors carefully prepared each scene to include a variety of objects representative of the target environment, ensuring a range of shapes, sizes, and textures. For example, the living room (Scene (A)) included items such as a coffee table, plants, and decorative elements, while the office (Scene (B)) featured desks, chairs, documents, and stationery. A complete list of the objects is shown in Table 10.1. The experimenter accessed each environment twice—once for each technique. For the manual modeling, the experimenter was first allowed to take pictures of the room and its objects to be used as visual references during the modeling process. The experimenter independently determined the number and type of reference images needed for accurate modeling and texturing. The time taken

to capture these references was included in the overall time measurement for the manual modeling process. Following this step, the experimenter recreated the entire scene using Blender. Modeling sessions were limited to a maximum of two hours per session and repeated over multiple days until the scene, including geometry and texturing, was fully completed. For the photogrammetry-based approach, the experimenter revisited the room and used a smartphone to capture the scene by photographing each object from multiple angles. The selected tools—Polycam and LumaAI—processed these images to generate textured 3D models.[3] Blender was subsequently used only to assemble the reconstructed assets into a coherent scene layout.

Three distinct 3D reconstructions were obtained for each scene—one for each modeling technique and tool. When the scenes were completed and assembled, Blender was used to extract quantitative metrics related to model complexity and level of detail and to generate renders with lighting settings similar to the original scenes. Subsequently, the experiment procedure's last phase consisted of exporting all reconstructed scenes to Unity3D,[4] a widely adopted game development engine, to assess their functional performance. This phase was essential to evaluate how each model behaved in a real-time environment, particularly in terms of rendering efficiency and interactivity. We created a scene for each reconstruction to obtain these insights and ran a real-time exploration with a first-person camera and free 3D movement for 5 minutes each.

10.2.3 *Metrics for Evaluation*

To obtain and evaluate the experiment's results, we computed a set of metrics. Each of the chosen metrics, explained in the following, aimed to capture insights into the different aspects of the evaluation process.

[3] The living room was subject to our first experiment [266], for which we will consider our preliminary outcomes in our results. Since the second tool was not present in the first work—i.e., LumaAI—the same pictures used on such a tool to generate the remaining models.

[4] https://unity.com/

- **Time for Completion.** This metric was employed to obtain insights on the *techniques efficiency*. For each technique, the total time required to complete the 3D reconstruction was measured in hours and minutes, starting from the experimenter's initial access to the room and ending with the completion of the final scene. This time tracking was intended to assess how much photogrammetry tools can significantly accelerate the 3D scene creation process compared to manual modeling.

- **Number of Polygons.** This metric was employed to obtain insights on the *3D models' complexity*. For each model of each scene, we measured the number of polygons, specifically triangular faces, that compose each mesh. A higher polygon count typically corresponds to greater visual detail, which can enhance realism but may also impact performance, particularly in real-time applications: higher polygon counts increase the demand for hardware and software resources to ensure smooth simulation [344]. This aspect is especially relevant in the context of the metaverse, where real-time rendering is essential for interactive and immersive experiences [369]. We note that the experimenter was not instructed to match a specific polygon count during manual modeling. In both approaches, the shared objective was to achieve a result that closely resembled the real-world reference from a visual standpoint.

- **Structural Similarity Index (SSIM).** This metric was employed to obtain insights on the *3D reconstruction realism*. The SSIM metric [340] compares two images based on three key components: luminance, contrast, and structural information. It ranges from –1 (maximum dissimilarity) to 1 (maximum similarity). We employed this metric to assess the visual similarity between photographs of the actual living room and the corresponding 3D reconstructions. To compute it, we first took three photos of each real room from different viewpoints, ensuring that all objects appeared in at least one image. We then generated three corresponding renders from the 3D scenes in Blender, carefully aligning the virtual camera angles to match the

real photographs and creating a similar lightning setting, simulating the act of taking the same shots within the virtual environment. SSIM was then calculated for each pair of real and rendered images. We opted to apply this method to the entire room scene rather than to individual objects, as our goal was to evaluate the overall realism of the reconstructed environment rather than the fidelity of single elements.

- **GPU Usage & Mean Frames Per Second (FPS).** These metrics was employed to obtain insights on the *scenes' functionality for real time rendering*. We measured the GPU usage required to run the real-time simulation of each reconstructed scene. To obtain this measurement, all reconstructed scenes were exported to Unity3D; we configured the game scene with a first-person controller, allowing free movement via mouse and keyboard input. The simulation was executed for five minutes on three different machines, each equipped with a distinct NVIDIA RTX GPU with from three different generations based on our availabilities: a second generation GPU (RTX 2080), a third generation GPU (RTX 3060), and a fourth generation GPU (RTX 4090). We recorded the average GPU usage percentage and average FPS during each session to assess the rendering performance across different hardware profiles.

- **Hausdorff Distance.** This metric was employed to obtain insights on the *differences among the 3D models*. It quantifies the geometric dissimilarity between two 3D shapes by measuring the maximum distance from a point on one mesh to the closest point on the other. A higher distance indicates greater dissimilarity between the models [16]. This metric was selected to evaluate differences between the generated and manually created models and between the generated models. In particular, it allowed us to investigate whether the two photogrammetry tools produced significantly different results when given the same input images. We computed the Hausdorff Distance and analyzed the resulting values for each pair of models represent-

ing the same object (manual vs. Polycam, manual vs. LumaAI, and LumaAI vs. Polycam).

10.2.4 *Threats to Validity*

This section presents the threat and limitations emerging from our research design.

A potential threat to internal validity arises from the dependence on a single participant's proficiency and familiarity with the tools employed in the experiment, specifically Blender, Polycam, and LumaAI. This reliance introduces concerns regarding the reproducibility of the results, as outcomes may vary with participants possessing different levels of expertise. For instance, a greater familiarity with Blender than with Polycam could introduce an implicit bias favoring manual modeling techniques over automated photogrammetric generation. Moreover, consistent task execution across both techniques is critical. In this study, the same co-author performed all modeling tasks using both methods, potentially introducing personal biases or methodological inconsistencies. These factors may influence the comparative results, not due to objective differences in performance, but rather due to subjective familiarity with the tools. However, given that this study aims to explore and demonstrate the potential of an automated modeling approach rather than to establish its definitive superiority, this decision was considered an acceptable methodological trade-off.

The generalizability of the study is inherently limited by its scope and context. The study's outcomes are influenced by the specific tools used during the experiment. Variations in software capabilities, as well as future technological advancements, may yield different findings, thereby affecting the broader applicability of the conclusions.

Another potential limitation pertains to the adequacy of the selected metrics in capturing the intended constructs. The evaluation relied on measures such as modeling time, polygon count, Structural Similarity Index Measure (SSIM), and GPU usage to assess quality and efficiency.

Although these indicators provide useful quantitative insights, they may not fully represent all dimensions of practical relevance, particularly those related to user experience in interactive applications or performance in real-time rendering contexts. For example, a model with a lower polygon count may perform better computationally but could compromise visual realism, thereby diminishing the immersive quality of the experience. As such, an exclusive reliance on these metrics may offer a partial view of the effectiveness and usability of each modeling technique.

10.3 ANALYSIS OF THE RESULTS

In the following section, we present the results obtained based on the evaluation metrics.

The experiment produced three distinct 3D representations for each environment, resulting in a total of nine reconstructed scenes—one per technique (Manual, Polycam, and LumaAI) for each setting. The scenes generated using the photogrammetry-based tools were processed and assembled within Blender to ensure consistency in layout and lighting. All the material produced during the study, including raw assets, models, and comparative visualizations, is publicly available in the online appendix [269]. Figure 10.2 shows an overview of the obtained scenes for each technique.

10.3.1 *Time for Completion*

As an initial insight, we measured the time required to complete each scene to evaluate the efficiency of each modeling technique. Specifically, the completion time was computed as the total duration from the initial data acquisition phase (manual reference photo collection or environment scanning) to the final 3D scene assembly in Blender. Since the two tools received input from the same videos, their completion time is summarized in a single measure. Table 10.2 reports the results for all nine scenes, organized by technique.



Figure 10.2: Overview of the obtained scenes.

As expected, the manual technique required significantly more time than the automated approaches. On average, scenes modeled manually required approximately 7 hours and 25 minutes, whereas those reconstructed using Polycam and LumaAI required only 2 hours and 12 minutes. These results suggest that **automated reconstruction techniques reduced modeling time by over two-thirds**. The observed variation in completion time across scenes within the same technique appeared to correlate with the number of objects and the overall level of detail in the original environment. For instance, Scene (A) was consistently the most time-consuming to reconstruct, regardless of the technique adopted, due to its higher complexity. This trend remained consistent for both manual modeling and automated photogrammetry-based reconstruction. However, such time differences across scenes for the automated techniques were less pronounced; this may be attributed to the underlying automation and repetitive process, as recording a video of and object is not directly related to its level of detail.

This initial measurement confirmed the notable acceleration achievable through photogrammetry techniques compared to manual modeling. Although automated tools still require time to capture detailed video sequences and to process the data to generate the 3D model, the total time

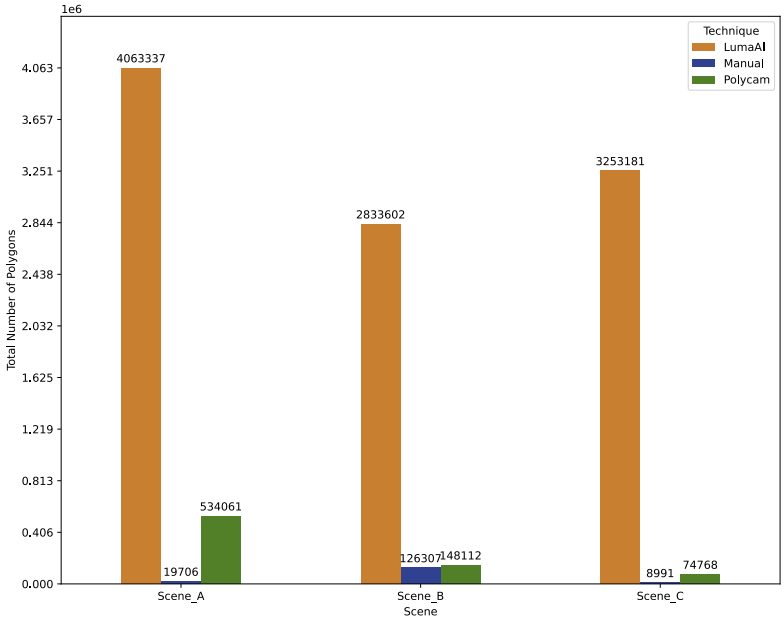


Figure 10.3: Total number of polygons for each scene and each technique.

investment remains significantly lower than that required for manual reconstruction, which is still markedly more time-intensive.

10.3.2 *Number of Polygons*

To assess the complexity of the resulting 3D models, the total number of polygons was computed for each scene and technique. The results, summarized in Figure 10.3, highlight considerable differences between the manual and automated approaches.

Manual modeling consistently resulted in the lowest polygon counts, with values ranging from only 8,991 in Scene (C) to 126,307 in Scene (B). This outcome reflects the inherently optimized topology achieved through manual mesh construction in Blender, where the experimenter operated in *Edit Mode* to manipulate each vertex and face starting from primitive shapes. This process naturally produces lightweight and uniform geome-

tries, even for complex or irregular objects. As an example, Figure 10.4 shows the polygon count and topology for the same work chair.

In contrast with the manual results, models generated with LumaAI exhibited extremely dense meshes, with polygon counts exceeding 2.8 million in all scenes and peaking at over 4 million in Scene (A). These results are consistent with the nature of NeRF-based photogrammetry methods, which aim to capture fine surface details through high-resolution reconstruction [286]. While such richness enhances visual realism, it poses challenges for real-time rendering, especially in resource-constrained environments like VR or mobile platforms. Polycam maintained a considerably more moderate polygon count, ranging from approximately 74,000 to 534,000. This balance suggests an internal optimization mechanism that reduces mesh density while preserving essential details. Regarding the two tools, this comparison highlights a key trade-off: Polycam provides a more lightweight output suitable for performance-sensitive environments, yet is more sensitive to finer details and may suffer from geometric incompleteness; LumaAI maximizes fidelity and surface detail, but generates meshes that may be computationally prohibitive without further optimization.

10.3.3 *SSIM Values*

To assess the visual fidelity of each reconstructed scene, the Structural Similarity Index (SSIM) was computed for three viewpoints (angles) per scene. SSIM compares rendered images of the 3D scene against real photographs of the original environment, quantifying visual similarity on a scale from -1 (no similarity) to 1 (perfect match). Table 10.3 reports the SSIM values for each technique across all scenes and angles. To obtain visual insights of the results, we generated the SSIM maps by overlapping the two pictures under examination. Figure 10.5 shows an example of the SSIM maps for Scene (A), Angle 3.

Results indicate that no single technique consistently outperformed the others across all scenarios. In Scene (A), Polycam achieved the highest similarity values overall (avg. SSIM $\approx$ 0.58), while the manual tech-



Figure 10.4: Comparison of the meshes obtained for the Working Chair object. The manually created chair contains the lesser polygons, resulting in a clearer mesh. The Polycam version increases the count, still within a reasonable range for interactive applications. However, despite its moderate complexity, the mesh includes a topological error—a visible hole in the backrest. In contrast, the LumaAI reconstruction reaches almost 1M polygons, delivering a highly detailed surface with no missing geometry but at the cost of an extremely dense mesh.

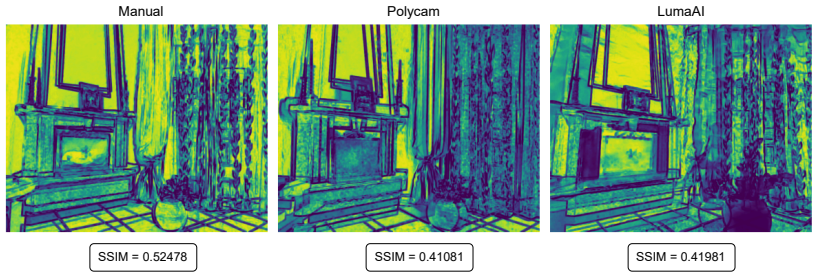


Figure 10.5: SSIM maps for Scene A, Angle 3. Higher SSIM values are represented by brighter yellow areas and lower similarity by darker blue regions. The manual technique displays uniform similarity across the entire image, especially on flat surfaces such as the walls and the floor. Polycam reconstruction captures higher similarity around key elements like the fireplace and curtains, though some noise and local inconsistencies are visible. The LumaAI result, while visually rich in geometry, shows more pronounced inconsistencies and a less homogeneous SSIM distribution.

nique produced slightly lower values and LumaAI consistently performed worst. This trend suggests that in complex, highly furnished scenes such as Scene (A), Polycam's approach better preserved the original visual appearance, possibly due to its more balanced mesh and texture generation pipeline. Conversely, in Scene (B), both Polycam and the manual technique achieved comparable scores (avg. SSIMs above 0.58), while LumaAI also returned satisfactory results. Here, the difference between techniques was less pronounced. Finally, in Scene (C), the manual technique consistently produced the highest SSIM values across all three angles (avg. SSIM ≈ 0.57), slightly outperforming Polycam and LumaAI. This result may be attributed to the relatively simple object shapes, which made manual modeling and texture mapping more effective.

Overall, the results confirmed that Polycam provided a robust compromise between automation and realism, achieving competitive SSIM scores while maintaining a moderate polygon count. Interestingly, despite LumaAI producing highly detailed and complete meshes, it did not consistently translate this detail into visual similarity with the real scene—suggesting possible limitations in texture generation or lighting reconstruction.

10.3.4 *GPU Usage & Mean FPS*

To evaluate the real-time performance of the obtained scene, which is required for metaverse scenes, we imported each of them on Unity and ran a simulation for five minutes. We simulated each scene on three machines with three NVIDIA RTX GPUs. The simulation results further illustrate the trade-offs observed in previous sections. As expected, both the scenes' polygon count and the hardware's computational capabilities significantly influenced the performance outcomes. The results of the simulations are summarized in Table 10.4.

For the RTX 2080, performance degradation was evident when handling LumaAI models. While Manual and Polycam models maintained acceptable frame rates around 55–58 FPS, LumaAI models caused a sharp drop to

approximately 30–32 FPS across scenes. GPU usage also increased notably for LumaAI, reaching values above 80%, reflecting the heavy computational load imposed by the dense and complex meshes. The RTX 3060, a more recent mid-tier GPU, provided a more balanced performance. Manual and Polycam models were handled comfortably at 60 FPS, with GPU usage remaining between 32% and 39%. However, even the RTX 3060 showed signs of strain when rendering LumaAI models, where GPU usage approached 80%, and frame rates dropped to approximately 35–37 FPS, depending on the scene. In contrast, the RTX 4090 easily managed all models with minimal GPU usage and exceptionally high frame rates. Manual and Polycam models were consistently rendered at 115–120 FPS across all scenes, with GPU usage below 15%. Even LumaAI models, despite their extremely high polygon counts, maintained frame rates above 90 FPS, with GPU usage peaking at 40%. Overall, these results confirm that the choice of modeling technique directly impacts performance, particularly in real-time applications. Manual and Polycam models proved to be manageable across a wide range of hardware, while LumaAI models, although visually rich, introduced significant computational overhead. Consequently, unless used in systems equipped with high-end GPUs like the RTX 4090, models generated through LumaAI may require substantial optimization to ensure satisfactory real-time performance.

10.3.5 *Hausdorff Distance*

To complement our analysis and further investigate geometric divergence at the object level, we computed the Hausdorff distance between the meshes generated by LumaAI and Polycam for each object. Given the high polygon count observed in the LumaAI models—often several times greater than those of Polycam—we expected substantial geometric differences. The Hausdorff metric enabled us to quantify these differences by measuring the greatest minimal distance between the two point sets representing each model. Table 10.5 summarizes the computed Hausdorff distances per object for all three scenes.

The results confirmed our original hypothesis. In Scene (A), the models exhibited the highest discrepancies, with several objects exceeding a distance of 1.0. Notably, the lamp (≈ 1.67), sofa (≈ 1.56), and curtain (≈ 1.35) were among the most divergent, likely due to their complex surfaces and the denser, less regular topology produced by LumaAI. In Scene (B), distances were generally lower, with most objects below 0.3. The lower values across the scene indicate a higher level of alignment between the two techniques when modeling simpler and more structured items, such as desks or electronic devices. Finally, Scene (C) yielded the smallest Hausdorff distances overall. All values remained below 0.3, and in several cases (e.g., meeting chair and cabinet) even below 0.1. This confirms that for geometrically simpler objects and more accessible angles, the differences between the two techniques become less pronounced.

These results support the fact that Polycam and LumaAI's geometric similarity is object-dependent. For small or regular-shaped objects, the difference is less pronounced, while for more articulated or partially occluded geometries, LumaAI tends to diverge significantly, possibly due to overfitting surface detail.

Summary of the results

The analysis of the experimental results examined the performance of each technique from multiple perspectives. First, photogrammetry tools accelerated the reconstruction process by approximately two-thirds compared to manual modeling, significantly reducing completion time. However, manual modeling still achieved a lower polygon count and cleaner mesh topology, making it more suitable for real-time 3D applications. The SSIM values indicated no technique consistently achieved a significantly higher realism score than the original scene. The most notable differences emerged during real-time simulations, where the more complex models generated by LumaAI resulted in poorer performance. Finally, the Hausdorff distance analysis between LumaAI and Polycam models revealed that the two tools tended to produce substantially different mesh topologies from the same input video, highlighting that the choice of tool is highly dependent on the specific context and the characteristics of the object to be reconstructed.

10.4 DISCUSSION

This section discusses some key points that emerged after analyzing the metrics results. First, we argue the main differences among the techniques and what influences them the most. Then, we provide a more in-depth comparison between the two tools. Finally, we highlight future work that could build upon our findings.

As a first overall observation, the results of this experiment confirmed and strengthened the findings reported in the previous study. As anticipated, the primary trade-off observed lies between processing time and the real-time usability of the reconstructed models. Manual modeling, which involves the direct intervention of a human expert to construct and optimize each object mesh, remains the most effective technique in terms of real-time performance and is not likely to be entirely replaced

with the current technologies. This approach enables complete control over the structure and cleanliness of the mesh, resulting in lightweight and topologically efficient models. However, it also requires significant time investment and the involvement of personnel with both technical and artistic expertise. In contrast, mobile photogrammetry tools offer a more accessible and efficient alternative. These solutions significantly accelerate the modeling pipeline and require minimal expertise, making them suitable for rapid prototyping or use by non-expert users. Nevertheless, the models they produce tend to lack control over mesh topology, include possible reconstruction flaws, and often result in geometries with high polygon counts. Such results increase the computational load and negatively impact performance in real-time environments, particularly in hardware-constrained platforms such as mobile or VR systems.

☞ **The performance of reconstruction techniques was highly dependent on the characteristics of the individual objects.** Three main dimensions emerged as critical factors: object size, surface properties, and geometric complexity. First, object size had a notable impact on photogrammetry-based methods. Large objects posed difficulties during the acquisition phase, as capturing all relevant angles often required more physical space and movement, increasing the likelihood of occlusions or incomplete coverage. This limitation affected the completeness and consistency of the resulting meshes. Although limited viewpoints for larger objects also challenged manual modeling, the human modeler could mentally reconstruct occluded or unseen parts of the geometry, mitigating this issue to a certain extent. Second, reflective surfaces introduced significant challenges for both image- and video-based reconstruction. Since reflections vary across viewing angles, they generate inconsistencies across frames, leading to texture artifacts, geometric inaccuracies, or even holes in the reconstructed mesh. These artifacts were recurrent in objects with glossy finishes, where photogrammetry struggled to produce stable reconstructions. In contrast, manual modeling allowed the designer to ignore or reinterpret reflection effects, producing more stable and uniform geometry. Third, the geometric nature of the objects played a crucial role. Surprisingly,

flat and straightforward objects—such as tables or wardrobes—proved problematic for photogrammetry algorithms. These approaches leverage light and shading variations to guide the reconstruction process, which is less effective when the surface lacks distinct features. Manual modeling, instead, was much more efficient in these cases, as simple shapes could be quickly assembled using basic primitives such as cubes or cylinders. Conversely, small and highly detailed objects—including plants, telephones, and keyboards—proved well-suited for photogrammetry. Their compact size facilitated full-angle coverage during scanning, and their intricate geometries provided abundant visual cues (e.g., edges, shadows, textures) that supported accurate reconstruction. Manual modeling, in contrast, would require substantially more time and effort to replicate the same level of detail, making it a less practical option for such objects. Figure 10.6 provides a visual summary of these observations, illustrating how different object features influenced the strengths and weaknesses of each reconstruction technique.

☞ **Can the photogrammetry tools replace the manual modeling? Short answer is no.** The short answer is no. Although photogrammetry-based tools offer significant advantages in terms of speed, ease of use, and accessibility, they cannot fully replace manual modeling for many professional applications. Photogrammetry dramatically accelerates the 3D reconstruction process and allows non-expert users to use it; however, it lacks the precision and control over mesh topology that manual modeling provides. The models generated through photogrammetry often result in dense and irregular meshes, making them unsuitable for real-time applications without substantial post-processing. Moreover, as previously highlighted, an important downside is represented by photogrammetry's struggle with certain surface types—such as reflective, transparent, or featureless materials—and its limited resolution of missing or occluded parts of an object. Manual modeling remains indispensable in scenarios that require high-quality, optimized meshes for performance-sensitive environments such as VR, mobile platforms, and real-time simulations. It enables the creation of clean, low-polygon structures tailored to the application's specific needs

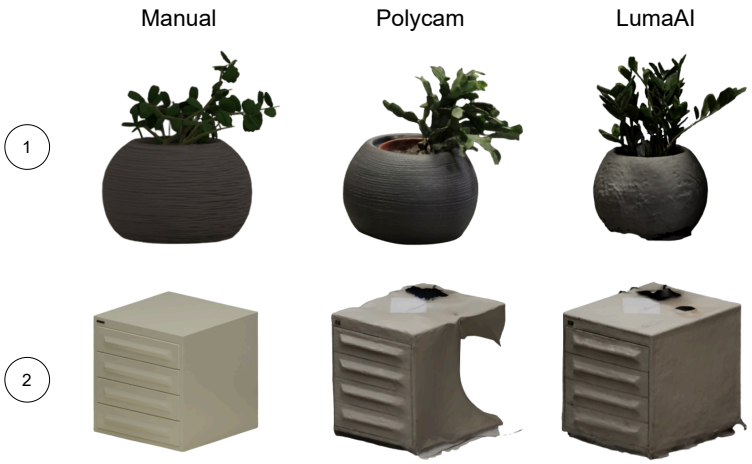


Figure 10.6: Comparison of two models generated using the three reconstruction techniques. Row 1 shows a plant, a complex and highly detailed object that appears more realistic when reconstructed with photogrammetry tools, while the manually modeled version appears less convincing. Row 2 shows a cabinet, a simple geometric object, where the manual modeling produced a clean and accurate result, whereas the photogrammetry-based reconstructions, particularly with Polycam, exhibited more distortions.

and allows creative adjustments beyond what is captured from reality. Additionally, manual intervention is often necessary to correct artifacts, refine textures, and optimize UV mapping, all of which are critical for professional-grade 3D assets. However, our findings confirm that rather than serving as a replacement, **photogrammetry tools should be regarded as complementary technologies.** They are particularly valuable for rapid prototyping, scanning complex organic objects, or generating assets for applications with less critical performance constraints. However, for scenarios demanding precision, optimization, and creative control, we argue that with the current technologies, manual expertise remains irreplaceable.

👉 **Which of the analyzed tool is the best choice?** Having assessed that manual effort is still needed, the comparison of the two tools' results gave us insights into which one is more suitable for specific scenarios. Indeed, both tools exhibited specific strengths and weaknesses that varied depending on the type of object and surface characteristics related to their underlying technologies. As a first consideration, LumaAI produced higher-fidelity meshes than Polycam, being able to generate complete reconstruction most of the time. With the same input video, Polycam often generates incomplete meshes with holes or distortion. However, the models generated by LumaAI were consistently heavier in terms of polygon count—with no control over such an output—resulting in dense and computationally demanding geometries that negatively impacted real-time performance. Polycam, in contrast, produced lighter models that were more compatible with hardware-constrained platforms, even though this sometimes came at the expense of reconstruction completeness. When analyzing the tools' performances, object type plays a significant role in tool performance. Polycam struggled with objects exhibiting mixed surface types—such as desks combining large flat surfaces with intricate details—leading to incomplete reconstructions and the presence of holes in the mesh. In these scenarios, LumaAI performed better, capturing both broad shapes and fine details more reliably, albeit with a heavier and more complex resulting mesh. Conversely, reflective surfaces represented

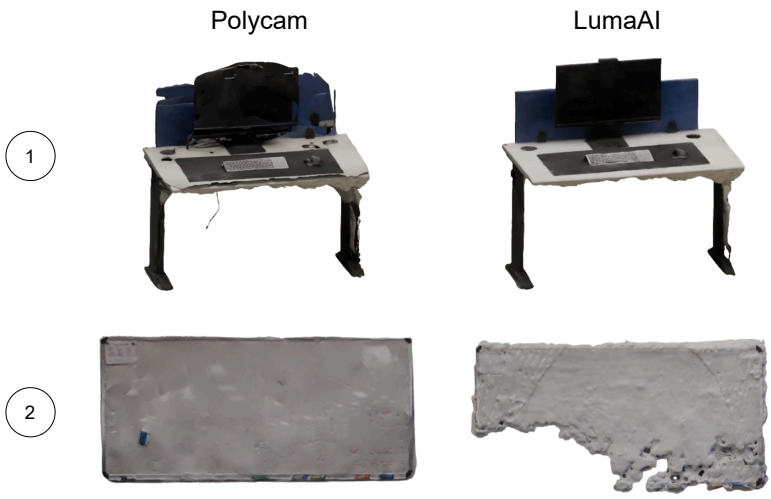


Figure 10.7: Comparison of two models generated with Polycam and LumaAI. Row 1 shows the working desk, a case where LumaAI outperformed Polycam. This suggests that in the presence of heterogeneous surfaces with varying levels of detail, Polycam's reconstruction tends to introduce inaccuracies, whereas LumaAI handles such complexity more effectively. Row 2 presents the whiteboard, where Polycam achieved a better result than LumaAI. This indicates that smooth, glossy, and reflective surfaces pose significant challenges for LumaAI, while Polycam demonstrates greater robustness in handling these material properties.

a significant challenge for both methods, but Polycam proved to be more robust. For instance, when reconstructing objects like the whiteboard, Polycam managed to produce a distorted yet complete model, whereas LumaAI failed to deliver a stable or coherent reconstruction. Figure 10.7 shows an example of this comparison. In summary, the choice between the two tools should be guided by (1) the specific requirements of the target application, balancing fidelity against performance needs, and (2) the object's characteristics and materials.

10.5 FUTURE WORK

This work opens several avenues for future research. First, the adoption of lightweight NeRF variants or hybrid optimization pipelines—such as Gaussian Splatting techniques—could be explored to address the performance limitations associated with current dense photogrammetric outputs, while also extending this investigation with novel practical recommendations. Second, the integration of post-processing steps, including mesh simplification, texture retargeting, and artifact correction, could be assessed to improve the real-time applicability of photogrammetry-derived models. Third, empirical studies evaluating user experience within metaverse environments reconstructed through different modeling techniques could reinforce these findings by incorporating human-centered evaluation metrics, such as perceived realism, immersion, and interaction quality. Finally, large-scale replications focusing on increasing the number of artists involved in the reconstruction process—rather than solely the end users of the developed models and scenes—could generate new insights, further validating or refining the results presented in this work.

Table 10.1: Overview of the objects of each scene to be reconstructed.

Scene	**Objects**
Scene (A)	Clock
	Painting
	Wardrobe
	Chimney
	Lamp
	Plant
	Sofa
	Curtains
	Air Conditioner
	Coffee Table
	Heater
Scene (B)	Whiteboard
	Printer
	Big Desk
	Office Chair
	Work Desk
	Keyboard
Scene (C)	Telephone
	Chair
	Big Whiteboard
	Cabinet
	Small Whiteboard
	Meeting Table

Table 10.2: Completion time for each scene.

Scene	Manual	Polycam & LumaAI
Scene (A)	10h 30m	2h 40m
Scene (B)	6h 35m	2h 10m
Scene (C)	5h 10m	1h 50m
Mean	**7h 25m**	**2h 12m**

Table 10.3: SSIM values for each image and technique across the three scenes.

Scene	Angle	Polycam	Manual	LumaAI
Scene (A)	1	0.58297	0.55420	0.44150
	2	0.63305	0.56612	0.43628
	3	0.52478	0.41081	0.41981
Scene (B)	1	0.61454	0.62902	0.60870
	2	0.58918	0.51791	0.54891
	3	0.54835	0.56796	0.53865
Scene (C)	1	0.52454	0.53834	0.49610
	2	0.56766	0.57940	0.54327
	3	0.54811	0.58899	0.54538

Table 10.4: Mean GPU usage (%) and FPS during Unity3D simulations for each GPU, scene, and technique.

GPU	**Scene**	**GPU Usage (%)**			**Mean FPS**		
		Manual	Polycam	LumaAI	Manual	Polycam	LumaAI
RTX 2080	Scene (A)	38	43	85	58	55	30
	Scene (B)	36	40	80	59	57	32
	Scene (C)	34	38	82	60	58	31
RTX 3060	Scene (A)	34	39	80	60	60	35
	Scene (B)	33	37	78	60	60	36
	Scene (C)	32	36	76	60	60	37
RTX 4090	Scene (A)	12	15	40	120	115	90
	Scene (B)	10	14	38	120	118	92
	Scene (C)	8	12	35	120	119	95

Table 10.5: Hausdorff distance between Polycam and LumaAI models for each object.

Scene	Object	Hausdorff Distance
Scene (A)	Clock	0.3617
	Painting	0.3952
	Wardrobe	1.0182
	Chimney	0.6171
	Lamp	1.6724
	Plant	0.8055
	Sofa	1.5657
	Curtains	1.3527
	Air Conditioner	0.3229
	Coffee Table	0.9791
	Heater	0.8034
Scene (B)	Whiteboard	0.2295
	Printer	0.1013
	Big Desk	0.2801
	Office Chair	0.9089
	Work Desk	0.1296
	Keyboard	0.0719
Scene (C)	Telephone	0.1306
	Chair	0.0570
	Big Whiteboard	0.1715
	Cabinet	0.0987
	Small Whiteboard	0.0797
	Meeting Table	0.2670

11

METASERGE — A SERIOUS GAME FOR RISK MANAGEMENT IN AN EDUCATIONAL METAVERSE

This chapter builds upon the paper submitted at the *International Conference on Software Engineering* (ICSE), where the author of this thesis was the second contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the SENEM prototype in Chapter 7, which was progressively developed throughout the thesis, this chapter focuses on the design of an interactive educational experience, thereby exploring the contribution of gamification to metaverse-based learning.

11.1 INTRODUCTION

Risk management is crucial for the success of software projects [4], and when carried out poorly it might lead to failure [67]. The Project Management Body of Knowledge (PMBOK) highlights risk management as one of the most complex knowledge areas, since it requires anticipating uncertainties and planning effective responses [163]. Its centrality is also reflected in software engineering curricula [44], where students are expected to develop the ability to recognize and address risks during project work. Despite this importance, teaching risk management effectively remains challenging. Traditional approaches—such as lectures, case studies, or paper-based exercises—can convey definitions and processes but often fail to reproduce the dynamic and collaborative nature of real projects [131].

In risk management education, board games such as Riskaware [166] and ARMI 2.0 [313] have been designed to introduce probabilistic reasoning in risk management. Annunziata et al. recently introduced SERGE [75], a serious game designed for risk management education [11]. It addresses a broad set of learning objectives, i. e., risk identification, mitigation planning, resource negotiation, and collaborative decision-making. However, its non-digital format introduces two limitations: it is designed for in-person participation only, and players must manage calculations and progress manually.

To overcome these limitations, we extended SERGE to a digital version within SENEM[1]—an educational metaverse enabled by software engineering practices [274], i. e., MetaSERGE.

Tools Selection Rationale

Compared to other serious games, SERGE was designed to address the complete cycle of risk management, making it broader in scope than alternatives. While originally developed as a physical board game, its characteristics make it a suitable foundation for exploring how metaverse environments can support experiential learning in software engineering. In addition, SENEM is an openly available educational metaverse, designed in accordance with software and metaverse engineering practices and empirically validated. Its architecture and documentation also make it suitable for replication and integration into classroom contexts.

Our decision to adopt a metaverse platform was intentional. Although the metaverse faces ongoing challenges [102], it offers features that extend beyond standard 2D applications. Learners are represented as avatars in a shared 3D environment, where they interact with artifacts and collaborate through spatial communication. This sense of immersion and presence may enhance attentional engagement and a sense of agency, which have been associated with improved learning outcomes [161]. The environment also supports embodied collaboration, where proximity, movement, and

[1] https://github.com/vipenti/SENEM_Metaverse

gesture can enrich teamwork and negotiation—key aspects of risk management practice [92]. The metaverse can support scalable and distributed participation, enabling learners in different locations to collaborate as if co-located and thus broadening access and inclusivity [199, 280].

By embedding SERGE in a metaverse environment, we aim to provide instructors with a tool that (1) allows students to learn by doing in immersive, consequence-rich scenarios, (2) broadens access by supporting remote, hybrid, and distributed classrooms, and (3) possibly reduces facilitator effort, making experiential learning more feasible at scale.

To gain preliminary insights into its effectiveness, we conducted a two-phase evaluation. A pilot study with two students informed interface refinements, followed by an evaluation with six students organized into pairs. Each pair completed a full MetaSERGE session and responded to the same questionnaire used in the analog study [11], along with the System Usability Scale (SUS) [54].

Preliminary results from the survey pointed to improvements in students' ability to apply risk management concepts in realistic project scenarios. Participants also found MetaSERGE intuitive and engaging, while the metaverse helped foster collaboration and preserved the dynamics of face-to-face gameplay in remote settings.

Overall, these findings suggest that MetaSERGE may extend its educational value possibly supporting both students and instructors. The digital format can ease facilitation and open opportunities for observation and feedback, while immersive collaboration may help make risk management education more accessible and adaptable. Future work will expand the range of scenarios and assess its impact in larger classroom settings.

Tool and Data Availability. The MetaSERGE tool, its execution guide, and the structure and results of the survey in details are available in the online appendix [288].

11.2 METASERGE: FROM BOARD GAME TO EDUCATIONAL METAVERSE

This section outlines the concept and learning objectives of the original game, describes its integration into SENEM, and presents MetaSERGE with its gameplay flow.

11.2.1 *The SERGE Serious Game*

SERGE [11] is a board game designed to improve competencies in software project risk management. The gameplay is structured into three sequential phases, each targeting a specific set of educational objectives derived from the PMBOK [163] risk management process and inspired by agile development practices. At the beginning of the game, players are introduced to a project scenario that outlines project parameters, including team size, budget constraints, and delivery timeline. Based on this initial briefing, players are encouraged to identify potential risks.

The first phase is *Risk Analysis*, which aims to improve students' analytical skills through a collaborative decision-making process. Players analyze a series of risk cards, each of which describes a potential risk that may occur (e.g., delivery delay of artifact, poor communication). Players evaluate the impact and probability of each risk using the Planning Poker technique [328]—assigning each card a high, medium, or low impact and a probability between 0% and 100% on a scale of 20.

The second phase is *Procurement*, which focuses on strategic thinking. Players must design a mitigation strategy by purchasing appropriate resources balancing a limited project budget (e.g., skills, tools) to address the risks analyzed in the first phase.

The third and final phase is *Risk Management*, which simulates three Scrum sprints. Players take turns rolling a die to simulate the project's progression. The outcome of each roll may trigger a random event (e.g., a scope change, a delay, etc.) or activate a specific risk identified earlier in the game. If risk occurs, the player could prevent it with resources acquired.

If not, the player may mitigate the risk by paying a fee using token or by accepting the risk and suffering its consequences. The player with the highest score at the end is declared the winner, but the game's focus lies more on reflective decision-making and managing risk trade-offs than on competition.

11.2.2 *Implementation in SENEM*

MetaSERGE, is built on SENEM [274], a validated educational metaverse that is enabled by software engineering practices. Our objective was to faithfully reproduce the physical SERGE experience—in which players gather around a table and interact through cards—within a digital environment.

SENEM already provides many of the functionalities needed for our purposes, making it a natural choice for hosting the game; it (1) supports navigation and interaction in a 3D environment through first-person avatars, (2) enables real-time multiplayer participation, and (3) offers multiple interaction modalities, i. e., spatial voice chat, text chat, and basic avatar gestures for non-verbal communication.

We developed MetaSERGE in **Unity3D**, adopting **Photon Unity Networking** (PUN) to handle distributed sessions, synchronization, and latency management. Game mechanics were encoded as digital rules that automate score calculations, resource checks, and event triggers, reducing facilitator workload. A dedicated **Turn Manager** orchestrates the game flow: it enforces turn-taking, validates each player's input, prevents out-of-sequence actions (e.g., drawing cards prematurely), and automatically transitions the group to the next phase once all actions are completed. To guarantee consistency across clients, we applied the **Observer design pattern**, ensuring that any change in game state—such as a card being played or a score updated—is instantly propagated to all participants.

On the front end, we designed a 3D scene within SENEM that replicates the physical meeting-room setting: a central table with surrounding chairs where players "sit" to initiate the game. This design preserves the collabora-

tive atmosphere of the analog version while embedding it in an immersive environment. By leveraging SENEM's modular architecture, MetaSERGE inherits features such as avatar embodiment, multimodal communication, and resource sharing. Finally, SENEM's inherent support for distributed participation enables students from different locations to connect and collaborate as if co-located, overcoming the spatial constraints of the physical board game. Building on this foundation, the next subsection describes the gameplay flow and user interactions of MetaSERGE, showing how the mechanics of the analog version were adapted and extended in the virtual environment.

11.2.3 *MetaSERGE in Action: Gameplay Flow and User Interaction*

MetaSERGE relies on the multiplayer interconnectivity provided by SENEM [274] to synchronize on the same play, at the start of a session, a player creates the game room and shares its name with the others, who then connect to the same room. Once all players have joined, they control customizable avatars and can freely explore the virtual space. A command menu is available at all times, providing access to the game's main functionalities: (1) a summary of gameplay phases, (2) informational cards describing the learning objectives of each stage, and (3) a player profile sheet with project details such as budget, duration, team size, and scope. The session officially begins when players sit at the central table, which triggers the transition to the first phase.

The turn manager component coordinates all gameplay phases. It locks and unlocks interactions when needed (e.g., preventing players from drawing cards out of sequence), validates inputs such as probability/impact choices, and automatically transitions the session from one phase to the next. This mechanism ensures that even in distributed sessions, all participants follow the same flow.

FIRST PHASE: RISK ANALYSIS Players collaboratively identify and analyze risks. Each risk is presented through a card drawn at random. For



Figure 11.1: First Phase: Risk Analysis

every risk, each player selects an impact card (Low, Medium, or High) and a probability card (0–100%, in 20% increments). After selecting, each player briefly justifies their choice to the group. This structured discussion fosters reflection, negotiation, and peer learning—core aspects of collaborative risk assessment. Figure 11.1 shows an example in which a player assigns High impact and 80% probability to the risk of unrealistic client expectations.

SECOND PHASE: PROCUREMENT. This phase focuses on resource allocation and strategic planning. Each player accesses their User Game Sheet and uses a limited set of tokens—categorized as Low, Medium, or High—to purchase resources. By strategically combining these resources, players build mitigation plans aimed at covering the most critical risks identified earlier. This phase is shown in Figure 11.2.



Figure 11.2: Second Phase: Procurement

THIRD PHASE: RISK MANAGEMENT. The final phase simulates the occurrence and handling of project risks, allowing players to test the effectiveness of their planning and procurement decisions. Unlike the original version, where players performed manual calculations, the digital implementation automates the logic and resolution process. Each player begins by rolling a virtual die weighted according to the probability scores assigned during the first phase.

- If a risk occurs and the player has the necessary resources, the system automatically applies the prevention strategy, awarding 3 points.
- If resources are missing, the system activates a mitigation plan by consuming a token, awarding 1 point.
- If neither prevention nor mitigation is possible, the contingency plan is applied, awarding 0 points (representing an unmanaged risk).

In addition, event cards can be triggered during the dice roll, introducing factors such as stakeholder changes, morale drops, or scope shifts that dynamically alter probability or impact values. The system updates risk cards accordingly, reinforcing the idea that risks evolve with project circumstances. At the end of three sprint cycles, the player with the highest score is recognized as having implemented the most effective risk management plan. Figure 11.3 illustrates how points are distributed based on player choices and available resources.

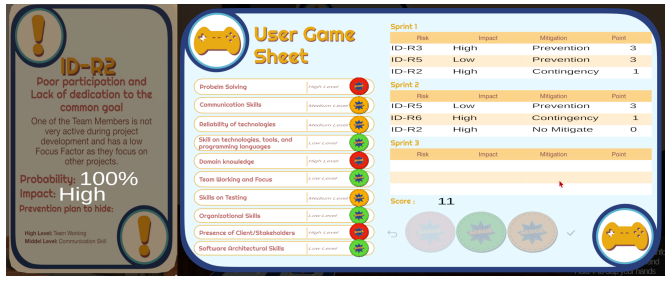


Figure 11.3: Third Phase: Risk Management

11.3 PRELIMINARY EVALUATION

This preliminary evaluation explores how MetaSERGE can support the teaching of risk management in software project management. The original SERGE [11] showed that serious games can make risk management concepts more engaging and practical for students. With MetaSERGE, we investigate whether embedding the game in SENEM [274] can add further benefits. In particular, we examine whether metaverse peculiarity, e.g., immersion, collaboration, and distributed participation, can enhance engagement and usability while maintaining the learning outcomes of the traditional version. To this end, we formulated the following research question.

> ***RQ.*** *To what extent could MetaSERGE provide benefits in terms of usability, engagement, and improvement of risk management knowledge?*

To address the research question, we followed the experimental design used in the original SERGE study [11], but adapted it into the context of an educational metaverse setting by running sessions in SENEM and using the same evaluation instruments. In addition, we introduced a usability assessment to reflect the digital nature of MetaSERGE. Specifically, we conducted a two-stage evaluation consisting of a pilot study with 2 students to refine the environment, followed by a small-scale evaluation with

6 students in pairs, where we assessed both knowledge acquisition and usability perceptions. All participants were master's students in their final year, enrolled in a project management course taught according to the PMBOK framework and aligned with the standards of the Project Management Institute (PMI). As part of the course, these students take on the role of project managers for groups of bachelor students, giving them direct responsibility for planning and managing project activities. They already had prior exposure to risk management concepts, which made them well-suited to evaluate MetaSERGE. For them, the tool might represent an opportunity to practice and refine decision-making skills in a simulated environment that mirrors challenges they encounter in their course projects.

Pilot study. The pilot study allowed us to test the technical feasibility of the metaverse implementation and observe how students interacted with the environment. Two participants played a complete session of MetaSERGE, communicating through the microphone feature. After the session, we conducted an open discussion to collect qualitative feedback on three aspects: (i) clarity of rules and instructions in the virtual setting, (ii) fluidity of interaction with digital objects such as cards and tokens, and (iii) the overall sense of presence and engagement when playing remotely. Participants noted the need for clearer organization of controls and more consistent presentation of information cards and user sheets. They also suggested simplifying card selection in the first phase and adding shortcuts to streamline discussion. Finally, they emphasized that constant access to reference materials would help maintain immersion and focus during gameplay.

Execution. After incorporating the pilot study feedback, we carried out the main evaluation with six students, working in pairs. Pairing was determined by availability. During the evaluation, participants first played a full session of MetaSERGE, going through all phases of the game, as shown in 11.2.3, and then completed the same risk management knowledge questionnaire used in the original study [11] to assess knowledge improvement. It contains scenario-based items that required students to identify risks,

evaluate their probability and impact, and suggest appropriate prevention or contingency strategies. The questions were designed not to test rote memorization, but rather the ability to apply risk management concepts in realistic project contexts. In addition, we administered a usability questionnaire inspired by the System Usability Scale (SUS) [54], adapted to MetaSERGE. The ten questions measured perceived frequency of use, complexity, ease of learning, integration of functions, and confidence in usage. Example statements included: *"I think I would like to use SERGE frequently for learning risk management"* and *"I felt very confident using SERGE."*

Results. Usability results show that most participants agreed MetaSERGE was easy to use and offered an intuitive interface. Participants agreed with the statement "*I felt very confident in using MetaSERGE*" and reported not needing technical assistance to complete the game. The structure of the game and the guided interface elements—such as the help menu and info cards—were frequently mentioned as supportive features. One participant stated, "*everything went smoothly*". These findings suggest that MetaSERGE offers a user-friendly experience, with interface design and built-in guidance that minimize barriers and let participants concentrate on the learning task rather than system mechanics.

Engagement results indicate that participants found the game valuable for reinforcing their understanding of risk management principles. Users responded positively to the game-based format and expressed a desire for repeated use: four of six participants expressed strong agreement with the statement "*I would like to use MetaSERGE frequently for similar training*". Three participants strongly agreed that most people would be able to learn the platform quickly, confirming its approachability. Open feedback also highlighted the value of collaborative elements, with one participant noting, "*I appreciated the initial discussion with the other team member.* These responses suggest that MetaSERGE can sustain learner attention and foster deeper involvement with the content.

Finally, knowledge-related results showed encouraging signs of improvement. Participants answered a high proportion of knowledge-based ques-

tions correctly, particularly those involving risk identification, probability, and impact estimation, and mitigation strategies. Over 80% of the questions were answered correctly by 4 out of 6 participants. These outcomes suggest that MetaSERGE's structure helped students connect abstract concepts to practical decision-making.

12

BETTER NOW: BRIDGING THEORY AND PRACTICE IN BLOCKCHAIN-ENABLED EDUCATIONAL METAVERSE

This chapter builds upon the paper published at the *International Workshop on Artificial Intelligence with and for Learning Sciences* (WAILS), where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building upon the theoretical blockchain framework introduced in Chapter 5 and the SENEM prototype presented in Chapter 7, this chapter consolidates these contributions into a concrete educational metaverse implementation, framed through the metaverse engineering perspective introduced in Chapter 4.

12.1 INTRODUCTION

Advances in Artificial Intelligence (AI), extended reality (XR), and distributed technologies are transforming education. Their convergence has given rise to the *metaverse*—a persistent, shared, and immersive environment for interaction among users and digital objects [201, 369]. In education, it fosters collaborative and experiential learning, enhancing engagement and accessibility through 3D spaces and avatars [274]. Yet, these benefits introduce challenges of trust, data integrity, and privacy—core to both learning sciences and ethical AI [158]. *Blockchain* offers a foundation for secure and decentralized learning ecosystems. Through immutability and transparency, it supports credentialing, assessment, and privacy-preserving record management [6, 76, 303], and can operate as

public, *private*, or *consortium* networks—differing in access control and governance—supporting persistent ownership and accountability in educational metaverse systems.

Recent studies highlight decentralized identity, verifiable credentials, and transparency as core principles, driving advances in blockchain-based learning and accreditation frameworks [227, 228, 238, 285]. However, most work remains conceptual, lacking systematic integration within operational immersive environments.

To advance this field, our prior study [101] introduced a theoretical blockchain framework for the educational metaverse, outlining architectural principles to address privacy, security, and interoperability. While conceptual, it required a realistic platform for implementation. SENEM (Software Engineering-eNabled Educational Metaverse) fulfills this need [274]. Developed with educators and students' needs, *SENEM* combines immersive classrooms, avatars, and multimedia tools, providing an effective environment for implementing and evaluating blockchain-based learning services. This paper contributes by: (1) implementing our blockchain framework within an immersive educational metaverse, bridging theory and practice; (2) engineering decentralized lecture-management functionality; and (3) provide feasibility through use-case scenarios and execution flows.

Our results show that the proposed blockchain framework can be concretely implemented within an educational metaverse. Integrated into *SENEM* through practical use case scenarios, we show how educational resources can be securely and transparently managed in a decentralized way. This work advances metaverse engineering by bridging theory and practice and supporting the development of future AI-enabled learning environments.

12.2 FROM THEORETICAL FRAMEWORK TO IMPLEMENTATION

12.2.1 *Blockchain Framework for Educational Metaverses*

The framework is structured around two pillars: (1) the *goals* that blockchain aims to achieve in educational metaverses, and (2) the *design strategies* guiding its integration. Its main objective is to enable secure, transparent, and decentralized management of educational data, addressing the trust and ownership issues common in centralized systems. Blockchain supports this goal through guarantees of privacy, authenticity, and verifiability of learning assets.

Three deployment models are considered: *public*, *private*, and *consortium* blockchains. The consortium model provides the most balanced governance structure for academic collaborations, allowing fine-grained control over openness and access. The framework is organized into four layers: (1) **Application Layer**, which hosts the metaverse interface and user interactions; (2) **Learning Layer**, responsible for handling academic progress, grades, and multimedia data; (3) **Cross-Chain Layer**, ensuring interoperability and security across multiple blockchains (which is not implemented within the scope of this study); and (4) **Blockchain Storage Layer**, which guarantees persistence through blockchain, IPFS, and smart contracts. While prior work defined the framework, no educational environment had yet implemented it. This study fills that gap by integrating the framework into SENEM and linking the metaverse front end with the underlying blockchain layers, as shown in Figure 12.1.

12.2.2 *Implementation*

Following metaverse engineering principles [102], the implementation focused on lecture slides as academic resources for blockchain integration in immersive learning.

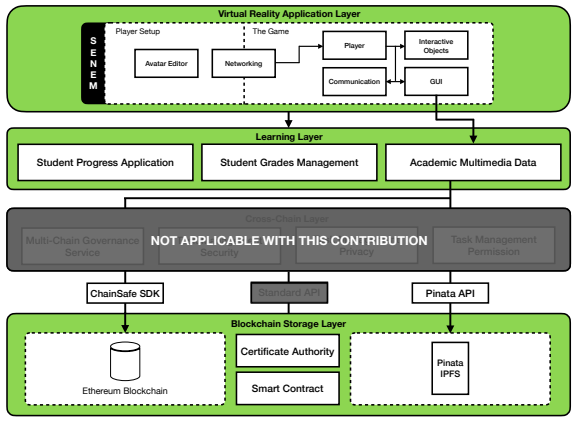


Figure 12.1: Framework evolution with SENEM

We identified four key functional requirements: **FR1.** *uploading*, **FR2.** *storing*, **FR3.** *modifying*, and **FR4.** *retrieving* lecture materials within SENEM.

Application Layer. *SENEM* [274] serves as the 3D virtual classroom where users interact through customizable avatars and multiple communication modes (voice, text, and gestures). The environment includes features such as a virtual projector and a collaborative whiteboard for multimedia presentations. To enable blockchain-based lecture management, two new interfaces were developed: an *Upload Panel*—i.e., Figure 12.2a—for storing materials on-chain and a *Download Panel*—i.e., Figure 12.2b—for retrieving them. Interface design followed four principles: immersive consistency, operational simplicity, clear system-state feedback, and restricted teacher-only control for blockchain operations.

Learning and Storage Layers. The learning layer manages multimedia content, while the storage layer integrates Ethereum and IPFS through **ChainSafeSDK** and **Pinata APIs**. Each user creates a **MetaMask** wallet to authenticate and establish content ownership. Smart contracts written in **Solidity** handle validation and on-chain recording, ensuring transparency and immutability. IPFS supports decentralized file storage and retrieval directly from SENEM's Unity interface, where successful uploads are visually confirmed within the classroom environment. Combined, these

technologies enable secure ownership, transparent verification, and persistent storage of educational materials.

The resulting system bridges theory and practice by linking *SENEM* to Ethereum and IPFS, demonstrating the framework's practical instantiation. It enhances integrity, transparency, and privacy in immersive learning while laying the groundwork for future empirical evaluation.

In the following section, we defined a set of use case scenarios to illustrate the flow of events and errors when using the new functionalities.

12.3 USE CASE SCENARIOS

UC-FR.1 LECTURE UPLOAD WITH IPFS. (MAIN SCENARIO)

FLOW OF EVENTS: The environment provides a panel for IPFS-based content management 12.2. Users can *upload* an entire lecture or *update* an existing file (see UC-FR.3); here, we focus on the former. Users select a file (.JPG/.JPEG) from their local device, which is then processed by creating a new Pinata IPFS group acting as a lecture folder. During the operation, feedback indicates the upload progress. Once completed, the system asks whether the lecture should also be stored on the blockchain; if confirmed, the process continues with UC-FR.2.

ERROR HANDLED: The system handles *empty folders*, *invalid files*, and *network interruptions*, notifying the user and restoring the environment. Pinata naming conflicts are resolved by replacing or renaming files.

UC-FR.2 ETHEREUM BLOCKCHAIN STORAGE

PRE-CONDITION: At least UC-FR.1 has been successfully executed once.

FLOW OF EVENTS: After the lecture is uploaded to IPFS, the system enables blockchain storage. This action triggers a transaction via the connected wallet. Users can verify transaction details within the wallet. Once confirmed, a smart contract records the lecture hash on the blockchain. Upon completion, the system provides confirmation of successful on-chain storage.

ERROR HANDLED: The system handles cases where *no wallet is detected* or the user *declines registration*, leaving the lecture stored only on IPFS. *Network or transaction failures* interrupt the process and generate an error notification.

UC-FR.3 UPDATE EXISTING LECTURE

PRE-CONDITION: The user update an existing lecture from UC-FR.1.

FLOW OF EVENTS: The user chooses the lecture to modify and uploads new slides. The system retrieves the existing lecture from IPFS and provides its details, allowing the user to replace the full lecture or add/remove slides. Throughout the update, the system displays progress and feedback messages. Once the operation is completed, the lecture can also be stored on the blockchain following the procedure in UC-FR.2.

ERROR HANDLED: The system handles *missing lectures*, *invalid files*, and *network failures*, notifying the user and preventing changes to the stored lecture.

UC-FR.4 VISUALIZE OR DOWNLOAD LECTURE

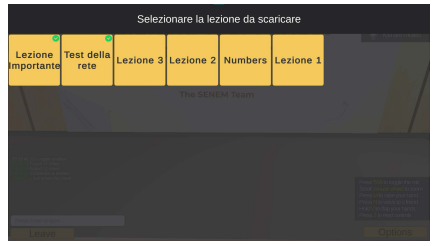
PRE-CONDITION: UC-FR.1 and UC-FR.2 must have been executed at least once.

FLOW OF EVENTS: Users access stored lectures through a dedicated panel (Figure 12.2b), which displays lectures stored on IPFS and those also registered on the blockchain, indicated by a green marker. The user selects a lecture to visualize or download, and the system displays a progress bar during retrieval. After completion, the slides load into the virtual projector for delivery.

ERROR HANDLED: The system handles *network issues* and *rate-limit errors*; in the latter, a retry mechanism automatically resumes downloads without data loss. Users are notified of all issues with corresponding corrective actions.



(a) UC-FR.1 Upload a new lecture or add new slides to an existing one.



(b) UC-FR.4 Visualize or download a lecture.

Figure 12.2: Panel for managing educational resources with Blockchain

13

THE GOOD AND THE BAD OF TEACHING SOCIAL DEBT AND COMMUNITY SMELLS USING VIRTUAL REALITY

This chapter builds upon the paper submitted at the *Empirical Software Engineering* (EMSE) [105], where the author of this thesis was the main contributor. The content reported in this chapter closely follows the original publication.

Connection with Chapters

Building on the metaverse engineering perspective established in Chapter 4 along with Chapter 7, this chapter addresses the need to evaluate how such a perspective can concretely support teaching and learning processes. To this end, it concludes the empirical part of the thesis through a controlled experiment focused on perceived quality and learning outcomes in metaverse-based education.

13.1 INTRODUCTION

Teaching the management of socio-technical aspects in software development, i.e., an inherently software project management activity, is a complex endeavor. Software development is a socio-technical process that involves stakeholders with diverse expertise, skills, and cultural backgrounds (the social) collaborating through technologies and on a technological product (the technical) [56, 157, 189, 319]. These differences have led to the recognition of socio-technical aspects as crucial for the success of software development, prompting educators to invest time in equipping students with the necessary skills to understand and manage these dynamics—at least to some extent—before entering the workforce. Nevertheless, teaching these aspects is often challenging due to the inher-

ently abstract nature of socio-technical concepts and the need to provide students with an immersive educational environment that allows them to apply classroom knowledge in practice [30, 71, 126, 367].

For these reasons, developing teaching approaches that incorporate immersive and modern methodologies, rather than relying solely on traditional lecture-based instruction, is essential. In this regard, research has explored various techniques for teaching the management of socio-technical aspects (e.g.,[12, 30, 45, 71, 140, 333]). For instance, Caulfield et al. [71], von Wangenheim et al. [333], and Annunziata et al. [12] advocated for the use of serious games to enhance learning, while Boiangiu and Stanica proposed a structured framework to assist instructors in teaching socio-technical concepts [45]. Additionally, Bavota et al. highlighted the effectiveness of role-playing-oriented projects in educational activities [30]. A common element across these approaches is the use of role-playing and immersive mechanisms to deepen students' understanding of key concepts. Empirical findings indicate positive outcomes, suggesting that these methodologies represent a promising direction for advancing this research agenda and overcoming the abstract nature of socio-technical aspects.

In line with the above, two concepts—originally introduced outside the educational domain—were specifically developed to help managers better measure and represent socio-technical aspects: social debt and community smells. Social debt, analogous to technical debt, refers to the hidden project costs resulting from suboptimal community structures and managerial decisions [61, 324]. Community smells, on the other hand, represent socio-technical patterns and characteristics (e.g., excessive formality, recurrent condescending behavior, or rage-quitting) that contribute to the accumulation of social debt, structured as a catalog of detrimental behaviors [61, 69, 192, 250, 324]. The introduction of these two concepts has significantly contributed to expanding research on socio-technical aspects in software engineering, further demonstrating the critical role of these factors previously highlighted in the literature. However, at the time of this study, the software engineering education community has not yet

explored their potential as pedagogical tools for teaching the management of socio-technical aspects. **We argue that this represents a missed opportunity, given that these concepts were explicitly designed to provide a structured framework for managing socio-technical challenges in software development** [61, 324]. Their integration into educational settings could offer students a more concrete foundation for understanding these aspects while enhancing immersion and representation in learning environments. Furthermore, in response to the need for immersive educational experiences, a promising solution to the aforementioned challenges—one that has already demonstrated potential in various areas of software engineering—is the use of virtual reality (VR) technologies (e.g., [3, 143, 291]. VR is a rapidly evolving technology that, despite its increasing adoption, remains constrained by hardware limitations. It enables users to engage in immersive, highly customizable virtual environments tailored to specific educational needs while also facilitating remote collaboration. In this context, VR allows instructors to design virtual classrooms and implement interactive, simulation-based scenarios that replicate complex managerial situations [148]. For example, an instructor could simulate a radio silence scenario—where a single individual mediates all communication between two clusters—by utilizing 3D human models within a virtual office setting. This approach eliminates the need to involve external companies or practitioners, thereby enhancing students' comprehension of socio-technical dynamics while reducing logistical complexity and costs.

This study aligns with this perspective by proposing a VR-based methodology designed to support instructors in teaching Social Debt and Community Smells in a university-level software engineering course. To this end, we designed and implemented a VR-based lesson that combines multiple instructional strategies—most notably, scenario-based learning [287, 302, 366] informed by the principles of meaningful learning [169, 219]. The core scientific contribution of our work is a structured and reproducible methodology for teaching these socio-technical concepts in immersive environments, supported by a publicly available and customizable VR educational tool. To assess the effectiveness of our ap-

proach, we conducted a controlled experiment using a between-subject design, involving 30 university students, randomly assigned to one of three groups: VR-based instruction, traditional face-to-face teaching, and online learning via Microsoft Teams. Our evaluation targets two key dimensions: (i) learning outcomes, measured through a multiple-choice quiz aligned with Bloom's taxonomy [42, 43]; and (ii) the quality of the learning experience, assessed across five validated dimensions—self-efficacy, immersion, engagement, perceived workload, and satisfaction.

The results of our experiment are encouraging and reinforce the value of our methodological contribution. We found that VR-based instruction performs comparably to, and in some cases slightly better than, traditional teaching methods, while also offering a more engaging and immersive learning experience, even in the presence of hardware constraints. In summary, this work contributes (1) a publicly available and reusable tool for instructors interested in teaching social debt through VR; (2) a set of practical guidelines for implementing such lessons; (3) empirically grounded insights to support educators in designing their own VR-based educational activities; and (4) directions for future research on teaching socio-technical aspects and, more broadly, software engineering through immersive technologies.

Structure of the paper. Section **??** presents background information and related work on socio-technical aspects in software engineering and the use of Virtual Reality in education. Section 13.2 details our methodological contribution, describing the design principles, structure, and implementation of the VR-based lesson on social debt and community smells. Section 13.3 reports on the controlled experiment conducted to evaluate the effectiveness of the proposed method, including our research objectives, experimental design, and data analysis. Section 13.4 presents the results of the study, focusing on both learning outcomes and quality of experience. Section 13.5 discusses the implications of our findings and outlines limitations. Finally, Section **??** concludes the paper and outlines future directions for research on the use of VR in software engineering education.

13.2 METHODOLOGICAL CONTRIBUTION — TEACHING SOCIAL DEBT AND COMMUNITY SMELLS THROUGH VR

The following sections detail the objectives and structure of the lessons, representing our main methodological contribution.

Section 13.2.1 outlines the learning objectives, while Section 13.2.2 discusses the principles applied in the design and development of the lessons, specifically focusing on *Meaningful Learning* principles [169, 219]. Building on these foundational principles, Section 13.2.3 provides an overview of the lesson's structure, describing the materials and components incorporated into the lessons.

13.2.1 *Lesson Goals*

The primary objective of the lesson was to teach software engineering students fundamental concepts related to social debt and community smells. This served to introduce them to the socio-technical aspects of software development and engineering, stimulate their curiosity, and provide them with foundational knowledge to equip them with tools that could prove useful in the context of a software development team.

The learning objectives for the lesson were defined using Bloom's Taxonomy [42, 43], a widely adopted framework in educational research. Bloom's Taxonomy categorizes students' learning into six hierarchical levels: Remember, Understand, Apply, Analyze, Evaluate, and Create. This structure aids in formulating objectives that are clear, measurable, and aligned with the cognitive processes involved in knowledge acquisition. By leveraging this taxonomy, we defined the following learning objective:

Social Debt and Community Smells Lesson — Learning Objective

By the end of the lesson, students will be able to:

1. Define the concepts of social debt and community smells and explain their role in socio-technical aspects of software development.
2. Identify examples of social debt and community smells in software development scenarios.
3. Apply foundational knowledge to analyze and propose potential strategies for addressing socio-technical issues within a software development team.

Starting from the above learning objective and always referring to Bloom's taxonomy [42, 43], we have identified and laid out the following sub-objectives in order to guide the design of the lesson and, subsequently, the assessment of the skills acquired. Therefore, the sub-objectives are as follows:

- Recall the definition of Social Debt and explain its implications in socio-technical systems (*Remember, Understand*).
- Differentiate between Social Debt and other types of debt in software projects (*Understand, Analyze*).
- Identify the characteristics of socio-technical anti-patterns and provide examples (*Understand, Apply*).
- Define Community Smells and compare them to code smells, highlighting their socio-technical nature (*Remember, Analyze*).
- Recognize specific types of community smells (e.g., Radio Silence, Black Cloud) and describe their impact on team dynamics (*Understand, Apply*).
- Analyze a given scenario to identify the presence of Social Debt or Community Smells (*Analyze*).
- Classify examples of socio-technical anti-patterns, distinguishing between social and technical components (*Understand, Evaluate*).

- Evaluate the potential effects of managing Social Debt on team productivity and software quality (*Evaluate*).
- Assess strategies for mitigating Community Smells and propose improvements to team communication structures (*Evaluate, Create*).
- Demonstrate an understanding of how addressing Community Smells can reduce Social Debt in software teams (*Apply, Evaluate*).
- Interpret graphical representations of community structures to identify potential socio-technical anti-patterns (*Understand, Analyze*).
- Apply foundational knowledge to critique team scenarios and suggest actions to improve collaboration (*Apply, Evaluate*).
- Explain the role of connected graphs in visualizing Community Smells (*Understand, Analyze*).
- Validate statements about the relationship between socio-technical anti-patterns and Social Debt (*Understand, Analyze*).

13.2.2 *Lessons Design Principles*

To build the lesson and design the experience, three main contributions were relied upon. The first one represents Bloom's taxonomy [42, 43] on the definition of objectives; as already noted in the previous section, this principle guided the definition of the objectives and (as we will see later) the learning assessment.

The other contributions are meaningful learning [169, 219] and Learning by Example [287]. Meaningful learning focuses on understanding and applying knowledge to solve relevant problems for the students participating the learning process [169, 219]. It involves higher-order thinking, critical thinking, problem-solving, and metacognitive skills, often verified through knowledge application in real-world contexts. On the other end, Learning by example involves acquiring skills and knowledge through the observation and analysis of specific instances or worked examples [287].

This method is particularly effective in fostering cognitive skill, as it allows learners to link theory with practice.

We applied the principles of value, learning from the particular to the general, fun and immersion. Such principles are common to both our contributions, and of particular interest to the proposed method. These principles are based on the concept that in order to foster proper learning, it is necessary that (1) what is being learned is perceived as valuable by students, (2) learning begins with concrete and specific examples and then moves to general and theoretical concept definitions, (3) students are engaged in a stimulating and enjoyable learning process, and (4) the learning experience is immersive.

These principles have profoundly guided the definition of the teaching method: in fact, socio-technical aspects are emphasized and presented for their important and central role in software development. In addition, the entire lesson (as will be seen later) is organized to always provide specific examples first and then definitions. Lastly, the use of virtual reality not only supports immersion and thus supports the impact of the aforementioned examples, but also allows for the creation of an innovative and enjoyable situation.

13.2.3 *Lesson Structure*

The proposed lesson comprises three main components: the slides and outline that structure the session, the virtual environment that facilitates the delivery, and the assessment materials specifically designed to evaluate the achievement of the learning objectives.

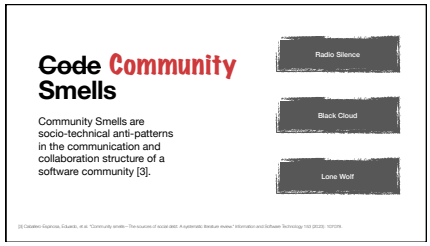
Building on the principle of moving from the specific to the general, the lesson introduces students to concrete examples and carefully crafted scenarios to illustrate the targeted concepts. This approach is particularly well-suited to teaching social debt and community smells, as these topics align naturally with the structure of anti-pattern catalogs. Community smells, being categories of socio-technical anti-patterns, are inherently scenario-based and can be effectively represented through contextualized



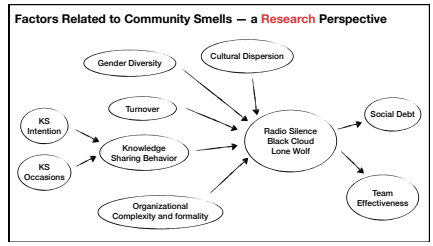
(a) The impact of unmanaged Social Debt.



(b) Social Debt definition.



(c) Community Smells definition.



(d) Research on Community Smells.

Figure 13.1: Some of the slides used during the lesson.

examples [287, 302, 366]. For instance, the community smell Radio Silence depicts a situation where an individual mediates all communications between two groups, creating a bottleneck. Such a scenario is both illustrative and conducive to student understanding, reinforcing the lesson's focus.

VR plays a pivotal role in this pedagogical approach. Through VR, students are immersed in animated scenarios, presented using 3D avatars that simulate community smells in a corporate context. This method not only introduces the concepts of social debt and community smells but also highlights their significance and practical impact. The underlying rationale aligns with broader applications of VR in education: by utilizing 3D models and the flexibility of virtual environments, it is possible to create small, interactive experiences that enhance realism and immersion. These **immersive scenarios** (terms that we will use for now on to refer to them) bolster the learning by example principle, fostering deeper comprehension, engagement, and retention of the presented concepts. The lesson is

structured around a set of supporting slides (some of them are shown in Figure 13.1; the all set is available in the online appendix [105]).

13.3 METHOD EVALUATION — A CONTROLLED EXPERIMENT

The *goal* of this study is to present a thorough comparison of our VR-based methodology, namely a virtual reality teaching approach designed to harness the full potential of the technology in alignment with the meaningful learning principle—with two conventional teaching baselines: face-to-face and online learning. The *purpose* of this comparison is to empirically evaluate whether virtual reality can yield improved results in terms of students' learning outcomes and the overall quality of their educational experience. The *perspective* targets the academic and educational community, including educators, students, and researchers, fostering interest in the exploration and advancement of educational innovation. Educators and students alike can benefit from understanding the potential advantages of meaningful learning facilitated by virtual reality technology, particularly for replicating lessons—like those described in the previous section—that involve abstract and complex concepts. For researchers, the focus is on identifying the fundamental characteristics that contribute to the success of a teaching method while also examining its scalability and potential impact on educational theory and innovation. These combined perspectives guide a comprehensive investigation of teaching methodologies aimed at advancing both practical applications and theoretical frameworks in education.

Based on this consideration, our paper is structured around the following main hypothesis:

> **Research's Main Hypothesis**
> *The use of virtual reality for teaching socio-technical aspects provides higher learning outcomes and improves the quality of the student experience compared to traditional baselines, such as classroom and online lectures.*

13.3.1 *Face-to-Face and Online Learning as Baselines*

The evolution of learning methods over the past decades has led to a growing diversification of educational strategies. The COVID-19 pandemic further accelerated this shift, pushing educational institutions worldwide to reevaluate traditional teaching models and adopt digital solutions. While this transformation was amplified by the pandemic, it had already begun before, sparking an ongoing debate between traditional *face-to-face* and technology-mediated *online* learning. These two approaches represent the main learning options offered by many universities and serve as fundamental methods for delivering education. Face-to-face learning refers to "*a method of instruction where course content and learning materials are taught in person to a group of students*." This approach is the most traditional, centered on direct interaction between teachers and students in a shared physical environment. In contrast, distance learning, which involves a geographic separation between students and teachers, has leveraged technology to create online learning. This is defined as "*teaching activities and information transfer facilitated by electronic platforms and digital tools, enabled by the Internet*." Importantly, e-learning is often a subset of the broader concept of distance education, which focuses on using technology to provide flexible, remote access to learning [137]. It is also worth noting that these two approaches are not mutually exclusive. They can be combined to create a hybrid or blended learning environment, merging the benefits of both methods [341].

13.3.2 *Research Questions (**RQs**) and Hypothesis*

To achieve the overall goal, a controlled experiment, using a between subject design [346], was conducted to compare the proposed virtual reality approach with two established teaching baselines: face-to-face lessons and online learning. The study primarily focused on the socio-technical aspects, specifically examining community smells that can adversely affect the dynamics and performance of development teams.

To ensure a clear and systematic evaluation, the study is structured around two research objectives with distinct dimensions of teaching effectiveness:

- **Research Objective 1** (RO_1) focuses on comparing the VR method with each baseline separately (VR vs. Face-to-Face and VR vs. Online) in terms of learning outcomes.
- **Research Objective 2** (RO_2) focuses on comparing the VR method with each baseline (VR vs. Face-to-Face and VR vs. Online) for each factor characterizing the quality of the learning experience (self-efficacy, immersion, engagement, perceived workload, and satisfaction), analyzed individually.

This pairwise comparison approach was chosen to isolate and evaluate the unique characteristics of the proposed VR method with each baseline, avoiding the potential confounding effects of combined analyses. Further details on each research objective, including the associated research questions and hypotheses, are provided in the following sections.

13.3.2.1 *Virtual Reality Vs. Baselines for Learning Outcome.*

Our first main objective is meant to assess whether our methodological contribution could provide better results in terms of learning outcome. To address this dimension, we developed specific research questions aligned with our RO_1, which can be stated as follows:

? Research Objective 1

To compare the effectiveness of the virtual reality—with our VR-based methodology as a teaching method—against face-to-face and online learning baselines in terms of learning outcomes.

> **RQ$_1$** *How does virtual reality teaching method compares with the face-to-face baseline in terms of learning outcome?*

- **Null Hypothesis** ($H1_0$): There is no statistical differences in *learning outcome* between virtual reality and face-to-face lecture.
- **Alternative Hypothesis** ($H1_a$): There is statistical differences in *learning outcome* between virtual reality and face-to-face lecture.

> **RQ$_2$** *How does virtual reality teaching method compares with the online baseline in terms of learning outcome?*

- **Null Hypothesis** ($H2_0$): There is no statistical differences in *learning outcome* between virtual reality and online lecture.
- **Null Hypothesis** ($H2_a$): There is statistical differences in *learning outcome* between virtual reality and online lecture.

13.3.2.2 *Virtual Reality Vs. Baselines for Quality of Experience.*

Our second main objective is meant to assess whether our methodological contribution described in the previous section could provide better results in terms of quality of experience. The quality of experience in education is a multidimensional construct that encompasses emotional, cognitive, and motivational aspects, reflecting how individuals perceive and interact with their learning environment. It integrates factors such as affective states (e.g., happiness, cheerfulness), cognitive efficiency (e.g., concentration and mental clarity), intrinsic motivation, and a sense of capacity or active engagement. This construct plays a crucial role in fostering not only immediate learning outcomes but also long-term motivation and well-being [297]. In our context, we defined the quality of the experience through five key dimensions, from now on referred to as proxies: self-efficacy, immersion, engagement, perceived workload, and satisfaction.

These proxies collectively represent the extent of the quality of experience for each method under investigation. Each proxy is further detailed in the section discussing the dependent variables of our experiment. Our RO_2 can be formulated as follows:

Research Objective 2

To compare the effectiveness of virtual reality—with our VR-based methodology as a teaching method—against face-to-face and online learning baselines in terms of self-efficacy, immersion, engagement, perceived workload, and satisfaction as proxies for the overall quality of the experience.

Given the above RO2, it is clear that there is a need to compare our methodological contribution with the five proxies. This leads to a complex comparison framework, as each proxy requires an evaluation against two baselines, resulting in 10 research questions. Each RQ includes both a null and an alternative hypothesis, leading to a total of 20 hypotheses. To manage this complexity and improve clarity, we adopt a *parametric* approach to formulating research questions with the proxies, while explicitly maintaining a clear distinction between our method and the baselines.

We define the set of proxies P as follows:

$$P = \left\{ \begin{array}{c} (P_1, \text{Self-efficacy}), (P_2, \text{Immersiveness}) \\ (P_3, \text{Engagement}), (P_4, \text{Perceived workload}), (P_5, \text{Satisfaction}) \end{array} \right\}$$

For each proxy $P_i \in P$, we define the RQ_3 for comparing VR with face-to-face learning, and RQ_4 for comparing VR with online learning. Both, followed by null and alternative hypotheses:

RQ_3 *To what extent virtual reality teaching method compares with the face-to-face baseline in terms of P_i?*

- **Null Hypothesis** ($H3_0$): There is no significant difference in P_i between virtual reality and face-to-face lecture.

$$H3_0 : \sum_{i=1}^{5} P_i(\text{VR}) = P_i(\text{face-to-face}), \quad \forall P_i \in P$$

- **Alternative Hypothesis** ($H3_a$): There is significant difference in P_i between Virtual Reality and face-to-face lecture.

$$H3_a : \sum_{i=1}^{5} P_i(\text{VR}) \neq P_i(\text{face-to-face}), \quad \forall P_i \in P$$

RQ$_4$ *To what extent virtual reality teaching method compares with the online baseline in terms of P_i?*

- **Null Hypothesis** ($H4_0$): There is no significant difference in P_i between Virtual Reality and Online Learning.

$$H4_0 : \sum_{i=1}^{5} P_i(\text{VR}) = P_i(\text{Online}), \quad \forall P_i \in P$$

- **Alternative Hypothesis** ($H4_a$): Virtual Reality leads to a significant difference in P_i compared to Online Learning.

$$H4_a : \sum_{i=1}^{5} P_i(\text{VR}) \neq P_i(\text{Online}), \quad \forall P_i \in P$$

13.3.3 *Participants*

Since the study aimed to conduct a controlled experiment, student participants were required to be recruited from the pool of computer science students at the University of Salerno, Italy. For this purpose, *Non-Probability Sampling* was adopted. Among the available techniques, *convenience sampling* was employed, in which participants were selected based on their

availability and accessibility [23]. It is acknowledged that achieving participant representativeness is very challenging. However, this technique was chosen for several reasons: (1) it is one of the most commonly used methods in empirical software engineering, (2) it is fast and low-cost, and (3) it does not require a sampling frame [23, 146, 274]. Although the results may not be broadly generalizable, specific criteria were established for participants before finalizing the sample. Participants were required to be students from our university enrolled in either a bachelor's or master's program in computer science. For bachelor's students, completion of the software engineering course was mandatory. Master's students were required not to attend the software project management course. Additionally, none of the participants were permitted to have prior knowledge of community smells or social debt. No strict additional criteria were imposed to avoid introducing bias into the results. However, participants were asked about their experience with virtual reality. It was not used to organize the virtual reality group; instead, it was used to assess whether participants experienced any discomfort, such as fatigue, motion sickness, or other health issues, while using the virtual reality technology. All participants in this study had some preliminary experience with virtual reality, particularly through the *computer graphics* course at the university, where they had the opportunity to develop and test virtual reality environments using head-mounted displays (HMDs). However, none of the participants was more experienced than the others. This approach was intentional, aiming to select participants in a way that would minimize any novelty effect while wearing the HMDs.

As stated in Figure 13.2a and 13.2b, at the conclusion of the recruitment process, 30 students were selected, consisting of 25 men and 5 women. Among the participants, 20 were enrolled in a master's degree program, while 10 were pursuing a bachelor's degree. To ensure fairness and eliminate bias, a between-subject design was adopted, where each student was randomly assigned to one of the three experimental condition students were randomly divided into three experimental groups—each containing 10 participants. Randomization was particularly important because the

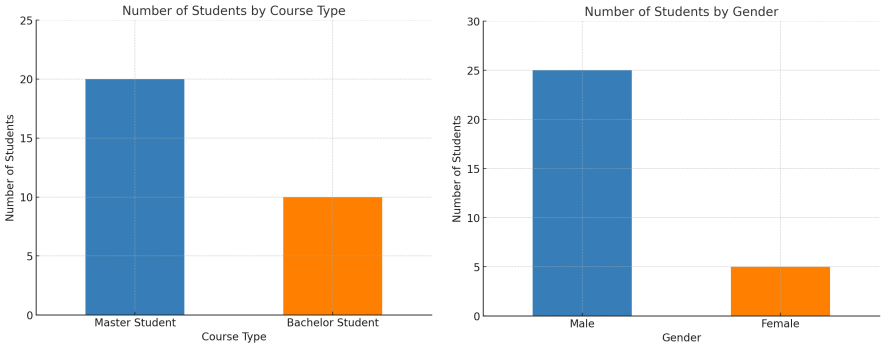
majority of students reported no significant discomfort when using the virtual reality hardware.

- **Group #1:** This group is the one composed of people who were involved in attending the virtual reality lecture, and from now on, will be referred to as *VR Group*. It is composed of 5 master's and 5 bachelor's students with little experience in virtual reality.
- **Group #2:** This group is composed of people who were involved in attending the face-to-face lecture, and from now on, will be referred to as *face-to-face Group*. It is composed of 7 master's and 3 bachelor's students.
- **Group #3:** This group is composed of people who were involved in attending the online lecture, and from now on, will be referred to as *Online Group*. It is composed of 8 master's and 2 bachelor's students.

Once participants were divided into their respective experimental groups, each group was assigned a single task: to actively participate in the lecture, replicating as closely as possible the behavior they would typically display during a traditional academic activity. Students were allowed to interact with the instructor at any time by calling for attention and asking questions.

For organizational reasons, all lectures, including the one with our VR-based methodology, were conducted on different days, ensuring that each session delivered the same information. The lessons were taught by an experienced author with decades of expertise in teaching software engineering and social debt. Additionally, the use of meaningful learning principles and the conversion of Community Smells examples into scripted scenarios helped mitigate potential inconsistencies in content delivery.

As a final incentive to encourage proactive student participation, each participant received a personalized gadget as a token of appreciation at the end of the experiment. Additionally, 10 students were randomly selected to receive a special reward: a €50 Amazon gift card.



(a) Type of Student's enrollment (b) Participants' Gender

Figure 13.2: Demographic Data for Students Involved in the Experiment

13.3.4 *Variables*

The research questions were based on the "One Factor, Three Levels" experimental design. The main factor, or *independent variable*, was the method of providing the lesson, which was carried out in three modes: face-to-face, online, and VR. These modes were compared through two *dependent variables*: Learning Outcome (LO) and the Quality of the Experience (QoE). Further details about these variables are provided below.

INDEPENDENT VARIABLE: "Lecture Mode"

- **Description:** The modality in which the lecture was provided to the students
- **Scale:** face-to-face, online, and VR

DEPENDENT VARIABLE: Learning Outcome (LO)

- **Description:** Degree of knowledge the students have assumed after the community smells and social debt lecture explanation.
- **Scale:** Quiz questionnaire with closed-question, aimed at measuring the learning outcome.
- **Operationalization:** Each answer was scored based on its accuracy: Correct (1 point) or Incorrect (0 point).

The dependent variable related to the quality of the experience was assessed through five main proxies: (1) *Self-Efficacy* (SEff), which measures the learner's confidence in their ability to succeed; (2) *Immersiveness* (IM), representing the extent of deep involvement in the activity; (3) *Engagement* (EN), capturing active participation and interest; (4) *Perceived Workload* (PW), assessing the mental and physical effort required; and (5) *Satisfaction* (ST). For engagement proxy, multiple measures were required to cover different aspects, such as Affective Engagement (AE), Behavioral Engagement (BE), Cognitive Engagement (CE), and Disengagement (DEr). On the one hand, SEff, IM, and EN proxies were measured using questionnaires validated in literature, employing a Likert scale from 1 to 5 and 1 to 7, which were adapted to the specific context [300, 339, 345]. On the other hand, PW and ST proxies were measured using questionnaires as is, employing a Likert scale from 1 to 10 [151, 173].

DEPENDENT VARIABLE: Quality of Experience

- **Proxy:** "Self-Efficacy" (SEff)
- **Description:** A metric used to measure the confidence a person has in performing actions required to achieve a goal, influencing their willingness to manage complex tasks.
- **Scale:** Likert Scale from 1 to 5 [300].
- **Operationalization:** Median of the answers.

DEPENDENT VARIABLE: Quality of Experience (QoE)

- **Proxy:** "Immersiveness" (IM)
- **Description:** A metric designed to assess the likelihood of an individual experiencing immersion, measuring the degree to which an environment captures the user's attention and fosters a sense of being fully present within the experience.
- **Scale:** Likert Scale from 1 to 5 [345].
- **Operationalization:** Median of the answers.

DEPENDENT VARIABLE: Quality of Experience (QoE)

- **Proxy:** "Engagement" (EN)
- **Description:** A multidimensional construct that describes the degree to which individuals are actively involved in the experiences. It provides a holistic understanding of how users emotionally, physically, and mentally interact with the environment.
- **Scale:** Likert Scale from 1 to 7 [339].
- **Operationalization:** Median of the answers.

DEPENDENT VARIABLE: Quality of Experience (QoE)

- **Proxy:** "Perceived Workload" (PW)
- **Description:** A metric designed to assess the subjectiveness experience of the effort required to perform a task, encompassing mental, physical, and emotional demands.
- **Scale:** Likert Scale from 1 to 10 [151].
- **Operationalization:** Median of the answers.

DEPENDENT VARIABLE: Quality of Experience (QoE)

- **Proxy:** "Satisfaction" (ST)
- **Description:** A metric designed to assess how likely participants were to recommend a product, service, or experience to others.
- **Scale:** Likert Scale from 1 to 10 [173].
- **Operationalization:** Median of the answers.

Additionally, we identify **confounding variables** that could influence the outcomes of our experiment. The primary factor we evaluated is whether participants have passed the *software engineering* exam. This evaluation is necessary for bachelor's students, as master's students are assumed to have already completed this requirement. However, for master's students, it is crucial to determine whether they have attended the *software project management* course, as topics such as community smells and social debt are covered within that program. Participants who report having no experience in software engineering or those who indicate prior experience with

community smells and social debt will be excluded from the experiment. Moreover, as mentioned in the previous section, participants were not assigned based on their experience. Instead, we employed a fully randomized method to allocate students into the three groups, ensuring the avoidance of potential bias stemming from preferences for a specific technology.

CONFOUNDING VARIABLE: "Knowledge of Software Engineering" (For Bachelors student)

- **Description:** A self-reported assessment of knowledge acquisition in software engineering exams and subject matter expertise.
- **Scale:** A Dichotomous Scale with two options: (1) Yes, students reported that they have knowledge of software engineering, and (2) No, students reported that they did not have knowledge of software engineering.
- **Operationalization:** Answer were scored as (1) for *"yes"* value, and (0) for *"no"* value.

CONFOUNDING VARIABLE: "Knowledge of Community Smells and Social Debt" (For Both Bachelors and Master Student)

- **Description:** A self-reported assessment of knowledge acquisition for community smells and social debt.
- **Scale:** A Dichotomous Scale with two options: (1) Yes, students reported that they have previous knowledge of Community Smells and Social Debt, and (2) No, students reported that they did not have previous knowledge of Community Smells and Social Debt.
- **Operationalization:** Answer were scored as (1) for *"yes"* value, and (0) for *"no"* value.

CONFOUNDING VARIABLE: Experience with Virtual Reality

- **Description:** The familiarity that students have with virtual reality experiences.
- **Scale:** A Dichotomous Scale with two options: (1) Yes, students reported that they had previous experience with VR, and (2) No,

students reported that they did not have previous experience with VR.

- **Operationalization:** Answer were scored as (1) for *"yes"* value, and (0) for *"no"* value.

Table 13.1: Summary of variables and measurement scales. The table includes two main dependent variables—Learning Outcome (LO) and Quality of Experience (QoE)—and the related engagement sub-dimensions.

Variable	**Scale**	**Operationalization / Description**
Learning Outcome (LO)	Quiz	Measure of students' knowledge after the lecture, based on a multiple-choice test. Correct answers = 1; incorrect = 0.
Self-Efficacy (SEff)	Likert (1–5) [300]	Students' perceived ability to perform tasks related to lesson content; computed as mean score.
Immersiveness (IM)	Likert (1–5) [345]	Extent to which students feel absorbed and present in the learning experience, reflecting full engagement.
Affective Engagement (AE)	Likert (1–7) [339]	Students' emotional involvement, capturing enthusiasm, interest, and enjoyment.
BE Compliance (BEc)	Likert (1–7) [339]	Degree to which students follow class norms and instructions during the session.
BE Effort Participation (BEe)	Likert (1–7) [339]	Students' active participation and attentiveness during learning activities.
Disengagement (DEr)	Likert (1–7) [339]	Tendency to withdraw or lose attention during the activity (reverse-scored).
Perceived Workload (PW)	NASA-TLX [151]	Self-reported mental and physical effort required to complete the task.
Satisfaction (ST)	NPS [173]	Students' overall satisfaction and willingness to recommend the learning method.

13.3.5 *Questionnaires for Measurements*

Assessing the impact of our VR-based methodology is essential for understanding the mechanisms that influence outcomes. In this study, a

variety of questionnaires were utilized to gather data on LO and the QoE. These dimensions are critical for evaluating the effectiveness of teaching in VR in comparison to face-to-face and online learning environments. In the following sections, we describe the questionnaires used and the tool used to provide the form for collecting data from participants; they are summarized in Table 13.1.

13.3.5.1 *Learning Outcome Measurement*

The first questionnaire aims to evaluate LO, specifically focusing on what students learned after engaging in a lesson about the socio-technical aspects that may arise within development teams. Given the absence of a validated questionnaire in the literature for this purpose, academic learning assessments, often formatted as quizzes, were not standardized for research. Nonetheless, the framework used to design the quiz aligned with models commonly adopted at our university and adhered to guidelines outlined in the literature [119].

The quiz comprised closed-ended questions, each offering four response options. Each correct answer was awarded 1 point, while incorrect or unanswered questions received 0 points. The quiz consisted of 13 closed-ended questions, and it was administered to all students in the same randomized order. The questions were crafted to encompass the entirety of the lesson's content, as outlined in Section 13.2.3. Various formats were employed, including multiple-choice, true/false, and practical scenario-based questions. For instance, one question posed was: "*What does the term 'Radio Silence' mean in the context of community smells?*" This question was directly linked to Section 3 of the slides, where community smells were elucidated through practical examples. This alignment with the official examination standards of our institution was intended to ensure ecological validity in the measurement of learning outcomes. As a result, a formal qualitative component specifically targeting learning outcomes was not included, since our primary objective was to assess performance under conditions that closely mirrored established academic practice.

13.3.5.2 *Quality of Experience Measurement*

The QoE was evaluated using five proxies: SEff, IM, EN, PW, and ST. Unlike LO, each proxy was measured using validated questionnaires from the literature, specifically designed for educational contexts. As mentioned in the previous section, the EN variable is divided into specific sub-dimensions. To ensure clarity, this section provides a detailed explanation of these sub-dimensions and how they were measured.

The first proxy representing the QoE is **SEff**. Based on psychological theories and research by Bandura [25], SEff is a key component of social cognitive theory, as it reflects an individual's belief in their ability to manage environmental demands through adaptive actions. It is considered an optimistic and confident perception of one's capability to handle specific stressors [25, 299]. In our educational context, SEff was used to assess students' confidence in applying the concepts and examples discussed during the lesson. This was measured using 10 questions adapted to the socio-technical context of the lesson. For instance, an original question from the Seff questionnaire, "*I am confident that I could deal efficiently with unexpected events*," was modified to align with the lesson's content: "*I feel confident in applying what I learned in this lesson to new situations*." Responses were evaluated using the original likert scale, ranging from "*not at all true*" to "*completely true*."

The second proxy is the **IM**. According to Sheridan et al. [306], it is a subjective sensation—a mental phenomenon that cannot be easily defined or measured using objective physiological parameters. The perception of the immersion in an environment may vary depending on the characteristics of the environment itself and individual differences. Fontaine [129] describes it as a matter of focus, which manifests during the execution of habitual, routine, and automated tasks that require minimal attention. However, in a novel environment, individuals tend to maintain broader and more distributed attention, engaging more deeply in the overall experience. To assess this dimension, the first version of *Immersive Tendencies Questionnaire* (ITQ) was employed [345], designed to identify and measure individual differences in the ability or tendency to feel present in a given

environment. In this study, the ITQ was adapted to fit the socio-technical context presented during the lesson. For example, the original ITQ question, "*Do you ever get extremely involved in projects that are assigned to you by your boss or instructor, to the exclusion of other tasks?*", was modified for the context of an online lesson into: "*Was I able to focus all my attention on the lesson without being distracted?*" The same 5-point Likert scale from the original ITQ was used, ranging from "Strongly agree" to "Strongly disagree." This adaptation ensured that the questionnaire remained contextually relevant while preserving its validity and alignment with the original framework.

The third proxy is *EN*. Wang et al. [339] define engagement as *the active involvement of students in classroom learning activities. It encompasses elements such as attention, interest, effort, and energy that students dedicate to their learning tasks. Notably, engagement is described as a multidimensional construct that is essential for predicting meaningful academic outcomes and is sensitive to educational interventions.*

EN variable is divided into the following dimensions:

- *AE*, which refers to positive emotions experienced during the lesson, such as interest, joy, and enthusiasm.
- *Behavioral Engagement*, which relates to observable behaviors such as participating actively in class, paying attention, asking questions, and tackling challenging tasks. This dimension is further divided into:
  - *BEc*, reflecting adherence to classroom expectations and rules.
  - *BEe*, indicating active and deliberate involvement in learning activities.
- *DEr*, which represents behaviors and attitudes opposite to engagement.

The original engagement questionnaire included 24 items, distributed across these five dimensions. However, for the purposes of this study, some

items were adapted or removed to align with the experimental context.[1] Specifically, five items were used to measure AE, two for BEc, four for BEe, and three for DEr (reversed in the analysis phase).

The last but one proxy is ***PW***, measured using the *NASA-TLX* (Task Load Index) [151]. The NASA-TLX is a widely recognized instrument designed to evaluate the perceived workload experienced during task performance. It assesses six core dimensions: mental demand, which reflects the cognitive effort needed for thinking, remembering, or problem-solving; physical demand, which pertains to the physical effort required to complete the task; temporal demand, indicating the pressure arising from the pace or time constraints; performance, representing the participant's self-evaluation of how well they believe they executed the task; effort, capturing the overall energy expended to accomplish the task; and frustration, measuring the level of stress, irritation, or annoyance experienced throughout the task. Each dimension is individually assessed and then combined to compute an overall workload score, offering valuable insights into participants' experiences, particularly in contexts that involve complex interactions with technological systems. The NASA-TLX questionnaire was utilized without modifications, maintaining its original structure and measurement scale, as it is a standardized and validated tool suitable for immediate application for our context of use.

Last but not least, **ST** was evaluated using the *Net Promoter Score* (NPS), a widely recognized metric for measuring customer satisfaction and reliability towards a product, service, or experience. The NPS is determined through a single, straightforward question that aims to ask whether users would recommend the system to friends or colleagues. Respondents indicate their likelihood on a scale from 0 to 10. Those who score 9 or 10 are categorized as *promoters*, signifying high satisfaction and a strong inclination to recommend. Those scoring 7 or 8 are viewed as *passives*, reflecting a neutral attitude, while respondents who score between 0 and 6 are designated as *detractors*, reporting dissatisfaction.

[1] For instance, in the *BEc* dimension, the original questionnaire included the item: "*I completed my assignment.*" Since no assignments were part of this experiment, this item was excluded to avoid confusion among students and to ensure the reliability of the results.

13.3.6 *Dissemination and Ethical Approval*

In this section, we describe the tools used to distribute the questionnaire explained earlier. We created the questionnaire using *Google Forms*[2] because it allows easy data collection, visualization with graphs, and seamless integration with *Google Sheets* and *Excel* for automatic data transfer.

The questionnaire was divided into 11 sections. The first section introduced the experiment to students, explaining our goals and the need to collect their responses anonymously. Since our study involved human participants, we submitted it for approval to our ethical board, receiving a formal approval[3] provided in our online appendix [105]. Students were informed that their participation was voluntary, and they could leave at any time without giving a reason. We also explained the necessity of data collection, ensuring that no personal information was recorded and that responses remained anonymous. Gender and enrollment type were collected only for statistical analysis. Before proceeding, students had to review and accept our data privacy policy.

Once they accepted, the questionnaire began. Section 3 included questions about the learning outcome with community smells quiz described in Section 13.3.5.1, and Sections 4 to 11 focused on evaluating the quality of experience using the proxies defined in Section 13.3.5.2. We designed three identical copies of the questionnaire for all experimental conditions. However, since virtual reality represents our methodological contribution and may generate more suggestions and feedback about the experience, we included a final text box specifically for students to provide any additional feedback.

[2] https://workspace.google.com/products/forms/

[3] Since the request for ethical approval had to be submitted before the development and experimental process, the title recorded in the ethical approval differs from the final title, as it was only temporary. Initially titled "*Immersive Education: Does It Really Work*?", the paper was later updated to reflect its actual title. Furthermore, since the approval report is a standardized document for all studies within the Department of Computer Science at the University of Salerno, we have chosen to censor, for privacy reasons, any content unrelated to our study.

Before distributing the final questionnaire to the experimental groups, we conducted a pilot study to check its clarity and effectiveness. This helped us identify potential issues, such as unclear wording, missing information, or questions that could lead to misinterpretation. The pilot participants provided feedback, which we used to refine the questionnaire before launching the full study, as an example of refinement.

13.3.7 *Data Collection Process*

In the following, we provide a clear description of how the experiments were performed. The workflow is composed of 3 main parts: the Welcome part, the Experiments Execution, and the Questionnaire Dissemination Collection.

WELCOME PART: Each session began with a welcome and introduction to ensure that participants felt comfortable and understood the objectives of the study. The researcher briefly outlined the experiment's goals and the need for students to attend the lecture. Participants were reminded that their data would be collected anonymously and that they were free to leave the study at any time without providing a reason.

EXPERIMENT EXECUTION: During the main session, students attended the same lesson across all three conditions (face-to-face, online, and VR), where they engaged with community smells concepts. The VR methodology used allowed students to immerse themselves in these scenarios, understanding how socio-technical issues manifest in software development teams. For the face-to-face and online sessions, students were free to choose their seats in a spacious and well-ventilated classroom. Meanwhile, those participating remotely attended the lesson from their homes, similar to how online learning was conducted during the COVID-19 pandemic. These two experiments were conducted simultaneously to avoid potential biases and to simulate a hybrid learning environment, where the instructor teaches both in-person and remote students at the same time. For the VR experiment, participants attended the session

on a separate day. They were seated in a large laboratory at designated workstations, ensuring proper distance to minimize distractions. Each student used a pre-configured Head-Mounted Display (HMD), with an account on VRChat specifically created for this study. The devices included 5 Meta Quest Pro, 3 Meta Quest 3, and 3 Meta Quest 2. While the Meta Quest Pro featured advanced sensors such as eye tracking and hand tracking, all headsets were configured to ensure an equal software and hardware experience across participants, without enabling additional features exclusive to the Quest Pro. Furthermore, all HMDs were connected to their respective workstations via Link cables and managed through SteamVR. This configuration enabled us to manage the varying native resolutions of the devices, providing a consistent visual experience across all devices. Specifically, the virtual environment was set up in SteamVR with a fixed image quality of 1800×1920 px across all headsets, without considering the device version. Before starting the main experiment, VR participants underwent a training session to familiarize themselves with the technology. This session helped them understand how to navigate the virtual environment and prepared them for potential issues, such as motion sickness. If a participant experienced discomfort, they were instructed to stop immediately. They also completed an 8-minute practice session in the experimental room, without interacting with the core components of the study, to avoid learning effects. After this, students took a short break to rest their eyes before proceeding with the main experiment.

QUESTIONNAIRE DISSEMINATION AND COLLECTION: At the end of each experimental session, all participants were required to complete the surveys about learning outcome and the quality of the experience using Google Form. It is worth noting that three identical copies of the survey were sent, each with a unique link assigned to a specific group of participants, i.e., VR Group, Presence Group, and Online Group. This approach ensured that the collected data was correctly linked to each group, preventing misclassification errors during the analysis phase. Finally, the experiment generates three distinct datasets–one for each

treatment–each containing both learning outcome and quality of experience data.

13.3.8 *Data Analysis*

The initial step involved organizing the data in Excel by dividing it into columns, with each representing a variable or sub-variable (such as engagement). The rows consisted of the participants, grouped by an ID (one group for each treatment).

The data analysis began with a preliminary examination to determine their characteristics and decide which type of test (parametric or non-parametric) would be appropriate. As expected, given the number of participants, the analysis revealed a non-normal distribution. For this reason, and considering the data size, we opted for a non-parametric test approach. This preliminary analysis was conducted in Excel.

After the preliminary analysis was completed, the data was imported into a smart notebook in Google Drive for the main analysis phases. At an initial stage, the focus was placed on validating the measurement process. In the context of this study, some of the variables were considered latent, meaning they were not directly observable and instead resulted from human perception, i.e., factors. These variables were Self-efficacy, Immersiveness, Affective Engagement, Behavioral Engagement—Compliance, Behavioral Engagement—Effortful Class Participation, and Disengagement. Although widely validated instruments from the literature were employed for measurement, it was deemed necessary to further validate them within the specific context of this study to enhance reliability. For this reason, Exploratory Factor Analysis (EFA) was conducted to validate the measurements [120, 239]. EFA is a technique within factor analysis aimed at identifying the underlying relationships between measured variables. It is commonly used in scale development to assess whether a set of items converges toward measuring the same construct, thereby validating the measurement process. Through EFA, it is possible to identify indicators that do not align with the overall trend of the variable intended to be

measured (due to reasons such as poorly formulated questions or those misunderstood by participants) and remove them to enhance the final measurement.

Following this, a Kruskal-Wallis test was performed, followed by a Dunn post-hoc test to identify significant differences between treatments [187]. This approach was applied to all dependent variables in the study.

13.3.9 *Threats to Validity*

To ensure the reliability and generalizability of the findings, it is essential to analyze potential threats to validity. This section categorizes these threats following the established framework: construct validity, internal validity, external validity, and conclusion validity [346].

13.3.9.1 *Construct Validity*

Construct validity refers to the extent to which the variables used in the study accurately measure the theoretical constructs they are intended to represent. In this study, two primary constructs were examined: *learning outcomes* and *quality of the learning experience*, assessed through five proxies (self-efficacy, immersion, engagement, perceived workload, and satisfaction).

A potential threat to construct validity arises from the operationalization of these constructs. While validated instruments from the literature were used to measure self-efficacy, immersion, engagement, and perceived workload, the assessment of learning outcomes was conducted using a custom-designed quiz. Although the quiz was structured following established guidelines, it may not fully capture all dimensions of student learning. Additionally, self-reported measures for engagement and self-efficacy introduce potential biases, as participants' perceptions may be influenced by external factors such as prior experience with VR or personal learning preferences—we controlled for these in our participants selection process.

To mitigate these threats, an Exploratory Factor Analysis (EFA) was performed to validate the measurement instruments and ensure that survey items accurately reflected the intended constructs [120, 239]. Furthermore, the learning outcome questionnaire was designed to align closely with course objectives and was piloted before the main experiment to ensure clarity and effectiveness.

Another potential threat is the lack of formal qualitative protocols. We included an informal qualitative component aimed at capturing spontaneous comments from VR participants, particularly to understand whether the methodological contribution in the VR condition could elicit general feedback about the animated scenario. However, we did not implement a formal qualitative protocol (e.g., semi-structured interviews or follow-up sessions), as the educational dynamics involved additional factors that go beyond technical implementation—e.g., internal and external distractions [150], emotions [164], moods [332], etc.—that fall outside the direct control of this study and would require a more targeted design and equipment. Given the exploratory nature of our work, we focused on assessing whether VR has the potential to enhance learning—alongside abstract contexts such as socio-technical aspects in software development—and to improve the overall experience compared to other conditions. A more in-depth investigation, with a stronger emphasis on qualitative analysis, is left for future research.

13.3.9.2 *Internal Validity*

Internal validity concerns the degree to which observed differences can be attributed to the experimental conditions rather than confounding factors.

First, participants were assigned to experimental groups using randomization to reduce selection bias. However, given the small sample size (30 students), complete balancing of individual characteristics (e.g., prior VR experience, motivation, or cognitive abilities) was not guaranteed.

Second, participants' learning and perceptions could have been influenced by factors unrelated to the teaching method, such as prior exposure to the topic or external discussions outside the experiment. This risk was

minimized by ensuring that participants had no prior knowledge of the specific socio-technical concepts (community smells and social debt).

Third, the use of different technological setups (e.g., VR headsets) might have affected engagement and perceived workload. To address this, the VR system was standardized across participants, and hardware limitations were minimized.

13.3.9.3 *External Validity*

External validity refers to the extent to which the findings can be generalized beyond the specific study conditions. Several factors may limit generalizability. In terms of population, the study was conducted with computer science students from a single university, which may limit its applicability to other disciplines or educational contexts. Moreover, the small sample size (30 participants) restricts broader generalization. Future studies should replicate the experiment with a more diverse and larger sample.

The VR technology used in the study may not be representative of future advancements in immersive learning tools. As VR hardware and software continue to evolve, newer technologies may offer different levels of immersion and usability, potentially influencing future outcomes.

13.3.9.4 *Conclusion Validity*

Conclusion validity pertains to the reliability of statistical conclusions drawn from the data.

First, the study involved a relatively small sample size, which may limit the statistical power of the analyses. Non-parametric tests (e.g., Kruskal-Wallis and Dunn post-hoc tests) were chosen due to the non-normal distribution of data, ensuring appropriate handling of small-sample statistical comparisons.

While validated instruments were used for most constructs, some self-reported measures (e.g., engagement and immersion) are inherently subjective. The use of factor analysis to validate these scales helped ensure measurement consistency.

All collected data were manually reviewed before analysis to identify and correct potential input errors. Data processing was conducted using structured notebooks to ensure traceability and reproducibility of the results.

13.4 FINDINGS OF THE CONTROLLED EXPERIMENT TO EVALUATE THE METHODOLOGICAL PROPOSAL

In the following section, we present the results of our statistical analysis to evaluate the VR-based methodology, which is thoroughly detailed in Section 13.2. We will first describe the results of the Exploratory Factor Analysis (EFA) to demonstrate the reliability of the chosen metrics and measurement instruments. Subsequently, we present the statistical test results, along with their significance, for each research objective. For a discussion on these findings, please refer to Section 13.5.

13.4.1 *Exploratory Factor Analysis*

The first step of the EFA involved using Cattell's scree plot method [70] to determine the number of factors formed by all indicators (i.e., the questions) used to measure the latent variables in the study (Self-efficacy, Immersiveness, Affective Engagement, Behavioral Engagement—Compliance, Behavioral Engagement—Effortful Class Participation, and Disengagement). This approach is well-documented and widely used in studies conducting EFA. It is important to note that the EFA was conducted separately for each factor considered in this study. Consequently, if the analysis revealed more than one factor within a set of indicators, this would indicate a measurement issue if the indicators were evenly distributed across multiple factors. However, if a single factor emerged or only a small subset of indicators formed a separate factor, only those specific indicators would be removed to retain a single-factor structure.

In the analysis conducted, more than one factor (i.e., two factors) was identified in only three cases: Self-efficacy, Immersiveness, and Effortful

Table 13.2: Items phrasing and Cronbach's α for EFA employed to validate the measurement process.

Factor	ID	α	Item phrasing
Self-Efficacy (SEff)	SE1	0.700	I understand the main lesson concepts.
	SE2	0.680	I can identify community smells in a dev. community.
	SE3	0.789	I can explain lesson topics to a classmate.
	SE4	0.686	I can apply what I learned to new situations.
	SE5	0.793	I can answer questions on lesson topics easily.
	SE6	0.873	I can perform well on a test about this lesson.
	SE7	0.804	I feel ready to discuss lesson topics.
	SE8	0.525	I am confident completing assignments.
	SE9	NA	I can solve difficulties with the lesson topics.
	SE10	0.660	I have mastered the lesson content.
Immersiveness (IM)	IM1	NA	I focused on the lesson without distraction.
	IM2	0.536	I felt involved in lesson activities/discussions.
	IM3	0.608	Time passed quickly during the lesson.
	IM4	0.658	I felt emotionally involved in the content.
	IM5	0.084	I had control and could interact meaningfully.
	IM6	0.732	I was curious about lesson topics.
	IM7	0.716	I was fully absorbed in activities.
	IM8	0.558	The lesson's challenges kept me engaged.
	IM9	0.598	I reflected on how content links to prior knowledge.
	IM10	0.474	I enjoyed and found the lesson stimulating.
Affective Engagement (AE)	AE1	0.508	I felt interested in class.
	AE2	0.764	I felt proud attending the class.
	AE3	1.000	I felt excited during the class.
	AE4	0.650	I felt happy in class.
	AE5	0.512	I felt amused or had fun in class.
BE Compliance (BEc)	BEC1	0.609	I listened carefully during the class.
	BEC2	0.609	I paid attention to key details.
BE Effort Participation (BEe)	BEE1	NA	I got really involved in class activities.
	BEE2	0.713	I formed new questions while participating.
	BEE3	0.766	I didn't want to stop at class end.
	BEE4	0.832	I actively joined class discussions.
Disengagement (DEr)	DE1	0.729	I was "zoned out," not following the lesson.
	DE2	0.846	I let my mind wander.
	DE3	0.724	I only pretended to follow the lesson.

Note. α = Cronbach's α; BE = Behavioral Engagement; DE = Disengagement (reverse scored); NA = item excluded from reliability analysis.

Table 13.3: Results of Mann-Whitney U test to check significant differences between the variables across the three different treatments (VR, Face-to-Face, Online).

Variable	VR vs Face-to-Face			VR vs Online		
	U Statistic	p	Effect Size (r)	U Statistic	p	Effect Size (r)
LO	61.500	0.362	0.230	60.500	0.408	0.210
SEff	62.000	0.333	0.240	29.500	0.100	-0.410
IM	56.000	0.666	0.120	40.000	0.429	-0.200
AE	**13.500**	**0.002**	**-0.730**	**4.000**	**< 0.001**	**-0.920**
BEc	67.000	0.180	0.340	36.500	0.312	-0.270
BEe	52.000	0.906	0.040	**18.000**	**0.014**	**-0.640**
DEr	62.500	0.325	0.250	67.000	0.167	0.340
PW	64.000	0.298	0.280	60.500	0.442	0.210
ST	32.500	0.171	-0.350	**19.000**	**0.017**	**-0.620**

Note: effect size is given by the Rank-Biserial Correlation.

Class Participation. In each of these cases, the second factor was composed of only one indicator (SE9, IM1, and BEE1, respectively). For this reason, the initial analysis supported the robustness of the proposed measurement model, and the procedure was limited to removing these three indicators before proceeding to the second step of the analysis.

The second step of the EFA involved assessing the Cronbach's α values for all indicators. The general guideline is that values above 0.7 indicate good reliability, allowing the items to be retained for subsequent EFA steps. Conversely, values below 0.7 but above 0.4 may be retained with caution, whereas values below 0.4 should be removed due to low reliability.

Table 13.2 reports the Cronbach's α values for all indicators. As shown, only IM5 from Immersiveness exhibited a value significantly below 0.4, while all other indicators exceeded the minimum threshold of 0.4 (30 indicators), with many also surpassing the optimal threshold of 0.7 (14 indicators). **Overall, the analysis validated the measurement process, as only 4 out of the original 34 indicators were removed, and no factors were excluded from the analysis.**

Table 13.4: Summary statistics for the variables of the study.

Variable	Median (M)			Mean (μ)			Standard Deviation (SD)		
	VR	F2F	Online	VR	F2F	Online	VR	F2F	Online
LO	3.000	4.000	4.000	3.100	3.500	3.400	0.994	0.707	0.966
SE	3.000	3.000	2.000	2.700	3.000	2.100	0.675	0.667	0.738
IM	4.250	4.500	4.000	4.250	4.300	4.150	0.589	0.789	0.474
AE	4.000	3.000	3.000	3.900	2.900	2.700	0.316	0.738	0.675
BEc	6.250	7.000	6.000	6.050	6.700	5.800	1.235	0.422	0.789
BEe	5.500	5.500	3.500	5.500	5.300	3.900	0.850	1.829	1.370
DEr	4.000	5.000	5.000	3.900	4.400	4.600	1.287	0.966	0.699
PW	7.500	9.000	8.500	7.650	8.600	8.400	2.001	1.265	0.775
ST	6.000	4.000	4.000	5.200	4.600	4.000	1.317	1.075	1.247

13.4.2 *RO_1 — Learning Outcome*

The initial analysis focused on the LO. This was assessed through a quiz where each correct answer was awarded 1 point, while each incorrect or unanswered question was assigned 0 points. The final score for each participant was the sum of their question scores, while the overall score for each group (VR, face-to-face, and online) was represented by the median.[4]

The analysis of LO did not reveal statistically significant differences between the VR, face-to-face, and online conditions (Table 13.3).

RQ1 **How does virtual reality teaching method compares with the face-to-face baseline in terms of learning outcome?** The results indicate that there is no statistically significant difference in learning outcomes between the virtual reality teaching method and the face-to-face baseline ($U = 61.500$, $p = 0.362$, $r = 0.230$). The median learning outcome score was slightly lower for the VR condition ($M_{VR} = 3.0$) compared to Face-to-Face ($M_{Face-to-Face} = 4.0$), but the overall scores remained comparable. Therefore, the null hypothesis ($H1_0$) cannot be rejected, suggesting that the VR-based teaching

[4]These choices aligned with the university guidelines familiar to students.

method yields similar learning outcomes to traditional face-to-face instruction.

RQ2 **How does virtual reality teaching method compares with the online baseline in terms of learning outcome?** The results show no statistically significant difference in learning outcomes between the virtual reality teaching method and the online baseline ($U = 60.500$, $p = 0.408$, $r = 0.210$). The median learning outcome score was lower for VR ($M_{VR} = 3.0$) compared to Online ($M_{Online} = 4.0$), but the mean values were close ($\mu_{VR} = 3.1$, $\mu_{Online} = 3.4$), with relatively low variance. Consequently, the null hypothesis ($H2_0$) cannot be rejected, indicating that the VR-based teaching method leads to learning outcomes comparable to those of online instruction.

Overall, these results suggest that the VR-based approach provided comparable learning outcomes to traditional and online methods, with no significant advantage or disadvantage in terms of knowledge acquisition as measured in this study. This is a result we find satisfactory, given that the use of visors is known to be annoying and could have distracted participants, reducing their attention and thus their learning.

13.4.3 *RO_2 — Quality of the Experience*

Regarding the second objective, we aimed to assess the quality of the experience using a series of proxy measurements. For each of these measures, the median was used to represent variables for individual respondents and for the three groups. The results are reported below (shown in Table 13.3 and Table 13.4) for each RQ.

RQ3 **To what extent virtual reality teaching method compares with the face-to-face baseline in terms of proxies used for the quality of the experience?** The results indicate that the virtual reality teaching method led to comparable levels of SEff ($U = 62.000$, $p = 0.333$, $r = 0.240$), IM ($U = 56.000$, $p = 0.666$, $r = 0.120$), BEc ($p > 0.05$)

compared to face-to-face instruction. Additionally, PW and DEr reversed, did not differ significantly between conditions. AE was significantly higher in VR than in face-to-face ($U = 13.500$, $p = 0.002$, $r = -0.730$), suggesting that VR fosters stronger emotional involvement. ST was also slightly higher in VR, though not statistically significant ($U = 32.500$, $p = 0.171$, $r = -0.350$). These findings suggest that while VR does not significantly outperform face-to-face learning in most experience-related dimensions, it enhances affective engagement, making it a promising tool for increasing emotional investment in learning activities.

RQ4 **To what extent virtual reality teaching method compares with the online baseline in terms of proxies used for the quality of the experience?** The comparison between the virtual reality teaching method and the online baseline revealed several significant differences. VR participants reported significantly higher AE ($U = 4.000$, $p < 0.001$, $r = -0.920$) and BEe ($U = 18.000$, $p = 0.014$, $r = -0.640$), indicating stronger involvement in learning activities. ST was also significantly higher in VR compared to online ($U = 19.000$, $p = 0.017$, $r = -0.620$). Conversely, no significant differences were observed for SEff, IM, PW, or DEr reversed, indicating that VR does not impose additional cognitive burden compared to online instruction. These results suggest that VR-based teaching significantly enhances engagement and satisfaction relative to online learning, making it a promising alternative for remote education.

The results indicate that the VR-based methodology significantly AE and BEe compared to the online condition, while maintaining levels of SEff, IM, and BEc comparable to face-to-face instruction. ST was also significantly higher in VR than in online but not in comparison to face-to-face. No significant differences were found for DEr reversed and PW, suggesting that VR did not impose additional cognitive burden compared to other modalities. Variability in responses, as indicated by standard deviations, was generally higher in the VR group for BEc and PW, reflecting more heterogeneous experiences among participants. In contrast, AE and

BEe showed lower dispersion in VR, suggesting a more uniform level of engagement. These findings highlight the potential of VR as an effective learning tool, particularly for increasing engagement and satisfaction in educational settings.

Summary of the Results.

The VR-based teaching method demonstrated learning outcomes comparable to both face-to-face and online instruction, highlighting its effectiveness as a viable alternative to traditional approaches. Moreover, it maintained levels of self-efficacy, immersiveness, and behavioral compliance on par with face-to-face learning, reinforcing its ability to provide an engaging and structured educational experience. Notably, VR significantly enhanced affective engagement and effortful class participation compared to online learning, showcasing its potential to foster a more interactive and immersive learning environment. Additionally, participants reported significantly higher satisfaction in VR than in online settings, further supporting its positive impact on the learning experience. Importantly, VR did not introduce additional cognitive burden, as indicated by perceived workload measures. These findings position VR as not only an equivalent but, in some aspects, a superior alternative to conventional teaching modalities, particularly for increasing engagement and satisfaction in educational context.

13.5 DISCUSSION AND IMPLICATIONS

Our results demonstrated that the proposed methodology for teaching social debt concepts to students is comparable, if not superior, to traditional approaches in terms of the quality of experience. This outcome is particularly encouraging, as it highlights how virtual reality can be beneficial in various aspects of software engineering—not only in general terms, as already demonstrated in several studies that have utilized and proposed it, but also for educational purposes.

13.5.1 *The Good and the Bad of Teaching Social Debt and Community Smells using Virtual Reality*

The evaluation of the VR-based teaching methodology provided valuable insights into its effectiveness and areas for improvement. To structure this discussion, we categorize the findings into two main aspects: *The Good*, which highlights the positive outcomes of the methodological approach and *The Bad*, which outlines the challenges encountered.

13.5.1.1 *The Good*

According to the results of the empirical study, we collected several good points in favor of our VR-based methodological proposal.

One of the key strengths of the proposed method is its demonstrated ability to effectively convey knowledge, performing on par with both face-to-face and online teaching—and in line with the findings of Hamilton et al. [148]. This result is particularly noteworthy because, as suggested by prior literature, the inherent challenges of virtual reality—primarily hardware-related—could have negatively impacted learning by distracting participants and reducing their ability to retain information [88, 125].

While the learning outcomes were satisfactory, the most compelling insights emerged from the assessment of the overall learning experience.

A major success of this approach lies in the visualization of socio-technical anti-patterns through animated scenarios. Participants consistently highlighted the effectiveness of these scenarios in facilitating the comprehension of abstract socio-technical concepts. One participant noted, 💬 *"The animated scenarios were extremely interesting and very useful for understanding; I wouldn't change anything."* The immersive nature of VR further encouraged engagement, as illustrated by another comment: 💬 *"The animated scenarios were definitely useful for putting myself in the environment and situation more quickly, leveraging the advantages of the tool compared to a traditional lesson."*

In addition, the results indicate that VR significantly enhanced emotional involvement in the learning process, leading to a more interactive

experience. The ability to visualize software development scenarios in a 3D environment provided a contextual understanding that would have been more abstract in traditional settings. As one participant remarked, 💬 *"I found the immersive scenarios very useful in helping me better understand the topics and concepts explained."* These findings not only underscore the effectiveness of scenario-based visualization but also help explain the positive learning outcomes—despite the presence of well-documented challenges associated with VR [88, 125], which will be better discussed later.

Another advantage of the VR-based approach was its ability to foster a highly interactive and motivating learning environment. Specifically, VR provided a more engaging alternative to online teaching, which was often perceived as less interactive. One participant emphasized this contrast, stating, 💬 *"The environment was extremely engaging and interactive, far more exciting than following a lesson on Teams."*

13.5.1.2 *The Bad*

Despite the previously-mentioned positive outcomes, certain aspects of the experience require refinement.

One issue highlighted by some participants concerned difficulties in viewing the slide content, particularly among those seated towards the back of the virtual classroom. For example, one participant reported: 💬 *"From medium-long distances, the slides appeared somewhat pixelated, and only at the end of the lesson, when I moved closer, did they become as sharp as the surrounding environment."*

Additionally, minor interface refinements could enhance usability. Some participants suggested improving the color contrast of notifications, while others noted occasional lag and overlapping interface elements: 💬 *"Sometimes there were lags, and also, the names of other users can sometimes cover the slides."*

Another important consideration is the physical strain associated with extended VR use—a well-documented challenge in the literature [88, 125]. Several participants found prolonged sessions uncomfortable, with

comments such as: 💬 *"Keeping the headset on for a long time can be slightly uncomfortable."* and 💬 *"Lessons longer than this might not be feasible for someone who has never used a headset before."*

13.5.2 *Implications for Teachers of Socio-Technical Aspects in Software Development*

The findings of this study provide several key insights that can inform educators on the effective use of VR for teaching socio-technical concepts in software engineering. Based on the results and participant feedback, we outline practical recommendations for teachers interested in integrating VR into their curriculum.

LEVERAGE SCENARIOS AS MUCH AS POSSIBLE The use of VR significantly enhanced students' comprehension of socio-technical anti-patterns and engagement by providing immersive scenarios. Moreover, the results demonstrated that VR fosters a highly engaging and interactive learning environment.

- 🔧 Educators interested in using our method and materials for teaching should focus primarily on narrating the scenarios effectively, allowing sufficient time for students to observe and internalize them.
- 💡 In contrast, teachers aiming to build their own virtual environments should heavily rely on this scenario-based approach to convey their lessons. However, developing such scenarios requires skills that are not yet widespread—both in programming and 3D modeling. Therefore, selecting the right expertise for development is crucial.

DO NOT UNDERESTIMATE HARDWARE LIMITATIONS Participants highlighted certain usability issues, such as text readability, lag, and the discomfort associated with prolonged headset use. Furthermore, some students, especially those with limited prior experience with VR, needed time to adapt to the virtual environment.

- Educators using our method and materials for teaching should avoid prolonged VR sessions. Additionally, introductory sessions should be provided to allow students to familiarize themselves with the VR environment before engaging in the lesson, reducing cognitive overload and ensuring a smoother learning experience.

- Teachers implementing VR should ensure that the learning environment is optimized for clarity and usability, including adjusting text size, refining interface elements, and scheduling breaks to mitigate fatigue.

Nevertheless, such limitations are expected to diminish with technological advancements—an evolution that, it is important to note, can only progress with increased adoption and integration into educational practices.

HARNESSING THE POTENTIAL OF AN IMMERSIVE REMOTE ENVIRONMENT Although this study focused on individual learning experiences, VR also offers significant opportunities for collaborative learning. This was further reinforced by feedback from participants in the VR experiment, who recognized VR as an effective tool for enabling a certain level of immersion even in remote settings.

- Educators using our method and materials for teaching could leverage the VR environment to facilitate deeper discussions, allowing students to navigate scenarios and create more interactive and engaging lessons.

- Teachers implementing VR should consider designing multi-user VR activities where students can collaborate to analyze scenarios, discuss potential solutions, and experience teamwork dynamics in virtual environments.

13.5.3 *Future Research Directions*

Based on the results obtained, their discussion, and the broader insights from this study, several future directions can be identified to guide further research on the use of VR for socio-technical aspects in software engineering education.

- **Generalizability and Sample Size.** The study was conducted with a relatively small sample size of 30 students from a single university. While the findings offer valuable insights, their generalizability to broader populations, including students from different disciplines, educational institutions, and cultural backgrounds, remains uncertain. Future studies should aim for larger and more diverse samples to strengthen the validity of the conclusions.

- **Hardware and Accessibility Constraints.** The accessibility of VR technology remains a significant limitation. Not all educational institutions or students have access to high-quality VR headsets, which could hinder the widespread adoption of this teaching methodology. Additionally, hardware performance variations may have influenced the learning experience, particularly in terms of slide readability and occasional lag issues. Future research should explore cost-effective VR solutions, cloud-based VR platforms, and their impact on the educational experience.

- **Adaptation and Learning Curve.** Some students, particularly those with no prior VR experience, may have required additional time to adapt to the virtual environment. This initial learning curve might have affected their ability to focus on the lesson content. While VR proved engaging, future implementations should consider introductory training sessions to help students acclimate to the technology before engaging in learning activities.

- **Long-Term Effectiveness and Retention.** The study focused on short-term learning outcomes and engagement. However, it remains

unclear whether the enhanced engagement observed in VR translates into better knowledge retention over time. Longitudinal studies tracking students' understanding weeks or months after the VR lessons could provide deeper insights into the long-term educational benefits of this methodology.

- **Comparison to Other Interactive Learning Methods.** While VR was compared to face-to-face and online learning, other interactive methods, such as gamification, serious games, or augmented reality (AR), could also offer engaging alternatives. Future research should examine how VR compares to these methods to determine the most effective strategies for teaching socio-technical concepts.

- **Personalization and Adaptive Learning in VR.** The current study adopted a uniform VR lesson structure. However, VR environments offer the potential for personalized and adaptive learning experiences. Future research could explore how AI-driven adaptive content delivery, based on students' prior knowledge and learning pace, impacts engagement and learning effectiveness.

- **Collaboration and Multi-User Interactions in VR.** While this study focused on individual learning experiences, future research could investigate how multi-user VR environments influence collaborative learning. Studying how teams interact in virtual environments and how this compares to traditional team-based learning methods could provide valuable insights into the role of VR in collaborative software engineering education.

- **Emotional and Cognitive Impact of VR Learning.** The study highlighted the immersive and engaging nature of VR-based lessons. However, future work could delve deeper into how VR affects students' emotional and cognitive load. For instance, using physiological measurements (e.g., eye gaze, heart rate variability) could help assess how immersion in VR influences distraction, cognitive workload, and stress levels during learning.

- **Measuring the Cost-Benefit Trade-Off of VR Implementation.** While the study showed positive results, the adoption of VR in education comes with costs related to hardware, software development, and training. Future research should conduct cost-benefit analyses to evaluate whether the educational gains of VR-based teaching justify the investment compared to other interactive teaching methods.

- **Exploring VR-Based Assessment Techniques.** The study primarily relied on quizzes and self-reported metrics for evaluation. However, VR enables novel assessment techniques, such as real-time behavioral tracking and scenario-based assessments. Future research should investigate how these methods could provide a more comprehensive evaluation of students' understanding and engagement.

Summary of the Discussion.

The study highlights the advantages of VR-based teaching for social debt concepts, demonstrating its ability to enhance engagement, emotional involvement, and interaction compared to traditional methods. Participants found animated scenarios highly effective in illustrating socio-technical issues, making abstract concepts more tangible. The immersive environment fostered greater motivation and active participation, particularly over online learning. Despite minor usability challenges, such as slide readability and prolonged headset use, VR provided a dynamic and engaging alternative to conventional teaching. These findings suggest that VR can significantly improve the learning experience by leveraging visualization, interactivity, and immersion in software engineering education.

PART IV

CONCLUSIONS, CONTRIBUTION AND NEXT DIRECTIONS

14

CONCLUSION

The objective of this thesis was to investigate the metaverse in the educational domain through two complementary, closely intertwined perspectives: a **theoretical** and an **engineered and empirically evaluated** one. From a theoretical standpoint, the research aimed to establish a structured foundation for understanding the metaverse as a socio-technical phenomenon. This required identifying the enabling technologies that constitute its backbone, uncovering the socio-technical issues that hinder its adoption, and clarifying how these technologies may help address the challenges identified. In parallel, the work examined which research and practitioner communities are best positioned to intervene on specific issues, thereby outlining a clearer agenda for advancing the metaverse.

On the other hand, the thesis develops an engineered and empirically evaluated perspective centered on the enabling technologies most frequently associated with metaverse development, such as artificial intelligence and blockchain. These technologies are examined not only from a technical viewpoint—through empirical comparisons and design studies—but also with explicit attention to their social and ethical implications when deployed in educational contexts.

The motivation behind this dual perspective lies in the evolution of the metaverse itself. Since the COVID-19 pandemic, the metaverse has often been framed as a promising environment for maintaining educational continuity during periods of social distancing. However, after that period, the term rapidly became a buzzword, frequently exploited for marketing purposes and widely misunderstood. In many cases, the metaverse was reduced to a synonym for a virtual reality game, whereas it should be understood as an immersive, multi-layered socio-technical system whose open challenges—technical, social, ethical, and organisational—remain largely unresolved.

All studies conducted within this thesis were designed and executed with methodological rigour. Each contribution was grounded in clearly articulated research questions and aligned with high-level goals through the *Goal–Question–Metric* (GQM) approach [62], ensuring consistency between intended objectives, methodological choices, and interpretation of results. The empirical corpus spans multiple methodological traditions: literature review studies (J01, C03, C04, C05), mixed-method investigations (J02, J03, C07, C08), and quantitative studies (C06, J04). Collectively, these works advance both the foundational understanding of the metaverse and its application in education, shedding light on how emerging technologies—such as artificial intelligence and blockchain—can concretely support and enhance metaverse ecosystems.

In other words, this dissertation contributes to the *body of knowledge* by clarifying the socio-technical nature of the metaverse and to the *state of practice* by demonstrating how enabling technologies can be operationalised. These contributions touch multiple research areas, including Metaverse Studies, Software Engineering, and the emerging field introduced in this thesis: *Metaverse Engineering*.

The main contributions of the dissertation can be summarised as follows:

1. A systematic and comprehensive taxonomy of socio-technical issues in the metaverse, highlighting their relationship with enabling technologies and identifying the research and practitioner communities that must converge to address them.

2. A set of empirical and design-oriented studies on enabling technologies in depth, how artificial intelligence, blockchain, and related technologies can support both technical requirements and social needs within educational metaverses.

3. The development of the first open-source, fully operational prototype of an educational metaverse, namely SENEM, built around the needs of students and educators and realised according to the metaverse engineering principles introduced in this thesis. The prototype

served as a platform for integrating and validating the enabling technologies discussed in the methodological part.

In the following sections, we discuss how the results of these studies collectively address the research questions that guided this work and how they contribute to the broader goal of structuring the metaverse as a socio-technical ecosystem that effectively supports education.

14.0.1 *RQ_A: The roles of metaverse enabling technologies and their socio-technical challenges*

The studies conducted in this dissertation clarify the role that enabling technologies play within metaverse ecosystems and the socio-technical challenges that accompany their adoption. Chapter 4 identifies artificial intelligence and blockchain as the most prevalent technologies in current research, highlighting their centrality in enabling interaction, automation, and trustworthy data management. The complementary works refine this picture: machine learning in Chapter 3 emerges as a key mechanism for monitoring and personalization in educational settings, while blockchain in Chapter 5 supports transparency and provenance in learning activities. Furthermore, accessibility-oriented analyses in Chapter 6 highlight how interaction modalities and assistive mechanisms shape the inclusiveness of virtual environments.

These opportunities coexist with a consistent set of socio-technical issues. Chapter 4 systematizes them into recurring social and technical concerns—including privacy, ethics, accessibility barriers, psychological well-being, and interoperability—that reappear across the other studies. Indeed, Chapter 3 evidences the psychological and ergonomic limits of AI-driven interaction; Chapter 5 raises questions of trust and security in decentralized infrastructures; Chapter 6 exposes persistent difficulties for users with physical, cognitive, or social impairments.

These results emphasize that technological innovation cannot be separated from the human, organizational, and ethical dimensions that drive its effectiveness.

Answer to RQ_A

Artificial Intelligence and *Blockchain* emerge as the most prominent enabling technologies in metaverse research, supporting interaction, automation, development, and secure data management. However, their adoption is strongly conditioned by socio-technical challenges—including *privacy*, *ethics*, *accessibility*, *psychological well-being*, and *trust*—that must be addressed to ensure inclusive and sustainable metaverse ecosystems.

14.0.2 *RQ_B: The Metaverse Engineering process*

The contributions addressing RQ_B show how the socio-technical challenges identified in this dissertation can be approached through a structured metaverse engineering process. Chapter 4 provides the basis for this process by defining metaverse engineering as a discipline that requires explicit requirement definition, interdisciplinary reasoning, and methodological transparency.

From this foundation, the following studies illustrate how these principles can be put into practice. Chapter 5 shows that high-level concepts must be translated into clear and technology-independent requirements and into architectural decisions that ensure consistency and reliability. Chapter 6 reinforces the need to integrate accessibility and inclusiveness at the earliest stages of design, treating them as essential components of the engineering workflow rather than optional refinements.

This trajectory becomes concrete in Chapter 7, where the development of SENEM demonstrates how requirement elicitation, prototyping, and iterative empirical evaluation can guide the progressive refinement of a metaverse platform. The use of rapid and continuous feedback—such as Rapid Iterative Usability Testing—highlights how engineering decisions benefit from systematic validation and user-centred adjustments.

Taken together, these contributions show that metaverse engineering develops through a coherent progression: conceptual grounding, method-

ological definition, and operational validation. RQ_B thus indicates that the development of metaverse systems requires a dedicated, evidence-based process capable of integrating socio-technical considerations and supporting informed and responsible design choices.

Answer to RQ_B

The metaverse requires a structured process—moving from conceptual grounding to methodological specification and iterative validation—to address its socio-technical challenges. This process, defined as "*metaverse engineering*," relies on clear requirements, accessibility-driven design, and continuous empirical refinement, enabling responsible and reliable integration of enabling technologies within the metaverse.

14.0.3 *RQ_C: How can enabling technologies be integrated, operationalised, and empirically evaluated within an educational metaverse environment?*

The contributions associated with RQ_C provide a comprehensive view of how enabling technologies can be—from the engineering perspective—concretely integrated and evaluated within an educational metaverse. Chapters 9 and 10 show how different approaches to 3D content creation—ranging from manual modeling to computer-vision and AI-assisted photogrammetry—can be operationalized to build virtual environments that balance fidelity, performance, and development effort. By empirically comparing techniques such as Blender modeling, MVS-based reconstruction, and NeRF pipelines, these studies offer practical guidelines on how to select or combine modeling workflows based on project constraints, thereby supporting sustainable and efficient scene development.

A complementary perspective emerges in Chapters 8 and 12, where the integration of advanced AI-based analytics and blockchain infrastructures within SENEM illustrates how enabling technologies can be embedded

into a metaverse while ensuring ethical, trustworthy, and decentralized content management. The emotion-recognition study demonstrates how privacy, informed consent, and transparency can be operationalized in practice, while the blockchain implementation shows how decentralized storage and provenance can support immersive educational interactions. Together, these works highlight the importance of aligning technological integration with ethical safeguards, maintainability considerations, and user-centred design principles.

Finally, Chapters 11 and 13 extend the evaluation of enabling technologies to the pedagogical dimension. The adaptation of MetaSERGE to a metaverse environment demonstrates how experiential learning can be enhanced through immersive interaction, while the VR experiment reported in the EMSE study provides systematic evidence on both the strengths and limitations of immersive instruction. These results show that technologies such as VR can increase engagement, immersion, and the perceived quality of experience, but their educational impact depends on careful instructional design and on managing cognitive and technological constraints.

Answer to RQ_C

Enabling technologies can be effectively integrated into an educational metaverse through coordinated attention to technical implementation, ethical and organizational requirements, and systematic empirical validation. The studies show that 3D modeling workflows, AI-driven emotion recognition, blockchain mechanisms, and VR-based learning can be operationalized and assessed in practice, providing a methodological foundation for robust and pedagogically meaningful metaverse environments.

14.1 LESSON LEARNED

The comprehensive analysis of the contributions developed throughout this dissertation makes it possible to identify three main lessons learned, each capturing the theoretical, methodological, and empirical value of the work conducted. Together, these lessons reflect the three main components of the dissertation—each in a complementary way: the theoretical foundations of the Metaverse, the methodological contributions supporting its engineering, and, finally, the empirical assessment and insights from its application in educational settings.

THE METAVERSE AS A SOCIO-TECHNICAL SYSTEM. The metaverse, as a software system, is often conceptualized primarily as a constellation of technical opportunities, as reported in several studies [335, 338]. However, this view captures only one dimension of its nature. As observed by Mystakidis [229], the metaverse extends across different contexts and purposes, and therefore cannot be framed solely as a technological artefact. Although the literature frequently describes it as the integration of various enabling technologies—virtual reality, artificial intelligence, distributed systems, blockchain—this fragmentation risks overshadowing the most critical element: what makes the metaverse genuinely complex is not the technology per se, but the way in which these technologies interact with people, their needs, their limitations, and the social, ethical, and organisational contexts in which they are embedded. This leads to the *first lesson learned*: any attempt to design or develop metaverse environments must begin with understanding the metaverse as a socio-technical system. Such an understanding does not provide ready-made solutions, nor does it serve as an engineering method in its own right. Rather, it provides the conceptual grounding that allows engineering processes to be more informed, more coherent, and more responsive to the real constraints and needs that emerge when people and technologies meet. It is this conceptual foundation that ultimately enables more responsible, realistic, and sustainable development practices for metaverse systems.

ALL FOR ONE, AND ONE FOR ALL. Recognizing the metaverse as a socio-technical system naturally leads to a broader consideration regarding how it should be studied and engineered. Current research described in Section 2.2 often progresses along separate disciplinary trajectories—i.e., VR focusing on the environments, AI on automation and inference, blockchain on trust and decentralization, and HCI and education on usability, accessibility, and learning. While each domain contributes valuable insights, this fragmentation results in a partial and unbalanced understanding of the phenomenon [102]. This motivates the *second lesson learned*: metaverse engineering must embrace a meaningfully multidisciplinary orientation, in which different communities work not in parallel, but in cooperation. "*All for one, and one for all*" captures this idea: progress in the metaverse does not arise from isolated expertise, but from the coordinated effort of multiple disciplines contributing to a shared objective. The present dissertation demonstrates this need by grounding its methodological exploration in the educational domain, where the interplay among technological affordances, learning dynamics, inclusiveness, and ethical constraints is particularly evident. Only through such integration is it possible to evaluate critically *when*, *why*, and for *what purpose* each enabling technology should be employed, ensuring that its adoption is consistent with user needs, ethical principles, and the specific requirements of the application domain. In this sense, multidisciplinarity is not a desirable accessory but a foundational condition.

EDUCATIONAL METAVERSE: THE REVELATION. A further implication emerges when considering the metaverse within educational contexts. As shown in Chapter 13, although virtual reality reliably enhances students' quality of experience and supports the understanding of abstract or difficult to replicate concepts, it does not yield higher learning outcomes when compared with traditional or online instruction. The absence of a clear learning gain highlights the need to investigate additional factors that may shape students' performance in immersive environments. Among these, distraction is a particularly relevant construct in educa-

tional research: internal distractions (e.g., thoughts, emotions, concerns) and external distractions (e.g., noise, movement, environmental cues) are known to affect attention, working memory, and retention [15, 86]. Yet their role within VR-based learning remains insufficiently understood. To address this gap, the present dissertation initiated an additional study aligned with the methodology in Chapter 13. A preliminary survey identified the most frequently reported distractions across physical and online environments and selected those most representative for a controlled experiment in VR. The ongoing experiment examines their effects on learning, attention, and perceived immersion, also comparing students' experiences across different headsets—including HTC devices and the Apple Vision Pro. This leads to the *third lesson learned*: VR offers a clear experiential advantage, but its educational effectiveness might depend on a deeper understanding of multiple factors. Advancing the metaverse for education, therefore, requires progressively refining the factors under investigation so that virtual environments can become not only engaging but also genuinely supportive of learning.

TO THE INFINITY AND BEYOND. While the previous lesson addresses the role of multidisciplinarity in metaverse research, this lesson highlights its implications for education. Beyond its role as an application domain, this dissertation shows that education also benefits directly from the metaverse engineering perspective. While the previous lessons emphasize the socio-technical nature of the metaverse and the need for multidisciplinary collaboration in research, the educational results reveal an implication in the opposite direction: metaverse engineering can itself serve as a foundation for teaching and curriculum design. This leads to the *fourth lesson learned*: metaverse engineering offers a clear conceptual and methodological structure for developing interdisciplinary educational pathways. By bringing together virtual reality, human–computer interaction, artificial intelligence, ethics, and software engineering within a unified framework, it supports the design of coherent and interconnected courses. Rather than treating these areas as separate subjects, this perspective allows them to be taught as complementary components of

a single socio-technical system. In this sense, the metaverse becomes not only a topic of study or an instructional tool but also a unifying paradigm for preparing students to navigate technical, human, and ethical dimensions in an integrated way.

14.2 FUTURE DIRECTION

The results of this dissertation point to several directions for future work. Further development of metaverse engineering is needed, particularly through clearer engineering approaches and frameworks, dedicated tools, and evaluation criteria that account for socio-technical quality and accessibility from the outset. Important opportunities also arise in the ethical and organisational domain. As AI and blockchain become more integrated into metaverse platforms, research must address transparency, informed consent, data governance, and responsible analytics to ensure trustworthy and sustainable educational ecosystems. Technological advances will continue to shape what is possible. Improved 3D reconstruction methods, scalable decentralised architectures, and privacy-preserving AI can enhance the realism, efficiency, and ethical soundness of metaverse environments. Exploring these technologies in combination may yield more robust and maintainable systems. Finally, the educational effectiveness of immersive environments warrants deeper investigation. The findings show that experiential gains do not automatically translate into learning gains, suggesting the need to better understand factors such as distraction, cognitive load, and instructional design. Comparative studies and adaptive learning strategies may help clarify how immersion can best support meaningful educational outcomes.

LIST OF PUBLICATIONS

The complete list of publications is reported below. The ∗ symbol highlights the publications discussed in this dissertation.

INTERNATIONAL JOURNAL PAPERS

J01 - **D. Di Dario**, F. Palomba, C. Gravino "*Another Brick in the Wall: A Systematic Mapping Study Toward Defining Metaverse Engineering Through Socio-Technical Issues*", *Computing Surveys (CSUR)* ∗

J02 - V. Pentangelo, **D. Di Dario**, S. Lambiase, F. Ferrucci, C. Gravino, F.Palomba. "*SENEM: A Novel Software Engineering-Enabled Educational Metaverse*", *Internation Journal of Information and Software Technology (IST)* ∗

J03 - **D. Di Dario**, V. Pentangelo, B. Scala, S. Lambiase, F. Palomba, C. Gravino "*The Good and the Bad of Teaching Social Debt and Community Smells Using Virtual Reality*", *International Journal of Empirical Software Engineering (EMSE) – Under Review* ∗

J04 - V. Pentangelo, **D. Di Dario**, V. De Martino, M. Dello Buono, S. Lambiase "*Towards AI-Powered Automatic 3D Scene Generation for the Metaverse: A Comparative Analysis of Manual and Photogrammetry Techniques*", *Cluster Computing: The Journal of Networks, Software Tools and Applications, 2025 – Under Review* ∗

INTERNATIONAL CONFERENCE PAPERS

C01 - U. Bilotti, **D. Di Dario**, F. Palomba, C. Gravino, M. Sibilio. "*Machine Learning for Educational Metaverse: How Far Are We?*", *IEEE 41st International Conference on Consumer Electronics (ICCE 2023)* ∗

C02 - **D. Di Dario**, V. Pontillo, S. Lambiase, F. Ferrucci, F. Palomba. "*Security Testing in The Wild: An Interview Study*", *IEEE 49th Euromicro Conference Series on Software Engineering and Advanced Applications (SEAA 2023)*

C03 - **D. Di Dario**, U. Bilotti, M. Sibilio, C. Gravino, F. Palomba. "*Toward a Secure Educational Metaverse: A Tale of Blockchain Design for Educational Environments*", *IEEE 49th Euromicro Conference Series on Software Engineering and Advanced Applications (SEAA 2023)* ∗

C04 - **D. Di Dario**, G. Sellitto, V. Pentangelo, M.L. Fede, F. Ferrucci. "*Breaking Barriers in the Metaverse: A Comprehensive Exploration of Accessibility for Users with Disabilities*", "*International Workshop on Artificial Intelligence with and for Learning Sciences: Past, Present, and Future Horizons (WAILS 2024)* ∗

C05 - **D. Di Dario**, V. Pentangelo, M.I. Colella, F. Palomba, C. Gravino "*Collecting and Implementing Ethical Guidelines for Emotion Recognition in an Educational Metaverse*", *The 32nd ACM Conference on User Modeling, Adaptation and Personalization (UMAP 2024)* ∗

C06 - V. Pentangelo, **D. Di Dario**, V. De Martino, M. Dello Buono, S. Lambiase "*Accelerating 3D Scene Development for the Metaverse: Lessons from Photogrammetry and Manual Modeling*", *The 2nd International Conference on Intelligent Metaverse Technologies & Applications (iMETA2024)* ∗

C07 - G. Annunziata, **D. Di Dario**, V. Pentangelo, G. Catolino "*MetaSERGE — A Serious Game for Risk Management in an Educational Metaverse*", *International Conference on Software Engieering–Software Engineering Education and Training (ICSE-SEET 2026) – Under Review* ∗

C08 - **D. Di Dario**, P. P. Pastore, F. Palomba, C. Gravino "*Better Now: Bridging Theory and Practice in Blockchain-Enabled Educational Metaverse*", "*The 2nd International Workshop on Artificial Intelligence*

with and for Learning Sciences: Past, Present, and Future Horizons (WAILS 2025) ∗

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