Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia

COPPE UFRJ

METASEE: AN APPROACH TO ENABLE THE METAVERSE-BASED SOFTWARE ENGINEERING EDUCATION

Filipe Arantes Fernandes

Tese de Doutorado apresentada ao Programa de Pós-graduação em Engenharia de Sistemas e Computação, COPPE, da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do título de Doutor em Engenharia de Sistemas e Computação.

Orientadora: Cláudia Maria Lima Werner

Rio de Janeiro
Maio de 2023

METASEE: AN APPROACH TO ENABLE THE METAVERSE-BASED SOFTWARE ENGINEERING EDUCATION

Filipe Arantes Fernandes

TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM ENGENHARIA DE SISTEMAS E COMPUTAÇÃO.

Examinada por:

____
Profª. Cláudia Maria Lima Werner, D.Sc.

____
Prof. Toacy Cavalcante de Oliveira, D.Sc.

____
Prof. Geraldo Bonorino Xexéo, D.Sc.

____
Profª. Debora Christina Muchaluat Saade, D.Sc.

____
Profª. Rosa Maria Esteves Moreira da Costa, D.Sc.

RIO DE JANEIRO, RJ – BRASIL
MAIO DE 2023

Arantes Fernandes, Filipe

MetaSEE: An Approach to Enable the Metaverse-based Software Engineering Education/Filipe Arantes Fernandes. – Rio de Janeiro: UFRJ/COPPE, 2023.

XVI, 258 p.: il.; 29, 7cm.

Orientadora: Cláudia Maria Lima Werner

Tese (doutorado) – UFRJ/COPPE/Programa de Engenharia de Sistemas e Computação, 2023.

Referências Bibliográficas: p. 169 – 193.

1. Software Engineering Education. 2. Immersive Learning. 3. Metaverse. I. Lima Werner, Cláudia Maria. II. Universidade Federal do Rio de Janeiro, COPPE, Programa de Engenharia de Sistemas e Computação. III. Título.

"And whatever you do, do it heartily, as for the Lord and not for men." (Colossians 3:23)

Acknowledgements

First of all, I want to thank God. If I got this far, it's because He, and only He, sustained me. Without his grace and mercy, none of this would be possible.

Furthermore, I would like to express my sincere gratitude to all the people who made this thesis possible. I would like to thank my advisor for her constant support and valuable guidance throughout the research process. Her patience, experience and encouragement were essential to the success of this work. I would also like to thank the participants in the experiments who voluntarily helped to corroborate my work.

My thanks also go to my colleagues and friends who have been by my side throughout this period. Their contributions and suggestions were invaluable and helped me to develop not only a clearer view of my work, but also provided moments of relaxation.

I would like to thank my family for all the love and unconditional support they have given me over all these years. Without their encouragement, I would not have made it this far. In particular, to my mother for her teachings, support and for always believing in me. To my wife, for her patience and understanding during the last years of my doctorate.

Once again, I thank everyone who contributed to the success of this project. I hope this work can be useful and contribute to the advancement of knowledge in our field of study.

Resumo da Tese apresentada à COPPE/UFRJ como parte dos requisitos necessários para a obtenção do grau de Doutor em Ciências (D.Sc.)

METASEE: UMA ABORDAGEM PARA PERMITIR A EDUCAÇÃO DE ENGENHARIA DE SOFTWARE BASEADA NO METAVERSO

Filipe Arantes Fernandes

Maio/2023

Orientadora: Cláudia Maria Lima Werner

Programa: Engenharia de Sistemas e Computação

Esta tese apresenta uma abordagem para habilitar a Educação de Engenharia de Software (EES) baseada no Metaverso. A abordagem define um conjunto de mecanismos para apoiar o projeto e desenvolvimento de aplicações de realidade estendida (XR apps), como por exemplo, um *framework* que suporta a definição de principais requisitos de XR apps, uma abordagem baseada em Linha de Produto de Software (LPS) para a instanciação de Web XR apps, bem como um componente reutilizável para a renderização de diagramas de classes UML em 3D. Além disso, um protótipo de plataforma foi implementado a fim de permitir que professores e alunos tenham experências no Metaverso. Para validar a abordagem, quatro experimentos foram conduzidos, cada um com o propósito de observar uma perspectiva específica. O primeiro experimento avaliou o nível de importância das diretrizes do *framework* no contexto da definição de requisitos de XR apps. O segundo experimento avaliou a aderência de um modelo de características em relação aos principais aspectos de Web XR apps. O terceiro experimento avaliou a facilidade de uso e utilidade de um componente reutlizável para a renderização de diagramas de classes UML em 3D. Finalmente, no quarto experimento, foi avaliada a usabilidade da plataforma. No total, 54 participantes (acadêmicos, desenvolvedores, professores e alunos) validaram a abordagem. De modo geral, os resultados dos experimentos demonstram que a abordagem é promissora e possui vantagens no apoio à SEE. Contudo, algumas limitações foram identificadas em cada perspectiva observada. Esta tese contribui para o campo da EES em fornecer percepções e o desenvolvimento de pesquisas futuras para habilitar a EES baseda no Metaverso.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

METASEE: AN APPROACH TO ENABLE THE METAVERSE-BASED SOFTWARE ENGINEERING EDUCATION

Filipe Arantes Fernandes

May/2023

Advisor: Cláudia Maria Lima Werner

Department: Systems Engineering and Computer Science

This thesis presents an approach to enable Metaverse-based Software Engineering Education (SEE). The approach defines a set of mechanisms to support the design and development of eXtended Reality applications (XR apps), such as a framework that supports the definition of main requirements for XR apps, a Software Product Line (SPL)-based approach for instantiating Web XR apps, as well as a reusable component for rendering UML class diagrams in 3D. In addition, a platform prototype was implemented in order to allow teachers and students to experience the Metaverse. In order to validate the approach, four experiments were conducted, each one with the purpose of observing a specific perspective. The first experiment evaluated the level of importance of framework guidelines in the context of defining requirements for XR apps. The second experiment evaluated the adherence of a features model in relation to the main aspects of Web XR apps. The third experiment evaluated the ease of use and usefulness of a reusable component for rendering UML class diagrams in 3D. Finally, in the fourth experiment, the usability of the platform was evaluated. In total, 54 participants (academics, developers, teachers and students) validated the approach. In general, the results of the experiments demonstrate that the approach is promising and has advantages in supporting SEE. However, some limitations were identified in each observed perspective. This thesis contributes to the field of SEE by providing insights and the development of future research to enable the Metaverse-based SEE.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Context

Software Engineering (SE) refers to the application of a systematic, disciplined, and quantifiable approach to developing, operating, and maintaining software (BOEHM, 1976). As a discipline, SE aims to provide effective solutions to complex problems by combining theoretical and practical knowledge (SOMMERVILLE, 2010). Consequently, software engineers are required to apply engineering principles in the design, development, maintenance, testing, and evaluation of large and complex systems, known as hard skills (OZKAYA, 2020).

These skills refer to technical skills and expertise that are required to perform specific tasks or complete certain projects. Specifically in SE, hard skills include knowledge of programming languages, databases, operating systems, software development methodologies, and tools. Developing hard skills is important because they are essential for software engineers to effectively design, develop, and maintain software applications (ROSCA, 2018). On the other hand, software engineers also need to develop personal attributes and interpersonal skills that enable individuals to work effectively with others, known as soft skills. These skills include communication, collaboration, problem-solving, adaptability, leadership, and time management. Developing soft skills is important because they enable software engineers to work effectively in teams, communicate effectively with clients and stakeholders, and adapt to changing project requirements (CHEN *et al.*, 2010b).

Therefore, developing both hard and soft skills is important for the holistic development of software engineers. While hard skills are essential for software development, they are not sufficient on their own. Soft skills are also necessary to ensure that software engineers are able to work collaboratively, communicate effectively, and adapt to changing project requirements (HIDAYATI *et al.*, 2020; MATTURRO *et al.*, 2019). Additionally, both hard and soft skills can lead to career advancement for software engineers. While hard skills may be essential for entry-level positions, soft skills become increasingly important as software engineers move into leadership roles and can help software engineers to progress in their careers and take on new responsibilities (HIDAYATI *et al.*, 2020; MATTURRO *et al.*, 2019).

1.2 Motivation

Technical competencies such as requirements engineering, modelling, programming, and testing, as well as the ability to communicate, to cooperate, to connect pieces of knowledge to discover solutions, and to think critically are skills strongly required by software engineers (OUHBI & POMBO, 2020). In this sense, Software Engineering Education (SEE) community has investigated how to aid software engineers in developing hard and soft skills (FERNANDES & WERNER, 2023; HIDAYATI *et al.*, 2020; MATTURRO *et al.*, 2019; OUHBI & POMBO, 2020).

SEE aims to integrate theoretical knowledge with practical skills in order to provide comprehension of fundamental concepts and principles and to equip learners with the necessary competencies to address authentic challenges (OUHBI & POMBO, 2020). It is not only a matter of academic instruction but also a commitment to cultivating competent professionals who are able to meet industry demands. As the software industry continues to evolve rapidly and expand globally, there are numerous obstacles to overcome in preparing software engineers who can create products that conform to international industrial standards for overseas markets (GAROUSI *et al.*, 2019).

In recent years, SEE has been conducting investigations to improve the quality of teaching by adopting diverse approaches and educational technologies. Traditional SEE methods, such as lectures and laboratory sessions, can provide students with a theoretical understanding of SE concepts (GAROUSI *et al.*, 2019). However, they may not provide students with opportunities to apply their knowledge to real-world problems or to develop soft skills, in addition to not attracting and retaining the attention and interest of the students (GAROUSI *et al.*, 2019; HIDAYATI *et al.*, 2020; ROSCA, 2018).

Therefore, as asserted by ALHAMMAD & MORENO (2018), the primary objectives of these efforts are to develop models for the SE curriculum and enhance the methods and techniques used in SEE. Various attempts have been made to define and modify the SE curriculum to align with the content and skills required for effective SE practice. Notable examples of these endeavors include the undergraduate curriculum standards (ADCOCK *et al.*, 2009; ARDIS *et al.*, 2015) and Software Engineering Competency Model (SWECOM) (SOCIETY, 2014). Additionally, compiling expert opinions on the knowledge to be imparted to SEE students may also be considered (DAVEY & TATNALL, 2008; LETHBRIDGE *et al.*, 2007).

In terms of methods and techniques employed in SEE, one approach involves transforming classroom projects into real-world scenarios by intentionally introducing unexpected complications or involving external organizations (CHEN & CHONG, 2011; DAWSON, 2000). Another technique involves using simulated environments in conjunction with lectures and projects to facilitate the comprehension of complex topics (BAKER *et al.*, 2005). Furthermore, gamification has been implemented as an approach to enhance the appeal of education by incorporating game mechanics and elements (PEDREIRA *et al.*, 2015). Collaborative learning, when combined with any approach, is particularly effective in developing critical thinking skills, deepening the level of comprehension, and fostering a shared understanding of the material (LOES & PASCARELLA, 2017). As highlighted by COCCOLI *et al.* (2011), computer-supported collaboration is crucial in SEE, as teamwork is commonplace in the industry for software engineers.

1.3 Problem and Research Question

One of the foremost challenges in higher education is to engage students (QUAYE *et al.*, 2019), which is considered a critical factor for their success in a course (HANDELSMAN *et al.*, 2005). Engaging students in SE courses poses a particular challenge, as these courses tend to be highly theoretical, with limited opportunities for practical work in the classroom (OUHBI & POMBO, 2020). As a result, many SE researchers have turned their attention to developing approaches that can enhance student engagement based on Immersive Learning (iL) (AKBULUT *et al.*, 2018b; BESSA & SANTOS, 2017b; FERNANDES & WERNER, 2021a; GULEC *et al.*, 2021b).

iL refers to an educational approach that aims to create a highly engaging and interactive learning environment by simulating real-world scenarios or experiences through the use of technology. iL typically involves the use of immersive technologies, such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), or sensory effects to enable learners to interact with digital content in a Virtual World (VW), which allows them to experience a sense of presence and to engage more deeply with the material being taught (DENGEL & MÄGDEFRAU, 2018; FERNANDES *et al.*, 2023). Its main goal is to create a more memorable and impactful learning experience that promotes critical thinking, problem-solving, and knowledge retention.

Most of the approaches that use immersive technologies in SEE are limited mainly to the reconstruction of intrinsically three-dimensional environments, communication between users through avatars, interaction and visualization of software artifacts in the same way as in traditional tools from SEE. One possible explanation for this scenario is the use of platforms for interaction and communication between avatars in the context of SEE. That is, the approaches do not explore the use of immersive devices that allow multimodal interaction through gestures or voice commands, for example, or do not explore the third dimension to enrich the visualization of the various aspects of the software.

SecondLife[1] and Open Wonderland[2] were used by CHEN *et al.* (2010b), WANG & ZHU (2009a) and NG & TANG (2012b) in order to support SEE, but are limited to providing specific features of SEE, such as code editing, test automation, debugger, version control, modeling diagrams, among others. On the other hand, FERNANDES *et al.* (2017), GULEC *et al.* (2021b) and MAYOR & LÓPEZ-FERNÁNDEZ (2021b) explore some specific functionalities for SE in VW. However, it requires technical skills to develop them, such as programming languages, persistent data, modeling 3D objects, using game engines, among others.

Despite efforts to improve the teaching and learning process in SE, SEE has still the main challenge of engaging students and providing adequate technology and tools to SE educators to incorporate it into SE courses (OUHBI & POMBO, 2020). Therefore, based on the challenges presented previously, the main problem investigated in this thesis is:

How to support Software Engineering Education through immersive learning?

1.4 Hypothesis

Basically, iL depends on XR apps, development tools, devices, and frameworks in order to support immersive experiences and enhance improving learning outcomes (FERNANDES & WERNER, 2023). XR app is any VR, AR, and MR application, i.e., applications that provide fully immersive experiences, as well as interaction and visualization of virtual objects that overlap with the real world. XR apps require specific tools to deploy it, as well as devices with compatible multimodal interfaces. Finally, iL frameworks aid researchers in understanding what are the main immersive affordances that can influence in improving learning outcomes, and practitioners designing and developing XR apps.

Since Facebook, now called Meta[3], in October 2021 announced a plan to create the Metaverse, this term has gained notoriety in both academia and industry. After this announcement, the possibility of using Metaverse for business, marketing, games, and education became even more popular (NARIN, 2021).

[1]https://secondlife.com/
[2]http://www.openwonderland.org/
[3]https://about.fb.com/news/2021/10/facebook-company-is-now-meta/

According to FERNANDES & WERNER (2023), the Metaverse is a network of XR apps connected to each other, over the Internet infrastructure, allowing network users, systems, and devices to access them. In other words, the Metaverse is a massively scaled and interoperable network of real-time rendered VWs that can be experienced synchronously and persistently by an effective unlimited number of users with an individual sense of presence, and with continuity of data, such as identity, history, entitlements, objects, communications, and payments (BALL, 2022). Conforming to DIONISIO et al. (2013), one of the main differences between XR apps and the Metaverse is *interoperability*. While XR apps do not have integration with each other, the Metaverse allows connected collection of information, format, and data standards, most of which focus on the transfer of three-dimensional (3D) models across VWs, in addition to involving communication protocol, identity, and currency standards.

1.4.1 Scenario and Research Hypothesis

Our research is based on the assumption that the Metaverse can aid SEE. Therefore, in order to clarify the real Metaverse contribution to SEE, a hypothetical scenario is presented below.

A SE educator at a university has knowledge about the advantages of immersive experiences in education. For this reason, he/she searches for some XR apps that can aid him/her in SE lectures. This educator finds some papers describing VWs specifically for SEE. However, all works are academic prototypes, and are not possible to access them. Unsatisfied with his/her search, this educator tries to create a VW from virtual space platforms, such as Frame VR[4], Mozilla Hubs[5], and Spatial[6]. All these platforms, offer many features, such as communication with text, voice and camera; customizing avatars; uploading of Portable Document Formats (PDFs), 360º figures and videos, 3D objects, changing the environment, among others. However, this educator faces another challenge: it is not possible to customize it for specific SEE features. For example, it is not possible to code, import code repositories, model Unified Modeling Language (UML) diagrams, among others. This educator only provides a VW for students to be able to communicate with each other.

The aforementioned scenario reflects an actual "*picture*" of iL in SEE (FERNANDES & WERNER, 2023), i.e., XR apps for SEE are inaccessible and virtual spaces platforms do not have mechanisms to implement SE features. A Metaverse-based SEE can help solve these challenges by providing SE-specific features, development tools, data interoperability between VWs, and broad coverage of SE topics. For this

[4]https://framevr.io/
[5]https://hubs.mozilla.com/
[6]https://www.spatial.io/

reason, the research hypothesis is:

The Metaverse-based SEE can provide adequate mechanisms to support immersive experiences.

1.5 Goals

Considering the research problem (Section 1.3) and hypothesis (Section 1.4), the main goal of this thesis is:

Develop and evaluate the Metaverse-based SEE approach that provides mechanisms to support the design and development of XR apps for SEE.

This generic goal can be decomposed into the following specific goals:

- Define a framework to help researchers and practitioners to better understand key concepts and guidelines to design XR apps for SEE;
- Identify the main requirements to enable the Metaverse for SEE;
- Develop and implement a Metaverse approach that provides tools based on software reuse techniques to support XR apps development and a platform of interoperable XR apps to support the adoption by SE educators and students;
- Analyze that the proposed approach can support SEE through the Metaverse in order to help the adoption of the Metaverse-based SEE by educators and students.

1.6 Research Method

The research method adopted in this thesis was inspired by the Design Science paradigm (HEVNER *et al.*, 2004), which is an approach to research that focuses on designing, developing, and evaluating innovative solutions to practical problems. It is typically used in fields such as engineering, computer science, and information systems, where new technologies or systems are needed to be developed to solve real-world problems. Overall, the Design Science paradigm is a pragmatic and action-oriented approach to research that is focused on creating practical solutions to real-world problems.

According to that paradigm and inspired by DALPRA (2018); DE FRANÇA COSTA (2019); DOS SANTOS (2016) and NUNES (2014), we conducted six phases in order to answer the proposed research question and check

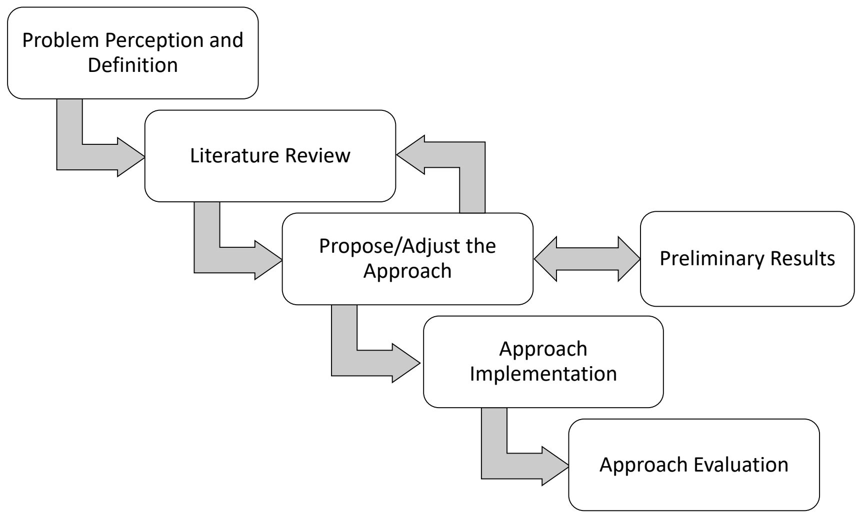


Figure 1.1: Research method

the research hypothesis. Figure 1.1 shows the main steps that were conducted during the research.

In the first phase, *Problem Perception and Definition*, we investigated SEE through iL and started the problem understanding through an ad-hoc literature review. We realized that XR apps developed are single-applications, i.e., there is no interoperability with each other. In addition, most XR apps addressed the software development process, such as Scrum and agile methods, and did not explore the real potential of immersive affordances, such as new ways of software visualization and interaction through multimodal interfaces.

For this reason, in the second phase (*Literature Review*), we performed a Rapid Review (RR) of iL in order to understand what the main affordances should be addressed and guidelines to develop XR app effectively in order to enhance improving learning outcomes in SEE. As a result, we have produced the first version of our framework. We noticed that most frameworks are theoretical and contributions are a cause-effect relationship study between affordances.

As result, in the third phase (*Propose/Adjust the Approach*), we proposed the Immersive Software Engineering Education (iSEE) framework in order to support the design of XR apps for SEE from existing VR spaces. In order to validate it, as well as verify the feasibility of VR spaces for SE, we conducted studies with XR and User Experience (UX) experts (*Preliminary Results*). From the results, we adjusted our approach, as well as we identified the need for further literature reviews.

Therefore, we expanded the scope of the study to a Systematic Literature Review (SLR) in order to get more evidence and we concluded that there are no frameworks to support XR app considering a range of variability involving immersive and learning affordances, mainly for SEE. Additionally, we performed a scoping review of the Metaverse for SEE and identified some literature gaps, such as the coverage of XR apps in SE topics is low; new ways of interacting and visualizing software artifacts are not properly exploited by immersive technologies; there are no mechanisms for collecting data implemented for the purpose of tracking improvement to achieve better performance and obtaining user experience data; and there is no support of tools and technologies for the development of XR apps. As one of the results, we established the fundamental requirements to enable the Metaverse-based SEE.

Considering the findings based on preliminary results, iL frameworks, and Metaverse for SEE reviews, we adjusted and defined the Metaverse-based SEE approach, named MetaSEE, aimed at supporting the engagement of students, decision-making by educators, and provision of mechanisms to facilitate XR apps development. MetaSEE allows students to choose which VW to "enter" or "exit", according to the approach and topic of SE addressed, in addition to ensuring data traceability for future analysis and improvement of teaching experiences. Additionally, developers have access to development and integration tools serving as support in the reuse of features by XR apps, as well as in the development of new applications.

In the fifth phase (*Approach Implementation*), we designed and deployed mechanisms to support the design and development of XR apps, as well as a solution to ensure the interoperability between XR apps for SEE.

Finally, in the sixth phase (*Approach Evaluation*), we planned 4 experiments in order to validate our approach from the point of view of importance, compliance, ease of use, usefulness, and usability. The findings indicated that improvements must be made in the 4 perspectives evaluated by the experiments. However, the approach is promising in order to support SEE.

1.7 Outline

This Ph.D. thesis is organized into 7 chapters. The present chapter provides an overview of the approach and the underlying motivation for the research conducted in this thesis. The identified problem is presented as a gap in the existing body of theory and practice, and the objective of this research is elaborated upon. Additionally, the methodology employed in this study, which has guided our scientific contribution, is explained in detail.

Chapter 2 presents the improvement in the scope of RR in iL framework through a SLR. From a meticulous selection of 15 relevant articles, a comprehensive overview of the contributions in the field was obtained, while simultaneously identifying gaps and research opportunities. The significance of this study lies in its contribution to the scholarly discourse on the concept of immersion and a better understanding of iL. Furthermore, the findings and discussions presented in this systematic literature review provide valuable insights that support our research approach.

Chapter 3 we performed a scoping review and the main contributions are: firstly, characterizing the current state-of-the-art of the Metaverse for SEE; and secondly, proposing a set of components that facilitates the classification of the Metaverse into five distinct layers. Additionally, the findings and discussions presented in this study contribute significant insights that provide robust support for our research approach.

Chapter 4 describes two cases conducted in order to validate iSEE framework and verify the feasibility of existing VR spaces, as well as provide insights to adjust our approach.

Chapter 5 presents our analysis based on findings and feedback of the Chapters 2, 3, and 4. As a result, we established a set of fundamental requirements in order to define our approach.

Chapter 6 presents the Metaverse-based SEE (MetaSEE) approach, which aims to support design and development, ensuring interoperability between XR apps for SEE. MetaSEE defines a conceptual framework to support the design of XR apps for SEE from technological and pedagogical affordances, main concepts and technologies to enable the Metaverse for SEE grouped in layers, mechanisms to aid the development and integration of XR apps for SEE, and a Metaverse for SEE architecture. In addition, the approach implementation is also presented in this chapter.

Chapter 7 describes the planning, execution, and results of 4 experiments carried out in order to verify the feasibility of the MetaSEE approach.

Chapter 8 concludes this document. We present a comprehensive examination of concluding reflections, elucidate the notable contributions made by this thesis, and discuss the inherent limitations of the research conducted. Finally, we posit potential avenues for future investigations in this field of study.

Chapter 2

Systematic Literature Review of Immersive Learning Frameworks

2.1 Introduction

Immersive technologies refer to computer systems (hardware and software) that enable a more intuitive human-computer interface through devices and sensors that interact with up to the 5 human senses. The main devices are Head-mouted Display (HMD), also known as XR headset, and interaction devices (e.g. data gloves, hand tracking, body motion capture system, etc.). In addition to hardware, Virtual Environment (VE), also known as a virtual world, it is a three-dimensional computer-generated space where users interact with each other (through avatars) or with other virtual objects (BIOCCA & LEVY, 2013). From the point of view of involving real and virtual world elements, MILGRAM *et al.* (1995) classify applications into VR, AR, Augmented Virtuality (AV) and MR. XR is an umbrella term that encompasses the entire spectrum of Milgram's continuum (LEE *et al.*, 2021c).

Immersive technologies for education have been used for several years, mainly because virtual environments give the user the feeling of being present in the context that is presented, in addition to allowing the virtual manipulation of objects (FIALHO & CATAPAN, 1999). In situations where being physically present would be too expensive, dangerous or impossible, immersive experiences bring many advantages, for example in the training of surgical skills, pilots and astronauts (FIALHO & CATAPAN, 1999). Furthermore, immersive experiences have greater engagement and allow greater interactivity of the student with the instructional material, encourage the collaborative construction of knowledge, present more contextualized tasks, less abstract instructions and favor reflective practice (LEE & WONG, 2014). To the specific use of immersive technologies to improve learning outcomes, the term iL is known to define this research scope.

Although virtual environments have already evolved a lot, there are still many research challenges involving immersive technologies in education (GHINEA *et al.*, 2014; PELLAS *et al.*, 2020). In addition to the complexity of generating computational solutions for the specifics of educational demands, generally developed by researchers in the field of computing, there are challenges regarding pedagogical and psychological aspects, as well as user experience, storytelling, simulator sickness and others. In parallel, devices have evolved rapidly, allowing the use of virtual environments both in traditional devices (desktop and mobile) and in immersive devices. Despite the range of devices, developing for the various platforms is also challenging in order to ensure effective platform-independent performance. These and other main challenges for the adoption of immersive technologies in education are grouped into 6 categories, according to the State of XR Report (LEE *et al.*, 2021c): access, affordability, inadequate XR teacher training programs, interoperability, lack of content and lack of infrastructure and tech support.

In order to solve the challenges mentioned above and to contribute to the evolution of research related to immersive technologies in education, iL Frameworks have been a strategy that researchers have found to define a basic conceptual framework to gather concepts and design a comprehensive understanding of a given phenomenon in the context of iL (REGONIEL, 2015). Therefore, considering the challenges of immersive technologies in education and frameworks as solutions to these problems, this systematic literature review aims to provide evidence on the state of the art of iL Frameworks. More precisely, we are interested in understanding what the purposes are, the elements that compose them and how the frameworks contribute to the solution of the main challenges, according to the State of XR Report (LEE *et al.*, 2021c), in addition to identifying gaps and opportunities for future research.

This chapter is organized as follows: Section 2.2 presents some previous secondary studies on Immersive Learning. Section 2.3 describes the research method and the article selection process. Section 2.4 presents the answers to the research questions. Section 2.5 discusses the relevant findings, as well as a research roadmap and, finally, conclusions and future work are presented in Section 2.6.

2.2 Related Work

In this section, we describe the process of selection of studies through a simplified review protocol in order to search for related works. In January 2021, we ran the following search string, adapted from the tertiary study of KITCHENHAM *et al.* (2009): *(TITLE-ABS-KEY("immersive learning" OR "immersive education") AND TITLE-ABS-KEY("review of studies" OR "structured review" OR "systematic review" OR "literature review" OR "literature analysis" OR "in-depth survey" OR* *"literature survey" OR "meta-analysis" OR "past studies" OR "subject matter expert" OR "analysis of research" OR "empirical body of knowledge" OR "overview of existing research" OR "body of published research")) AND (EXCLUDE(DOCTYPE,"cr")).* Only the Scopus search engine was used, as it indexes a variety of digital libraries. Furthermore, it is not our focus to rigorously perform the selection of other secondary studies related to this one. As a result of the search, 16 documents were returned, 7 of which were secondary studies in iL, which will be described in the following.

SNELSON & HSU (2020) and WU *et al.* (2020) investigated learning performance through immersive technologies. More specifically, WU *et al.* (2020) compared the effects of immersive VR with non-immersive VR. As a result, the 35 studies analyzed indicated that immersive VR is more effective than non-immersive VR. In addition, they also identified that immersive VR has a great impact on K-12 learners; Science, Technology, Engineering and Mathematics (STEM) and in the development of specific skills and in the simulation of real situations. On the other hand, SNELSON & HSU (2020) focuses on applications that use low-cost equipment through 360º videos. The authors investigated how 360º videos are used and what are their advantages and disadvantages in education.

HUANG *et al.* (2021) performed a systematic review in order to find primary studies that report the use of Augmented and Virtual Reality (AVR) for language teaching. Authors found 88 articles published in 2011 and 2020, which were analyzed from the following perspectives: tools used, student profile, main findings, reason why virtual learning environment are used and their implications. The study mainly concludes that AVR raises the level of learning; university students are the main users of immersive technologies and the benefits found are improved learning outcomes and increased motivation.

NTABA & JANTJIES (2021) focus on how immersive technologies can support distance learning. More precisely, they investigated what the challenges are and how AVR is used to support distance learning.

QIAO *et al.* (2021) and REY-BECERRA *et al.* (2021) focus on training. QIAO *et al.* (2021) investigated the effectiveness of immersive virtual reality simulation in interprofessional education. Among the 12 primary studies selected, it was concluded that immersive technologies value the approach of shared and team learning. REY-BECERRA *et al.* (2021) synthesized outcome criteria to measure the effectiveness of work at heights training with VR in various contexts. From the 21 documents analyzed, the results support safety managers and practitioners, providing a catalog of training methods, effects and assessment indicators.

Finally, MORGADO & BECK (2020) performed a review of secondary studies and produced a literature review protocol specifically for the scope of iL.

In general, the works above sought evidence of improvement in learning outcomes after intervention with immersive technologies. Each study focused on a context, application domain and immersive technology type. Our study differs from the others, as we are interested in obtaining the state of the art of frameworks that support the advancement of iL research, being cause and effect models of variables that influence learning, as well as guidelines to support the practice of developing immersive educational environments and recommendations for use by educators and students. Therefore, we consider the absence of a systematic review on iL frameworks as a gap in the literature that must be filled.

2.3 Research Method

The research method of this secondary study follows three main phases of a systematic literature review proposed by KITCHENHAM & CHARTERS (2007). The first phase is associated with planning the review, in which the protocol is developed and evaluated. Once the protocol is defined and validated by the researchers involved, it begins the phase of conducting the review, in which the objective is to select the primary studies, extract and perform the data synthesis. Finally, the last phase defines the mechanisms for the dissemination of the results found with the study. The review process is detailed below.

2.3.1 Research Questions

In this study, the following main research question was defined: *what is the state of the art of iL frameworks?* A framework is understood as a supporting structure that aims to guide the achievement of iL objectives. In order to answer this main question, secondary research questions were defined:

- RQ1: What definitions of iL were adopted in primary studies?
- RQ2: What are the types of frameworks and how do they support iL?
- RQ3: What are the elements that compose the frameworks?
- RQ4: What are the methods used to validate the frameworks?

The purpose of RQ1 is to identify the meaning of iL used by the authors, since its definition is not consolidated by the technical literature. RQ2 aims to understand how frameworks support the use of XR in teaching and learning, for example, frameworks support the development of immersive applications or the use of virtual environments, such as Second Life[1]. One of the main contributions of this review is

[1]https://secondlife.com/

related to RQ3. Immersion, sense of presence and flow, among others, are common terms in this area, but they have ambiguous definitions. For example, SLATER (2003) states that immersion is related to the characteristics of immersive devices, while JENNETT *et al.* (2008) define that it is associated with cognitive issues. In this way, this research question aims to identify the main elements that compose each framework, as well as the meaning of the concepts and theoretical background that contributed to the design of the frameworks. Finally, RQ4 has identified the purpose of understanding how the frameworks were assessed.

2.3.2 Search Process

It was established as a search process the construction of a search string that automatically returns articles in the Scopus, IEEE Xplore, ACM Digital Library, Science Direct and Web of Science databases. In order to support the definition of the search string, a set of terms was established following the PIO paradigm (KITCHENHAM & CHARTERS, 2007):

- *Population*: immersive education, immersive learning, immersive teaching, immersive training;
- *Intervention*: augmented reality, mixed reality, virtual reality, extended reality;
- *Outcome*: framework, design, guideline, model.

The "OR" boolean operator was used to join the related terms and the "AND" boolean operator to join the terms of population, intervention and outcome. In addition, "NOT" boolean operator was used as a filter strategy to avoid articles on artificial intelligence without the context of human learning (RADIANTI *et al.*, 2020). In this way, the search string is defined as: *("immersive education" OR "immersive learning" OR "immersive teaching" OR "immersive training") AND ("augmented reality" OR "AR" OR "mixed reality" OR "MR" OR "virtual reality" OR "VR" OR "extended reality" OR "XR") AND (framework OR design OR guideline OR model) AND NOT ("artificial intelligence" OR "deep learning" OR "machine learning" OR "neural network").*

The search string has been validated in the Scopus database to be able to return the following control articles: DENGEL & MÄGDEFRAU (2020); GUPTA *et al.* (2019); IP *et al.* (2018); KLIPPEL *et al.* (2020); and SCHOTT & MARSHALL (2018).

These control articles were defined by four reviewers: one professor and researcher with large experience in experimental software engineering; two postdoctoral researchers; and one doctoral student. All reviewers are interested in immersive technologies in software engineering education. After this validation, the search for the articles started.

2.3.3 Selection Criteria and Procedure

This section describes the conduction of the review phase. In November 2021, the search string was executed in the title, abstract and keywords metadata for each database. We do not limit the publication date, as we intend to obtain the maximum number of studies from the technical literature. In the end, 1721 results were obtained: ACM (127), IEEE Xplore (841), Science Direct (163), Scopus (277) and Web of Science (313). In order to start the selection procedure, the following exclusion criteria were applied by reviewers while reading title, abstract and keywords:

- EC1: Duplicate article;
- EC2: Article not being a primary study;
- EC3: Article being a work in progress or short paper;
- EC4: Article not published in journal, conference or book chapter;
- EC5: Authors having a most recent article;
- EC6: Article not reporting as main contribution generic method or approach that supports the development or selection of immersive educational applications.

After applying these criteria, 28 studies were eligible for full text reading and the following inclusion criteria were applied:

- IC1: Article being accessible for download;
- IC2: Full text article written in the English language;
- IC3: Article answers at least one research question from the review.

As a result, 12 articles were selected. During the reading of each article, three steps were performed at the same time: data extraction; quality assessment and snowballing. For each article, the one-level backward snowballing technique WOHLIN (2014) was carried out in order to identify other studies potentially relevant for this secondary study through bibliography references. The first two steps were applied for each article selected by the snowballing. At the end, 3 studies were added to this review.

After the inclusion criteria and snowballing, 15 articles (see Table 2.1) were selected to compose the final set of articles for this secondary study. Figure 2.1

shows all the steps taken to find the final set of articles. The organization of the steps was inspired by the PRISMA method (MOHER *et al.*, 2009).

Primary Studies
DENGEL & MÄGDEFRAU (2020)
GUPTA *et al.* (2019)
IP *et al.* (2018)
KLIPPEL *et al.* (2020)
SCHOTT & MARSHALL (2018)
ABDELAZIZ (2014)
AGUAYO *et al.* (2020)
CARDONA-REYES *et al.* (2019)
CHAN *et al.* (2019)
DALGARNO & LEE (2010)
FOWLER (2015)
DE FREITAS *et al.* (2010)
KOUTROMANOS & MIKROPOULOS (2021)
LEE *et al.* (2010)
MISBHAUDDIN (2018)

Table 2.1: Final set of selected primary studies

An electronic spreadsheet was used to support the data extraction process as well as the quality assessment. The quality of selected articles was evaluated according to the questions:

- QA1: How clear was the framework's purpose?
- QA2: How well was the way of using the framework described?
- QA3: How well were the framework elements described?
- QA4: How well was the framework validation performed?

All researchers reviewed each article's score, according to the following scale (one value per question): 0 - poorly; 0.5 - reasonably; 1 - well. Considering this score, 2 studies reached 4 points, 3 studies reached 3.5 points, 3 studies reached 3 points, 2 studies reached 2.5 points, 3 studies reached 2 points and 2 studies reached 1 point. Regarding quality questions, QA1 was attended by 84% of studies, QA2 by 47% of studies, QA3 by 75% of studies, and QA4 by 63% of studies. Despite the low score, we decided to maintain the studies because we have identified several gaps that can produce interesting discussions and insights for future research, mainly from the perspective of using and validating the frameworks.

Briefly, Table 2.2 shows the number of studies selected through the sources, studies excluded according to the inclusion and exclusion criteria and, finally, the studies selected for data extraction. As a consequence of the objective of getting the most out of iL frameworks and defining the state of the art, 1724 studies were selected and only 15 were included for analysis. We understand that this result is due to the

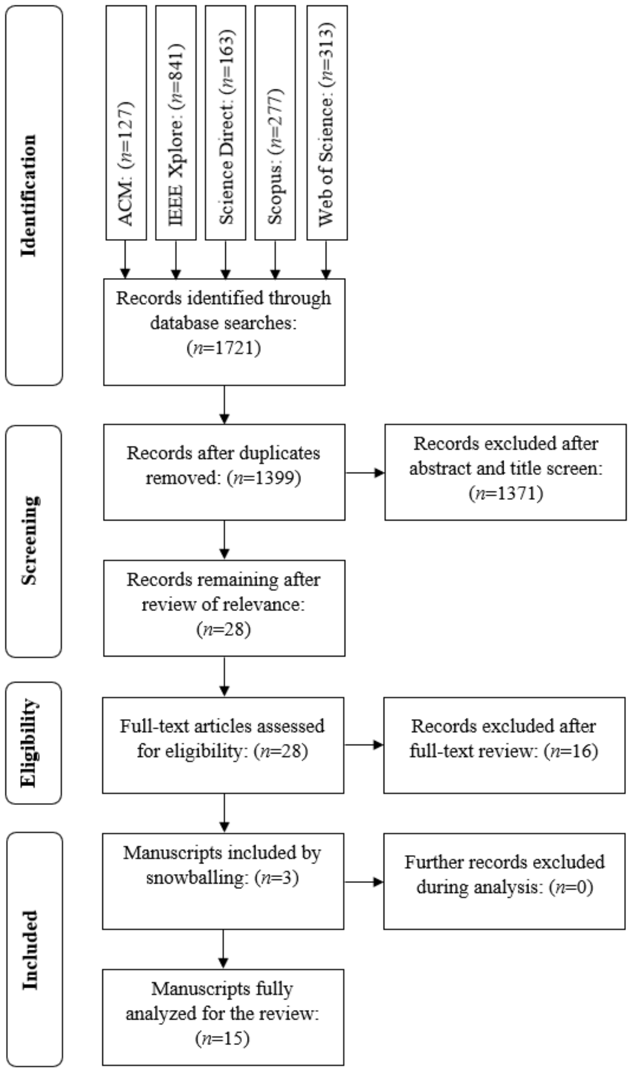


Figure 2.1: Overview of the filtering process

inclusion and exclusion criteria, as well as the important terms that make up the search string. For example, many works have been recovered for applying immersive technologies in teaching, but they were just virtual worlds and not approaches or models to support iL. One of the possible reasons is that "framework" is a dubious term. It can refer to both an approach and a reusable programming tool.

2.3.4 Threats to Validity

Despite the contribution of this study, we identified some threats to validity. The analysis is based on the 15 selected articles. For a secondary study, this number of articles can compromise the results. iL is a recent area of research and this fact may explain the amount of studies. Another factor that should also be considered is the use of the term "immersive learning" and its variations in the search string. A search with related terms, such as virtual learning worlds, iL experiences, and others, could lead to a large volume of articles that would be out of scope. One of the main

Table 2.2: Studies Selected and Included

Source	#papers selected	#papers excluded	#final papers
ACM	127	127	0
IEEE Xplore	841	837	4
Science Direct	163	163	0
Scopus	277	270	7
Web of Science	313	312	1
Snowballing	3	0	3
Total	1724	1709	15

reasons for keeping the focus of our study was to obtain works that respond at least to RQ1. Furthermore, the research method was based on systematic literature review guidelines (KITCHENHAM & CHARTERS, 2007) to ensure the quality of this study.

Out of 15 articles, 4 did not validate the approach and this factor can be considered a threat to validity. These articles were kept with the aim of obtaining the maximum amount of studies and achieving a more assertive overview of the area. Furthermore, even though they did not meet some defined quality criteria, they are studies published in journals and conferences and reviewed by the scientific community peers.

2.4 Results

The previous section we presented how the 15 primary studies were selected, that is, what sources were used, search string defined, inclusion and exclusion criteria and other details of the selection process. In this section, we will answer each research question based on the data extracted from the primary studies.

2.4.1 What definitions of iL were adopted in primary studies (RQ1)?

From 15 selected studies, 5 defined iL with two points of view. Firstly, the following authors believe that iL is related to, mainly, pedagogical and subjective aspects. In the case of DENGEL & MÄGDEFRAU (2020), the authors did not define it directly, but we understand that iL is the achievement of learning outcomes through educational virtual environments. Therefore, the authors established variables (immersion, presence and learning potential) influence the learning outcomes. In the study ABDELAZIZ (2014), the authors believe that the iL concept supports self-regulated, self-determined, self-controlled, informal and life-long learning through a cognitive engagement network that starts with the student and goes through the pro-action engagement, acting engagement, reflection engagement, and reaction phases.

On the other hand, iL is defined considering technological aspects (CARDONA-REYES *et al.*, 2019; KLIPPEL *et al.*, 2020). iL is immersive experiences for place-based education (KLIPPEL *et al.*, 2020). In other words, it is to support the learning through immersive virtual field trips. According to CARDONA-REYES *et al.* (2019), the users must achieve their learning objectives through a transfer of iL based on virtual reality to the real world with real situations through hands-on activities, interacting with objects and events in the simulated world.

A definition that is between the two points of view above is used by IP *et al.* (2018): iL is to use technologies, especially computer graphics and human-computer interaction technologies, to create simulated virtual worlds, in which learning can take place by employing appropriate instructional and pedagogical approaches. The authors consider technological and pedagogical aspects.

We believe that understanding the definition of iL is very important for the advancement of future research. Through the findings, we realized that there is no consensus about what is iL. Clearly there is a separation between pedagogical and technological aspects. Although in DENGEL & MÄGDEFRAU (2020) the educational virtual environments are considered, the authors highlight that immersion, presence and learning potential are main variables to achieve iL. Moreover, ABDELAZIZ (2014) focused on an approach based on the constructivist model. Only IP *et al.* (2018) highlighted the importance of pedagogical and technological aspects.

In addition to the definition given by the authors, we identified two papers (DENGEL & MÄGDEFRAU, 2020; KOUTROMANOS & MIKROPOULOS, 2021) published in ILRN (2022). This conference aims to connect researchers, educators and developers in order to discuss how XR can provide various opportunities for education. Thus, we also consider iL as a recent research area.

Therefore, in our point of view, iL could be defined as a research area that investigates how to improve the learning outcomes through the relationship between the triad immersive technologies, psychological and pedagogical aspects. Considering the main elements extracted from each framework (see Section **??**), these three aspects were confirmed.

2.4.2 What are the types of frameworks and how do they support iL (RQ2)?

In general, from the point of view of the objective, the works were categorized into theoretical and practical. Theoretical frameworks are models that establish the relationship between factors that influence learning outcomes or the adoption of immersive technologies, as well as elements that support the design of learning activities in immersive educational environments. On the other hand, we consider work that establishes guidelines or development models that support the production of immersive educational environments as practical frameworks.

In addition to this broad categorization between theoretical and practical framework, we created subcategories to establish a better understanding regarding the contribution of each work. Table 2.3 shows the classification of theoretical frameworks and Table 2.4 of practical frameworks.

About theoretical frameworks, the works ABDELAZIZ (2014); DE FREITAS *et al.* (2010) were classified as *design of learning activities*. More specifically, ABDELAZIZ (2014) aims to be immersive Web-based learning model for supporting learning through phases that virtual worlds should provide to students to achieve learning, while DE FREITAS *et al.* (2010) aims to be an evaluation methodology for designing learning activities in virtual worlds as well as evaluating learning experiences.

Factors that influence learning outcomes category classifies works that define elements that are related to and influence learning outcomes. In general, the works model a causal relationship of the main elements that each author considers important in iL to explain the influence of learning outcomes through immersive educational environments. These elements for some authors are denominated affordances (CHAN *et al.*, 2019; DALGARNO & LEE, 2010; FOWLER, 2015; SCHOTT & MARSHALL, 2018), objective and subjective factors (DENGEL & MÄGDEFRAU, 2020) and variables (KLIPPEL *et al.*, 2020; LEE *et al.*, 2010).

In the *factors that influences teachers' intention* category the model proposed by KOUTROMANOS & MIKROPOULOS (2021) determines the teachers' intention to use Augmented Reality applications. This work, based on Technology Acceptance Model (TAM) (DAVIS, 1989), helps to understand what are the main characteristics that applications must have to comply with educational purposes, from the teacher's point of view.

Regarding practical frameworks, AGUAYO *et al.* (2020) and MISBHAUDDIN (2018) define a set of *guidelines* and design principles for immersive environment development for educational purposes. Specifically, AGUAYO *et al.* (2020) considers design principles and processes that can enhance learning outcomes within free-choice settings, such as museums and visitor centres and (MISBHAUDDIN, 2018) developed a general framework that transports all elements of the classroom (from instructor's point-of-view) to the immersive virtual environment.

Lastly, in the *development model* category, the works that minimally define a development process to be followed (steps), the actors involved (students, instructors and developers), the types of immersive technologies, as well as software design tools are included (CARDONA-REYES *et al.*, 2019; GUPTA *et al.*, 2019; IP *et al.*, 2018).

Table 2.3: Classification of Theoretical Frameworks

Subcategories	Primary Studies
Design of learning activities	DE FREITAS *et al.* (2010) and ABDELAZIZ (2014)
Factors that influence learning outcomes	CHAN *et al.* (2019); DALGARNO & LEE (2010); DENGEL & MÄGDEFRAU (2020); FOWLER (2015); KLIPPEL *et al.* (2020); LEE *et al.* (2010); and SCHOTT & MARSHALL (2018)
Factors that influence teachers' intention	KOUTROMANOS & MIKROPOULOS (2021)

Table 2.4: Classification of Practical Frameworks

Subcategories	Primay Studies
Guideline	MISBHAUDDIN (2018) and AGUAYO *et al.* (2020)
Development model	CARDONA-REYES *et al.* (2019); IP *et al.* (2018); and GUPTA *et al.* (2019)

2.4.3 What are the elements that compose the frameworks (RQ3)?

During data extraction, the elements of each framework were categorized in order to group similar aspects among them and, mainly, to assist in data analysis. This categorization emerged during the reading of the works, considering the reviewers' experience in the areas of immersive technology and education. When it comes to immersive technology, two fundamental aspects must be considered while developing an application: technological (devices, infrastructure, platform etc.) and psychological (the feeling of being present in the virtual world, emotions, awareness etc.). In education, the main aspect considered in this work context was the pedagogical. Therefore, the frameworks elements were grouped into technological (e.g., mobile learning, virtual space, platform, instructional media), psychological (e.g., sense of immersion, construction of identity, motivation) and pedagogical (e.g., learning context, learning outcomes, learning potential, context) aspects, in addition to their combination. All tabulated data considered in this analysis can be accessed at the electronic address http://reuse.cos.ufrj.br/static/ilframeworks/index.htm. Figure 2.2 presents an overview of the result of categorizing the frameworks elements.

Through this analysis, in most of the works, the concepts of immersion and sense of presence were approached, but with divergent views. Some of them consider immersion as a technological property and others as a mental state of belonging to the virtual world. In addition, some authors claim that immersion and a sense of presence can be considered as a psychological aspect, that is, a feeling of belonging

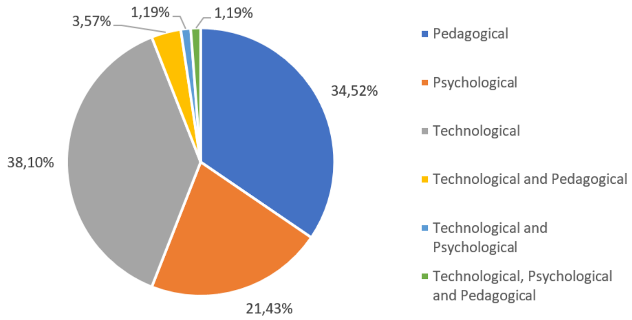


Figure 2.2: Overview of the framework elements

to the virtual world. These and other findings will be discussed in detail in Section 2.5.1.

2.4.4 What are the methods used to validate the frameworks (RQ4)?

Finally, the last research question aims to understand how the frameworks were validated. Out of 15 works, 4 did not validate the proposal. Table 2.5 presents a list of the works and the type of validation.

Table 2.5: Frameworks Validation

Categories	Primay Studies
Action research	KLIPPEL *et al.* (2020) and AGUAYO *et al.* (2020)]
Post-test	ABDELAZIZ (2014)]
Pre- and post-test	CARDONA-REYES *et al.* (2019); CHAN *et al.* (2019); DENGEL & MÄGDEFRAU (2020); KOUTROMANOS & MIKROPOULOS (2021); LEE *et al.* (2010); SCHOTT & MARSHALL (2018)
Pre- and post-test and observation of student performance	DE FREITAS *et al.* (2010) and IP *et al.* (2018)

Most studies adopted the validation strategy through *pre- and post-tests*. Participants answer a questionnaire (pre-test) to record their knowledge before the intervention, as well as obtain demographic data. Afterwards, the participants perform some tasks and, at the end, answer another questionnaire (post-test). Some works chose to add *observation of students performance* to the pre- and post-test. DE FREITAS *et al.* (2010) used video observations of the real world and the in-world sessions as well as recordings and chat logs, and IP *et al.* (2018) lexical analysis of the learners' comments.

The works KLIPPEL *et al.* (2020) and AGUAYO *et al.* (2020) used the strategy that can be classified as *action research*. Specifically, KLIPPEL *et al.* (2020) carried out a set of evaluations and the results were used to evolve their proposal, and

AGUAYO *et al.* (2020) defined their guidelines based on feedback during the development of immersive applications. Finally, ABDELAZIZ (2014) selected a group of students and divided them into a control group and an experimental group. Each group was selected according to the already known profile and, at the end of the task a *post-test* questionnaire was used.

2.5 Discussion

In this section, we discuss the main findings, how frameworks solve the main barriers to adoption, and also propose some issues to include in the research roadmap on iL frameworks.

2.5.1 What is immersion and presence?

Immersion and presence are concepts found in frameworks and their definitions are antagonistic, that is, some authors have divergent understandings about these concepts.

For example, CARDONA-REYES *et al.* (2019); DALGARNO & LEE (2010); DENGEL & MÄGDEFRAU (2020); KLIPPEL *et al.* (2020) and LEE *et al.* (2010), understand that immersion corresponds to the properties and capabilities of technology to stimulate the human sensory system. All these works were based on Slater's works (SLATER, 1999, 2003; SLATER & WILBUR, 1997). From this point of view, immersion is a quantifiable description of the technology, that is, one must consider the quality of the graphic display, stereo audio, haptic sensor, motion sensor, among other characteristics of the device. By focusing in detail on this idea of immersion, the authors are concerned with establishing which technological capabilities the devices provide in order that experiences can match expectations of interaction with the virtual environment.

The works SCHOTT & MARSHALL (2018) and CHAN *et al.* (2019) understand that immersion can be defined as a mental state in which the user is surrounded by another reality demanding his/her attention. This definition of immersion is similar to the concept of presence, also called by some authors as a sense of presence. All works that define the concept of presence are unanimous in stating that it is a user's mental state of belonging to the virtual environment in which they are interacting. For FOWLER (2015), immersion goes beyond technological and psychological points of view. In this framework, the learning experience is also considered, called pedagogical immersion, in which it is the pedagogical state that arises from learning in a virtual environment.

The above works explicitly defined the understanding of immersion and presence according to the application context. Table 2.6 presents the definitions of each framework, as well as the reference used for each concept, that is, we present the references adopted by primary studies for the concepts of immersion and presence. Some primary studies have their own definition, such as (CHAN *et al.*, 2019; FOWLER, 2015; LEE *et al.*, 2010). Although some works have not explicitly defined immersion and presence, the meaning of these concepts can be understood throughout the reading of the full text, as in the case of ABDELAZIZ (2014); IP *et al.* (2018) and DE FREITAS *et al.* (2010), in which the understanding is that immersion is a mental state, contrary to AGUAYO *et al.* (2020); GUPTA *et al.* (2019) and MISBHAUDDIN (2018), which understand immersion as a technological aspect. Exceptionally, KOUTROMANOS & MIKROPOULOS (2021) does not address these concepts.

Through the discussions above, it can be seen that the concept of presence is well defined, while immersion has several understandings. In order to understand the relationship between the definitions of the concepts with the objective of each framework, Table 2.7 presents the mapping between the framework categories, as well as the subcategories, with the types of immersion. Most of the works that consider psychological immersion are theoretical frameworks and the works that consider technological immersion are equally grouped between theoretical and practical frameworks. In particular, all theoretical frameworks that consider technological immersion are concentrated in the *influences learning outcomes* category. Only FOWLER (2015) defined immersion as a set of technological, psychological and pedagogical aspects.

Through the above analysis, we observe that the concept of immersion will vary according to the purpose of each framework. For example, the models of DALGARNO & LEE (2010); DENGEL & MÄGDEFRAU (2020); KLIPPEL *et al.* (2020); and LEE *et al.* (2010) establish which variables influence learning outcomes in virtual environments. In order to isolate the characteristics of the devices with their ability to "immerse" the user in the virtual environment, the term immersion was defined as a technological aspect and presence as a psychological aspect of belonging to the virtual environment. From this point of view, an immersive device is not a guarantee to provide the user with a complete sense of presence, because it depends on other factors, such as the proper functioning of the interaction between the user and the virtual environment, motion sickness, fidelity in the graphical representation, interference from the environment external, among others. The works ABDELAZIZ (2014); CHAN *et al.* (2019); DE FREITAS *et al.* (2010); IP *et al.* (2018); and SCHOTT & MARSHALL (2018) prioritize other variables and consider immersion as a psychological state of belonging to the virtual environment (psychological immersion).

Table 2.6: Immersion and Presence Concepts

Concepts	Primary studies	Definitions	References
Immersion	DENGEL & MÄGDEFRAU (2020)	Quantifiable description of technology	SLATER (2003)
	KLIPPEL *et al.* (2020)	It refers to system characteristics	SLATER (1999)
	SCHOTT & MARSHALL (2018)	A state where the user (the learner in this context) is surrounded with another reality claiming their complete attention	MURRAY (1997)
	CARDONA-REYES *et al.* (2019)	Immersion technology aspects are considered to offer the user the feeling of presence in an artificial environment as if he/she were in a daily learning situation	LAVALLE (2020)
	CHAN *et al.* (2019)	The mental state of total absorption in the virtual environment enabled by, in addition to a high degree of real-time interaction, the rich information perceived through multiple sensory channels	BURDEA & COIFFET (2003)
	DALGARNO & LEE (2010)	Immersion relies on the technical capabilities of VR technology to render sensory stimuli	SLATER (1999, 2003, 2004)
	FOWLER (2015)	A concept that can bridge both the technological, psychological and pedagogical experiences	own definition
	LEE *et al.* (2010)	Techonological properties	own definition
Presence	DENGEL & MÄGDEFRAU (2020)	Perception of non-mediation	LOMBARD & DITTON (1997)
	KLIPPEL *et al.* (2020)	Mental state	SLATER & WILBUR (1997)
	SCHOTT & MARSHALL (2018)	The subjective experience of being in one place or environment, even when one is physically situated in another	WITMER & SINGER (1998b)
	CHAN *et al.* (2019)	Equal to immersion	own definition
	DALGARNO & LEE (2010)	Presence or sense of presense is context dependent and draws on the individual's subjective psychological response to VR	SLATER (1999, 2003, 2004)
	FOWLER (2015)	It is the psychological state that can arise from an immersive system	own definition
	LEE *et al.* (2010)	It is the psychological sense of "being there" in the environment generated by the system	own definition
		Presence is a human reaction to immersion	SLATER (2003)
		Presence refers to the user's subjective psychological response to a system	BOWMAN & MCMAHAN (2007)
		The sense of presence in a 3-D environment occurs as a consequence of the fidelity of representation and the high degree of interaction or user control, rather than just a unique attribute of the environment	DALGARNO *et al.* (2002)

Table 2.7: Immersion Mapping

Category	Subcategory	Psychological Immersion	Technological Immersion	Technological psychological and pedagogical Immersion
Practical Framework	Guideline		AGUAYO *et al.* (2020) and MISBHAUDDIN (2018)	
	Model Development	IP *et al.* (2018)	GUPTA *et al.* (2019), CARDONA-REYES *et al.* (2019)	
Theoretical Framework	Design of Learning Activities	ABDELAZIZ (2014) and DE FREITAS *et al.* (2010)		
	Influences Learning Outcomes	CHAN *et al.* (2019)	DENGEL & MÄGDEFRAU (2020), DALGARNO & LEE (2010); KLIPPEL *et al.* (2020) and LEE *et al.* (2010)	FOWLER (2015)
	Influences Teacher's Intention	SCHOTT & MARSHALL (2018)		

In our view, immersion should be considered as a technological aspect and presence as a psychological aspect of belonging to the virtual environment. In this way, we believe to facilitate the understanding of these trivial concepts and support the identification of the potential of devices and virtual environments to "immerse" the user and transmit a sense of presence. Therefore, the greater the involvement of the human senses together with the human-computer interaction intuitive, the greater the degree of immersion and potentially the user will achieve the sense of presence. For example, Oculus Quest 2 has the greatest potential to provide presence compared to Google Cardboard, meaning the former is more immersive than the latter, however the reach of the sense of presence depends on several factors throughout the immersive experience.

Therefore, we conclude that immersion must be considered as an objective aspect that characterizes the technological capacity to evoke the user's feeling of presence in a virtual environment and presence a subjective aspect in which the user believes "being there" in the virtual environment that he/she is interacting with.

2.5.2 Finding Solutions to Barriers to Adoption

As presented in Section 2.1, one of the objectives of this work is to verify how the frameworks solve the main challenges pointed out in the State of XR Report

(LEE *et al.*, 2021c). This report is a body of knowledge based on research-based evidence on “what works” in iL. Organized by the Immersive Learning Research Network (iLRN), a nonprofit organization that connects researchers and educators, experts grouped the main barriers to adoption of XR into:

- *Access (B1)*: it addresses issues related to limiting the distribution of immersive technologies;
- *Affordability (B2)*: economic availability;
- *Inadequate XR Teacher Training Programs (B3)*: training programs on topics related to immersive technologies;
- *Interoperability (B4)*: much immersive content is still locked into certain hardware, software and commercial frameworks;
- *Lack of Content (B5)*: challenge of finding immersive instructional content;
- *Lack of Infrastructure and Tech Support (B6)*: ensuring access to immersive experiences considering the available infrastructure.

As presented above, the State of XR Report LEE *et al.* (2021c) describes the main challenges for the adoption of immersive technologies in education. In this way, we are interested in finding out if the frameworks help, in some way, in solving the main challenges identified by the report. In this sense, we developed questions that correspond to the barriers to adoption in order to support the mapping:

- Do frameworks consider aspects of audience disability (B1)?
- Do frameworks consider the economic availability for the feasibility of immersive experiences (B2)?
- Do frameworks consider aspects of technical and pedagogical support to institutions and educators (B3)?
- Do frameworks consider interoperability aspects between applications and devices (B4)?
- Do frameworks consider aspects of resource reuse (B5)?
- Do frameworks consider infrastructure aspects (B6)?

By rigorously analyzing the data extracted from the frameworks, we found that no work directly addresses the above questions. Considering our classification of works, we expected some response from practical frameworks rather than theoretical ones. This can be explained because adoption barriers correspond to technological and practical aspects rather than theories and pedagogical approaches.

As can be seen in Figure 2.2, the elements of each framework are analyzed and categorized. We observed that practical frameworks address generic or context-specific issues. For example, IP *et al.* (2018) showed a methodology for supporting the design of iL experiences to MOOC learners through iterative stages and AGUAYO *et al.* (2020) proposed a set of design principles and guidelines for self-determined mixed reality learning. Both works are domain-specific. On the other hand, GUPTA *et al.* (2019) adopted Information-Centric Systems Engineering (ICSE) principles to guide the development of immersive technologies, but did not consider specific aspects of XR.

In this sense, when reflecting on this critical point of frameworks and considering the background of the researchers, we present below a research roadmap that defines important issues about iL frameworks.

2.5.3 Research Roadmap

As regards the frameworks analyzed in this secondary study, in the identified gaps, as well as the experience of reviewers in iL and Software Engineering, we list below some aspects that are fundamental to support the development for iL, which can be considered as research roadmap.

Level of Immersion

Since human beings have five senses (smell, taste, sight, hearing and touch) to interact with the world they live in, researchers have sought to make users interact with virtual environments in the same way as they interact with the real world, making the immersive experience more complete. Thus, it is important to define which human senses will be involved during the iL experience and which will be the forms of interaction with the virtual environment. This decision will directly influence the choice of immersive devices.

Immersive Devices

We consider traditional devices as multimedia (desktop, tablet and smartphone) and Multiple Sensory Media (MulSeMedia) (GHINEA *et al.*, 2014) as immersive devices that raise the level of multimedia immersion and add other human senses such as smell, taste and touch, in addition to providing more natural and intuitive interactions. Examples of mulsemedia devices are XR headsets, haptics, motion sensors and others. Each immersive device has characteristics that will influence the experience as a whole. For example, the immersive experience via smartphone is more limited when compared to the XR headset. At the same time, the associated cost (B2) must also be considered, as pointed out by the State of XR Report (LEE *et al.*, 2021c). Considering devices that meet desired immersion levels and affordability is a challenge that must be taken into account to meet audience requirements.

Development Tools

Developing for XR is complex, because it needs a multidisciplinary team that involves skills such as coding, game design, 3D modeling, storytelling, user experience and others. For each specialty a set of tools is needed to produce the artifacts. For example, to create 3D objects and scenarios, it is necessary to master 3D modeling tools such as Blender[2], 3DS Max[3] and Maya[4]. Software engineers are not required to master these tools, nor have the ability to model 3D objects, but they must be able to specify the trivial development tools related to the chosen platforms. Therefore, priority must be given to which platform the application will run on, that is, whether it will be a native or web application.

Then the development environment to implement the virtual environment features must be chosen. Most immersive device manufacturers provide the Software Development Kit (SDK) according to development environments such as Android, iOS, Web, Unity[5], Unreal[6] and others.

Therefore, if Google Carboard will be used in an immersive experience and the virtual environment must be downloaded to the smartphone (native), the developer must choose the development environment that they are most used (Android NDK, iOS or Unity) and import the SDK. If the virtual environment is ran via browser, it is necessary to choose a tool compatible with the parameters of the virtual environment so that the immersive experience is not impaired. Examples of web frameworks are WebXR[7], A-Frame[8], Babylon.js[9] and React 360.

Identifying technologies and developing applications that are interoperable (B4) is another step towards mitigating problems related to adoption barriers.

User Experience

Unlike applications based on the Windows, Icons, Menus, and Pointer (WIMP) interface, immersive applications need attention to avoid uncomfortable experiences.

[2]https://www.blender.org/
[3]https://www.autodesk.com/ products/3ds-max/
[4]https://www.autodesk.com/products/maya/
[5]https://unity.com/
[6]https://www.unrealengine.com/
[7]https://immersive-web.github.io/
[8]https://aframe.io/
[9]https://www .babylonjs.com/

Instructions on how to interact with the virtual environment must be accessible at all times. Oculus Quest 2 Controller, for example, has 6 buttons for each hand and this can be a lot of information for the user. Therefore, the environment must provide a training section so that the user can gradually get used to the virtual environment. In addition, the virtual environment must maintain a stable Frames per Second (FPS) rate, preferably 60 FPS, to keep camera movement in the environment corresponding to the user's head movement, avoiding discomfort. For this, a series of restrictions in the development is recommended, such as limiting the amount of polygons; using just one camera instead of *post-processing effects* for *draw calls* needed in the scene; use of panoramic images (360º) and others.

Simulator Sickness

Simulator sickness is a very important aspect in XR and one that no iL framework has addressed. Users may experience uncomfortable symptoms (such as eyestrain, fatigue, dizziness, ataxia) that make the immersive experience difficult. REGAN & PRICE (1994) found that individuals exposed to the virtual environment had symptoms for up to 5 hours after the experience. The severity and duration of these symptoms can be influenced by the time of exposure to the virtual environment and the intensity of the experience (KIM *et al.*, 2005). Thus, the way the user will move in the virtual environment is an important precaution to avoid discomfort during and after the experience. In this example, implementing the teleportation technique reduces the probability of the user presenting motion sickness symptoms instead of walking freely through the virtual environment.

Accessibility Technologies

As presented in the State of XR Report (LEE *et al.*, 2021c), one of the issues preventing the adoption of immersive technologies is the inadequacy of applications and devices for people with disabilities (B1). WalkinVR[10] is the first major app that allows for adjustments in XR experiences based on users' height and various disabilities. However, more research and new applications are critically needed to address these issues and involving both academia and industry is paramount.

Experience Reuse

From the point of view of Software Engineering, software reuse is an approach that starts from the principle of enhancing the use of existing software, aiming to reduce production and maintenance costs, guarantee more agile deliveries, try to

[10] https://www.walkinvrdriver.com/

add more quality and maximize the return on investment of software (WERNER *et al.*, 1997).

Following this line, Domain Engineering (DE) and Application Engineering (AE) can be applied as techniques to improve the development of immersive applications. DE is the process of identifying and organizing knowledge about a class of problems, the problem domain, to support its description and solution (PRIETO-DIAZ, 1990). For example, there are domains (e.g. STEM, health and military education) that have common characteristics and that, therefore, their applications could be built from the same process and artifacts, thus promoting the reuse of common concepts and functionalities.

While DE is concerned with developing artifacts for reuse, AE builds applications based on the reuse of artifacts and models generated by DE. According to NORTHROP *et al.* (2007), AE develops software products based on the artifacts generated by the DE process.

Therefore, the adoption of software reuse techniques as a development strategy has the potential to allow the reuse of assets involved in immersive experiences (B5), as well as improving the quality of applications.

Below, we list some aspects to support teachers and instructors in adopting immersive teaching experiences.

Immersive Platforms

iL supports teaching in any field of knowledge. Therefore, teachers and instructors do not have the skills to develop applications and therefore need tools to support their classes. There is a range of platforms that provide immersive content.

Talespin's training platform[11] puts the user directly into a guided scenario, in a realistic two-person discussion situation. Engage VR[12] and Unimersiv[13] are online training and education platforms that have immersive content from various areas of knowledge.

In addition, teachers and instructors can create virtual spaces and insert their contents. Frame VR[14] and Mozilla Hubs[15] are examples of current web tools that allow one to create virtual classrooms where students can access simultaneously through avatars, communicate and interact with each other. Furthermore, Second Life[16] and Open Wonderland[17] are virtual spaces that have been much explored by

[11]https://www.talespin.com/
[12]https://engagevr.io/
[13]https://unimersiv.com/
[14]https://framevr.io/
[15]https://hubs.mozilla.com/
[16]https://secondlife.com/
[17]http://openwonderland.org/

the scientific community.

Therefore, these immersive platforms must be prepared to support educators (B3). These professionals do not have technical skills and need intuitive tools to support the adequacy of instructional content to immersive technologies.

Available Infrastructure

Using immersive experiences in teaching still emerges as a challenge, as immersive equipment still requires considerable investment. Therefore, the choice of device that will be used in the teaching and learning process directly impacts the pedagogical performance. Desktops and smartphones are more common devices among people than XR headsets. On the other hand, the educational institution can choose to purchase immersive devices, but it will require a high investment.

Another point is the hardware configuration and Internet connection speed (B6). Virtual environments demand high performance in image processing and take up a lot of storage space. In the case of a web application, the connection quality will also impact the performance of learning activities.

Improved Learning Outcomes

This is one of the great challenges in iL. Ensuring improved learning outcomes through immersive experiences still requires further empirical studies. Increasing the degree of immersion of devices is not a guarantee of high academic performance. The sense of presence and pedagogical aspects (quality of instructional content and pedagogical theories) are also important and must be considered to achieve effectiveness in learning outcomes. Therefore, further studies are needed on how to improve learning considering technological, psychological and pedagogical aspects.

Learning Analytics

Through the analysis carried out in this study, it was identified that no framework considered the monitoring of student learning in virtual environments. In general, virtual environments immerse students in instructional content, but learning data are not captured to analyze students' educational performance. We believe that Learning Analytics (LA) can provide valuable information about actual performance and improve the teaching-learning process. For example, through biofeedack sensors, heart rate, breathing, sweat, and temperature readings it is possible to indicate whether the student in a particular section felt any discomfort (REIS & MARQUES, 2021).

2.6 Final Remarks

This systematic literature review aimed to identify the state of the art of iL frameworks. Through the 15 selected articles it was possible to obtain an overview of the contributions and identify gaps and research opportunities.

Through the research questions, we identified that the authors have divergent understandings about iL (RQ1), as well as the definition of immersion. In addition, we grouped the works regarding the purpose of use and we found that there are frameworks to support the design of learning activities, identify which factors influence the learning and intention of teachers, guidelines and development models (RQ2). We also found that frameworks are composed of three main aspects: technological, psychological and pedagogical (RQ3). Finally, most of the frameworks were validated through a questionnaire, but 4 articles did not validate the proposal (RQ4).

The relevance of this study lies in the discussion and definition of the concept of immersion, better understanding of iL, identification of gaps and the proposal of a research roadmap so that frameworks can address the development of immersive environments greater detail, as well as the use of experiences immersive by teachers and instructors. In addition, the evidence that contributes to the proposal of our approach found in this review is described in Chapter 5.

Chapter 3

Scoping Review of the Metaverse for Software Engineering Education

3.1 Introduction

The Metaverse term was created by Neil Stephenson in his science fiction novel named Snow Crash in 1992. In this novel, humans in the physical world enter and live in the Metaverse (a parallel virtual world) through digital avatars (in analogy to user's physical self) via a VR equipment. Metaverse, literally a combination of the prefix *"meta"* (meaning transcendence) and the suffix *"verse"* (shorthand for universe), is a computer-generated world with a consistent value system and an independent economic system linked to the physical world (WANG *et al.*, 2022b).

There are many Metaverse definitions in the literature. For example, according to FORTE *et al.* (2010), the Metaverse is a "virtual space where an individual's cyber community can share social interactions without the constrains of the physical world". From the point of view of KIM *et al.* (2012), it is a "collective online space created by combining some physical reality enhanced by a 3D virtual world and a physically permanent virtual space". On the other hand, DIONISIO *et al.* (2013) define it as "an integrated network of 3D virtual worlds in an independent virtual world or an attractive alternative realm for human sociocultural interaction". "A world where virtual worlds combine immersive VR with physical actors, objects, interfaces, and networks in a future form of the Internet; a social virtual world that parallels and replaces the real world" is a Metaverse definition presented by HUGGETT (2020). However, a definition that is closer to the state of the art and practice is presented by FERNANDES & WERNER (2022), in which "the Metaverse is a network of XR apps connected to each other, over the Internet infrastructure, allowing network users, systems, and devices to access them".

The Metaverse provides a beneficial training environment, which is close to the real environment for individuals to gain experience (PATLE *et al.*, 2019). One of the Metaverse's advantages is enabling students to attend their classes virtually and providing elements that are involved in the real classroom. Students in the Metaverse can interact with teachers and communicate with classmates through their avatars. This can create an immersive learning opportunity that enhances the students' learning motivation (TLILI *et al.*, 2022).

Specifically, about the Metaverse for SEE, there are a number of benefits that can support learning outcomes in SE, such as, allow students to interact with 3D environments and virtual objects in a way that simulates real-world scenarios in the SE context (hands-on learning); visualize complex systems, such as software architecture and algorithms, in a way that is more intuitive and easier to understand (visualization); facilitate collaboration between students, allowing them to work together in a shared virtual environment (collaboration); provide students with access to simulations and experiences that might otherwise be difficult or impossible to replicate in the physical world, such as simulations of interviews with stakeholders to elicit requirements or improve public speaking skills; improve retention of information and skills, as students are more engaged and have more opportunities to practice and apply what they have learned (improved retention), among others.

Some works have been elaborated in order to support the improvement of SE learning outcomes through the Metaverse (CHEN *et al.*, 2010b; FERNANDES & WERNER, 2021c; GULEC *et al.*, 2021b; INAYAT *et al.*, 2016a; NG & TANG, 2012b; OCHOA & BABBIT, 2019a; RODRIGUES *et al.*, 2016a). Most of them simulate real development environments and allow interaction and communication with other users through avatars, which are geographically distributed. In general, these experiences consist of assisting the teaching of software processes, allowing the student to play the main roles in software projects, using techniques of certain development process models (e.g., Scrum and prototyping), navigating in different environments (e.g., meeting rooms and programmers' room), communicating with other avatars, interacting with and viewing UML diagrams in the same manner as they are treated in tools (FERNANDES *et al.*, 2017).

Moreover, several literature reviews were conducted related to the Metaverse. HUYNH-THE *et al.* (2022) conducted a survey to explore the role of Artificial Intelligence (AI) in the foundation and development of the Metaverse. SUN *et al.* (2022b) present a review of how Metaverse is changing big data and how the future of Metaverse meets big data. A review of the application of digital twins and Metaverse in the field of fluid machinery pumps and fans is presented by YANG *et al.* (2022a). KAWARASE IV & ANJANKAR (2022) conducted a review on how the metaverse can be used in medicine. From the point of view of the Metaverse in education, IWANAGA *et al.* (2022); KYE *et al.* (2021); LIN *et al.* (2022); SARITAŞ &

TOPRAKLIKOĞLU (2022); TLILI *et al.* (2022) are secondary studies that investigated how the Metaverse is applied in education in general, and specifically in some areas of healthcare. However, no literature review was conducted to summarize the findings related to the Metaverse in SEE and provide future insights.

Therefore, considering the advances in the Metaverse and the gap in literature reviews, this work aims to provide the state-of-the-art of the Metaverse for SEE through a scoping review of the literature. This study has two main contributions: (i) provides an overview of the Metaverse for SEE research; and (ii) establishes research opportunities to enable the Metaverse for SEE.

This chapter is organized as follows: in Section 3.2 related works are discussed, as well as the need to characterize research on Metaverse for SEE. The research questions, as well as the procedures performed for the selection of primary studies are presented in Section 3.3. The results and discussions of the review's findings are detailed in Section 3.4 and Section 3.5, respectively. Finally, Section 3.6 provides some conclusions.

3.2 Related Work

Considering Facebook's announcement in 2021, the Metaverse term had growing notoriety. According to Figure 3.1, the main searches on the Internet were performed from October 2021.

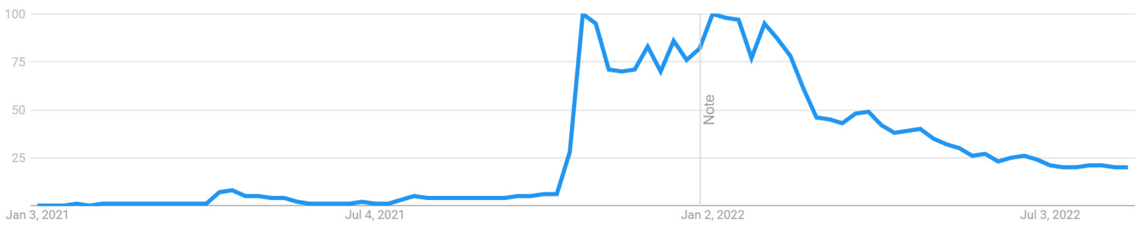


Figure 3.1: Search result of the "Metaverse" term on Google Trends

In order to find related work, in December 2022 we searched works from Google Scholar with the search string *"Metaverse AND (survey OR review OR mapping OR literature)"* and performed the backward snowballing process (JALALI & WOHLIN, 2012), i.e., for each work it was verified the potentially related work from the references. Secondly, in the same period, we searched works from Scopus with the same search string used on Google Scholar in the title, abstract, and keywords fields. Considering works published as *article, book chapter, conference paper, conference review, and review,* 15 documents were returned. According to Figure 3.2, we can observe the considerable evolution of publications from 2021. From the point of view of the *reviews*, also we find similar behavior, as shown in Figure 3.3. There is an increase in publications from 2021 and most are written in English. Table 3.1 shows an overview of the related work from Google Scholar and Scopus. Before removing duplicated papers and selecting only articles written in English, we analyzed 50 related works.

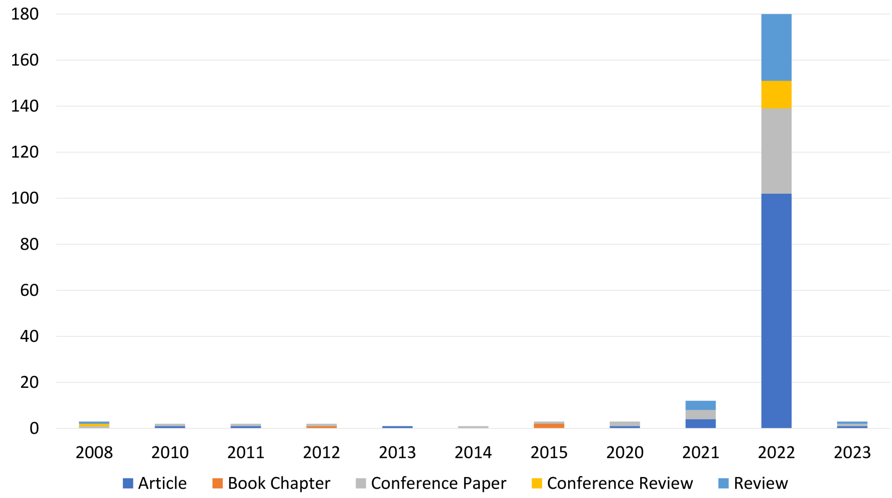


Figure 3.2: Evolution of publications over time from Scopus

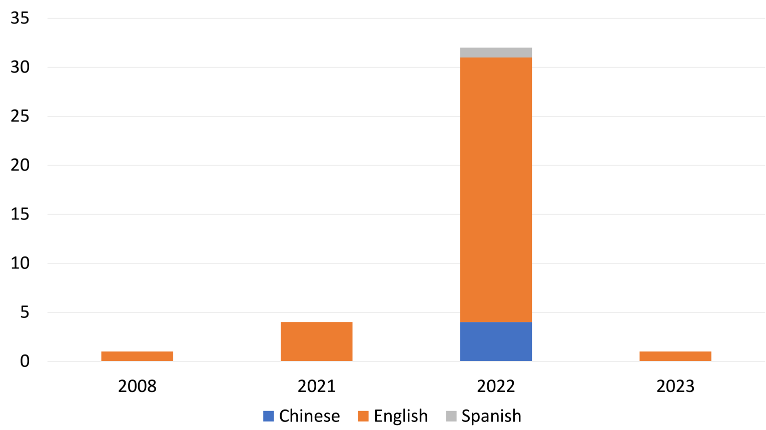


Figure 3.3: Reviews from Scopus

Focus	Reference	Contributions
AI	HUYNH-THE *et al.* (2022)	Survey to explore the role of AI in the foundation and development of the Metaverse
AI and blockchain	YANG *et al.* (2022b)	Survey on AI and blockchain technologies that can play essential roles in the Metaverse
Big data	SUN *et al.* (2022b)	A review of how Metaverse is changing big data and how the future of Metaverse meets big data
Blockchain	AKS *et al.* (2022)	A review of data security and privacy in the Metaverse
	GADEKALLU *et al.* (2022)	Survey to provide blockchain technical perspectives for the Metaverse

Continued on next page

Table 3.1 – *Continued from previous page*

Focus	Reference	Contributions
Blockchain and Building Information Modeling (BIM)	HUANG *et al.* (2022a)	Review on how BIM technology and blockchain can be integrated with Metaverse
Blockchain and Intelligent Networking	FU *et al.* (2022)	A survey on the gains of blockchain, intelligent networking, and the combination of both in providing the immersive experiences of the Metaverse
Business	SETIAWAN *et al.* (2022)	It discusses essential factors that the Metaverse offer for business based on 7 Layers of the Metaverse
Computational arts	LEE *et al.* (2021b)	Survey on the potentials of computational arts in the Metaverse
Concepts	ABBATE *et al.* (2022)	A bibliometric literature review that includes a summary of the most important scientific articles and journals in the subject area, as well as the most prolific and prominent authors, organizations, and nations
	ALMOQBEL *et al.* (2022)	Review on the Metaverse definitions
	DINCELLI & YAYLA (2022)	Review to synthesize how the Metaverse affordances are utilized in the information systems field
Digital twins	YANG *et al.* (2022a)	A review of the application of digital twins and Metaverse in the field of fluid machinery pumps and fans
Edge computing	WANG & ZHAO (2022)	A survey on the mobile edge computing-based Metaverse
	CHANG *et al.* (2022)	Discuss the role of sixth generation (6G)-oriented edge intelligence into the Metaverse
	XU *et al.* (2022)	Survey on the edge-enabled Metaverse to realize its ultimate vision
Education	TLILI *et al.* (2022)	A systematic literature review of the Metaverse appplications in education
	IWANAGA *et al.* (2022)	Review on the Metaverse in anatomy education
	SARITAŞ & TOPRAKLIKOĞLU (2022)	Review that investigates the reflections of the concept of the Metaverse in education
	KYE *et al.* (2021)	A literature review about the Metaverse for educational applications
	LIN *et al.* (2022)	Survey that focuses on current technologies, challenges, opportunities, and future directions for Metaverse in education
Intelligent transportation systems	NJOKU *et al.* (2022)	A review on Metaverse for data-driven intelligent transportation systems
Marketing	GIANG BARRERA & SHAH (2023)	Review that presents discussions about the impact of the Metaverse on Marketing
Medicine	KAWARASE IV & ANJANKAR (2022)	A review of how the Metaverse can be used in medicine
	GARAVAND & ASLANI (2022)	A scoping review on the Metaverse in the health field
	PETRIGNA & MUSUMECI (2022)	A scoping review to provide evidence on the use of the Metaverse in healthcare
	BANSAL *et al.* (2022)	A survey on the Metaverse in the healthcare field

Continued on next page

Table 3.1 – *Continued from previous page*

Focus	Reference	Contributions
	SUN *et al.* (2022c)	A systematic review to provide a reference for the rational and effective application of the Metaverse etaverse by plastic surgeons in the future
	CHENGODEN *et al.* (2022)	It provides a comprehensive review of the Metaverse for healthcare, emphasizing on the state of the art, the enabling technologies for adopting the Metaverse for healthcare, the potential applications and the related projects
	WU & HO (2022)	Scoping review of the Metaverse in emergency medicine
Mental health	WANG *et al.* (2022a)	A systematic review to provide a state-of-the-art of the mental health benefits through the Metaverse
	USMANI *et al.* (2022)	Survey to provide the Metaverse applications in the treatment of mental health disorders
Security and privacy	VLADIMIROV *et al.* (2022)	A survey that considers the threats that a realistic digital clone, aka avatar of a person can have in the wrong hands
	CHEN *et al.* (2022b)	It presents an overview of the technologies and some potential security and privacy issues in the Metaverse
	SUN *et al.* (2022a)	Review of the Metaverse concepts and technologies as well as focus on the security and privacy issues that exist in the Metaverse
	HUANG *et al.* (2022b)	Review that discusses security and privacy issues for the Metaverse
	CANBAY *et al.* (2022)	Review that focuses on privacy concerns in Metaverse
	WANG *et al.* (2022b)	Survey on the Metaverse related to security and privacy aspects
Smart city	KUSUMA & SUPANGKAT (2022)	It provides an overview of the Metaverse supporting technologies and their adaption to smart cities as a reference for related research
Social goods	DUAN *et al.* (2021)	Survey on Metaverse applications related to social goods
Technologies and concepts	PARK & KIM (2022)	A Metaverse taxonomy composed in hardware, software, contents components and major approaches into user interaction, implementations, and applications to classify the studies of research institutes
	CHEN *et al.* (2022a)	A review on the Metaverse definitions and their architecture
	SCHMITT (2022)	It presents a bibliometric review of the term Metaverse and the technologies involved to build it
	NING *et al.* (2021)	Overview of the Metaverse development in terms of technologies, VR, social media, national policies, industrial projects, and infrastructures
	MYSTAKIDIS (2022)	Overview related to technologies, principles and affordances for the Metaverse
	LEE *et al.* (2021a)	Review of eight types of key technologies to enable Metaverse, as well as six user-centric pillars to form the Metaverse ecosystem

Continued on next page

Table 3.1 – *Continued from previous page*

Focus	Reference	Contributions
	AL-GHAILI *et al.* (2022)	Review on the Metaverse's definitions, properties, architecture, and applications
	RAMESHWAR & KING (2022)	The state of the art on Metaverse from Caribbean researchers
Technology acceptance model	ABURBEIAN *et al.* (2022)	Survey to investigate variables that may affect users' acceptance of the Metaverse
Virtual commerce	SHEN *et al.* (2021)	A systematic literature review on consumer behaviors and design of virtual commerce applications

Table 3.1: An overview of the related works from Google Scholar and Scopus

HUYNH-THE *et al.* (2022) conceive a comprehensive investigation of AI-based methods concerning six technical aspects that have potentials for the Metaverse: natural language processing, machine vision, blockchain, networking, digital twin, and neural interface. YANG *et al.* (2022b) investigate the state-of-the-art studies across the Metaverse components, digital currencies, AI applications in the virtual world, and blockchain-empowered technologies in order to discuss how blockchain and AI fuse with the Metaverse. SUN *et al.* (2022b) reviewed how to make sense of the Metaverse technology through big data in detail, including the relationship between big data and the Metaverse, the key tasks, and the technical requirements when the Metaverse meets big data. In addition, the authors focused on the security and privacy issues, as well as existing countermeasures, that arise when big data collide with the Metaverse, providing a comprehensive overview for related researchers.

AKS *et al.* (2022); GADEKALLU *et al.* (2022) present blockchain-based methods for the Metaverse from technical perspectives, such as data acquisition, data storage, data sharing, data interoperability, and data privacy preservation. For each perspective, the authors discuss the technical challenges of the Metaverse and then highlight how blockchain can help. HUANG *et al.* (2022a) present how BIM technologies and blockchain are regarded as significant roles in the ever-expanding Metaverse. For example, Metaverse applies BIM technologies to create and design the fundamental components of the virtual world, such as buildings, cities, and even plants, in which anyone can safely and freely engage in social activities that transcend the limits of the physical world. FU *et al.* (2022) explore how the combination of blockchain and intelligent networking can benefit the Metaverse, including distributed computing, network, and equipment management, and blockchain optimization, aiming to bridge the physical and virtual worlds, thus forming a more credible, secure, and efficient ecosystem to provide users with an immersive experience.

SETIAWAN *et al.* (2022) define the essential factor of the Metaverse for business based on 7 Layers of the Metaverse. Every layer has its own essential factor that is useful for business. YANG *et al.* (2022a) classify the application status of pumps and fans in fluid machinery through literature research and comparative analysis from the perspective of digital twins and the Metaverse. Furthermore, future research on fluid machinery is prospected, aiming at the existing problems of fluid machinery in the simulation model, maintainability test, visual monitoring, and other aspects.

In terms of networking, CHANG *et al.* (2022); WANG & ZHAO (2022); XU *et al.* (2022) investigated challenges and solutions for the Metaverse. Precisely, XU *et al.* (2022) discuss the computation challenges and cloud-edge-end computation solutions and concepts that leverage next-generation communication systems for users to be telepresent and teleoperate in the Metaverse, and CHANG *et al.* (2022) investigated three Metaverse systems based on 6G edge intelligence to introduce the integration of this technology into the Metaverse, and discuss some of the core challenges. WANG & ZHAO (2022) presented a fundamental research and application scenarios like XR of Mobile Edge Computing (MEC), as well as the future research challenges of mobile edge-based Metaverse are presented.

According to security and privacy, there are some literature reviews about this area. WANG *et al.* (2022b) focus on presenting a comprehensive survey of the security, and privacy in the Metaverse. Authors elaborated on the typical security threats in the Metaverse by classifying them from the following dimensions: identity, data, privacy, network, economy, physical/social effects, and governance. VLADIMIROV *et al.* (2022) conducted research in the field of communication security and privacy and analyzed the main threats that can occur when important personal information is transmitted from the point of view of 3D reconstructed models of people in the Metaverse. CHEN *et al.* (2022b) expound on the security and privacy guarantees brought about by the Metaverse's development through five technologies: Blockchain, Interactive Technology, Cloud Service and the Internet of Things (IoT), AI, and Digital Twins. In addition, some vital open problems and opportunities are discussed in detail. SUN *et al.* (2022a) present the technical framework and application status of the Metaverse, i.e., the authors focus on current security threats and solutions to the Metaverse, and propose the challenges and future directions for the Metaverse. HUANG *et al.* (2022b) identified the four core characteristics that help define and summarize the current progress of using cutting-edge technologies under the umbrella of the Metaverse. CANBAY *et al.* (2022) focus on privacy concerns in the Metaverse, present some measures in order to minimize these concerns, and provide a comprehensive list of personal data collected and processed in the Metaverse.

From the point of view of the technology acceptance, ABURBEIAN *et al.* (2022) investigate how developers might enhance the Metaverse to meet users' expectations and let the users interact with this technology better from extended technology acceptance model.

In general terms of the Metaverse, reviews established technologies, affordances, and essential aspects for the implementation of the Metaverse. DINCELLI & YAYLA (2022) reviewed the immersive VR literature in the information systems field to provide a holistic view of opportunities, and five affordances were identified: embodiment, interactivity, navigability, sense-ability, and create-ability. ABBATE *et al.* (2022) present some significant theoretical contributions, such as bibliometric and network analyses identifying the most influential papers and countries in terms of published articles and total citations. ALMOQBEL *et al.* (2022) conducted a systematic literature review and reviewed articles to understand how researchers are using the term "metaverse". The authors categorized the main characteristics that researchers have defined as being properties of the Metaverse. PARK & KIM (2022) discuss the concepts and essential techniques necessary for realizing the Metaverse into three components (i.e., hardware, software, and contents) and three approaches (i.e., user interaction, implementation, and application). MYSTAKIDIS (2022) presents the main technologies, such as VR, AR, and MR, principles (i.e., interoperable, open, hardware agnostic, and network) and affordances (immersion, embodiment, presence, and identify construction) involved to the development of the Metaverse. LEE *et al.* (2021a) provide a comprehensive framework that examines the Metaverse development under the eight enabling technologies: XR, Human-Computer Interaction (HCI), AI, blockchain, computer vision, IoT and robotics, edge and cloud computing, and mobile networks. Furthermore, authors proposed the six pillars of the Metaverse ecosystem: avatar, content creation, virtual economy, social acceptability, security and privacy, and trust and accountability. NING *et al.* (2021) introduce the development status of the Metaverse, from the five perspectives of VR object connection: VR space convergence, management technology, fundamental common technology, and communication and computing infrastructure. CHEN *et al.* (2022a) analyzed the definitions of the Metaverse into different categories and summarized some characteristics of varying category definition, and discussed the architecture of the Metaverse from the point of view of computing, logical, physical, and protocol. SCHMITT (2022) provides guidelines and implications for researchers, managers, and practitioners in terms of value creation opportunities for corporations, but also highlights the risks and challenges for businesses, governments, and broader society. AL-GHAILI *et al.* (2022) provide a framework providing solutions to a number of issues and concerns that researchers paid much attention to. RAMESHWAR & KING (2022) present the impact the Caribbean is having on its evolution in areas of XR and Non-Fungible Token (NFT). It adds to the literature to encourage future research in this area as a mechanism to develop strategies that promote the region's innovation, competitiveness, and sustainability.

Finally, some works investigated how the Metaverse contributes to application areas. LEE *et al.* (2021b) present a comprehensive survey on computational arts, in which seven critical topics are relevant to the Metaverse, describing novel artworks in blended virtual-physical realities. NJOKU *et al.* (2022) discuss how Metaverse solutions can be applied to data-driven intelligent transportation systems in order to provide more intelligent systems. The review identified three dominant challenges: vehicle fault detection and repair, testing new technologies, and anti-theft systems. GIANG BARRERA & SHAH (2023) offer a synthesis of existing Metaverse related knowledge with marketing focus and integrate technology-focused literature with secondary data on business practitioners' views to identify emerging themes.

In the health field, WU & HO (2022) examine articles about the concept of the Metaverse in emergency medicine, and extracted additional domains, such as education, prehospital and disaster medicine, diagnosis and treatment application, and administrative affairs. GARAVAND & ASLANI (2022) present a review and identify the application areas of the Metaverse technology in the health field. USMANI *et al.* (2022) present a survey of potential applications of the Metaverse in the treatment of mental health disorders. WANG *et al.*'s (2022a) analysis structure covers three themes: meditation or mindfulness task, design considerations (crucial factors impacting meditation, and enhanced by technology), and VR and related technology. The results of the review indicate that the current works have a profound accumulation of utilizing VR immersion to improve users' presence (letting them be away from their daily stressful life). DUAN *et al.* (2021) propose a three-layer Metaverse architecture for social good from a macro perspective, containing infrastructure, interaction, and ecosystem.

KUSUMA & SUPANGKAT (2022) conducted a literature review and expected to give a better understanding on how to embrace the Metaverse in the smart city field, such as simplifying city monitoring by using IoT devices and digital twins and making data visualization more realistic. SHEN *et al.* (2021) perform a systematic literature review to synthesize research on consumer behaviors and design of virtual commerce applications.

In the education field, TLILI *et al.* (2022) conduct a systematic literature review of the Metaverse in education and reveal the research trends, focus, and limitations of this research topic, such as research gap in lifelogging, audience profile, few studies focusing on mobile learning, hybrid learning, and micro learning, and no study focused on using the Metaverse for students with disabilities. KYE *et al.* (2021) review the literature and define 4 types of the Metaverse and explain the potential and limitations of its educational applications. IWANAGA *et al.* (2022) present a review and survey of the Metaverse in anatomy education and found that the Metaverse has achieved only limited use among non-clinical anatomy educators to date although it has been used much more in the clinical realm. SARITAŞ & TOPRAKLIKOĞLU (2022) present a systematic literature review on the use of the Metaverse in education and conclude that in the first studies on Metaverse in education, the concept was discussed in the context of 3D software, while in later studies, the concept of Metaverse began to be discussed in the context of digital reality technologies. According to LIN *et al.* (2022), research and cases show that combining with Metaverse is a feasible method to achieve relative equality in educational opportunities.

In this related works section, we intended to present a brief overview of the Metaverse literature reviews. We could verify what are the main concepts involved (e.g., virtual world, affordance, interaction); what technologies can be integrated (e.g., AI, blockchain, edge networking, digital twins); what technologies can benefit from it (e.g., business, medicine); and in what areas the Metaverse has been applied (e.g., education, marketing, business, computational arts). From this analysis, we could observe a gap in the context of the Metaverse for SEE. Therefore, this work aims to investigate the state-of-the-art of the Metaverse applied in this context.

3.3 Research Method

The goal of this study is to obtain evidences about the state-of-the-art of the Metaverse for SEE. This secondary study has been based on the original guidelines as described by KITCHENHAM & CHARTERS (2007) and followed the general purpose for conducting scoping reviews (MUNN *et al.*, 2018). In order to support the understanding of some related terms, we treat XR apps as any VR, AR, MR, and XR based application. The steps in the scoping review method are documented below.

3.3.1 Research Questions

In this study three general research questions were defined as follows:

- RQ1: What are the educational aspects addressed by XR apps?
- RQ2: What are the technological aspects addressed by XR apps?
- RQ3: How are the evaluation aspects addressed by primary studies?

Our purpose is to obtain an overview of the aspects related to the educational context of the SEE (RQ1), development technologies (RQ2), and how studies were evaluated (RQ3). Therefore, in order to obtain the state-of-the-art and achieve the goals of this study, secondary research questions were defined:

- RQ1.1: What are the SE topics addressed?
- RQ1.2: What are the target audiences of XR apps?
- RQ1.3: What are the features of XR apps addressed?
- RQ2.1: What are the technologies adopted for XR apps development?
- RQ2.2: What are the kind of Reality-Virtuality Continuum modality addressed by XR apps?
- RQ2.3: What are the devices used by XR apps?
- RQ3.1: How are the evaluations designed?
- RQ3.2: What are the materials used to obtain the evaluation outcomes?

3.3.2 Search Process

Population, Intervention, Comparison and Outcomes (PICO) approach was adopted in order to formulate search strings from research questions, as suggested by KITCHENHAM & CHARTERS (2007). In SE, *Population* may refer to specific SE role, category of software engineer, or an industry group (KITCHENHAM & CHARTERS, 2007). In this study, the population are primary studies in SE. *Intervention* refers to a software methodology, tool, technology, or procedure that addresses a specific issue (KITCHENHAM & CHARTERS, 2007). In this study, we defined the education as intervention. *Comparison* has the purpose of comparing with the intervention. As our purpose is only to characterize, this category is not applicable in this study. Finally, *Outcomes* is the Metaverse for SEE.

From PICO established, the identified keywords are "*software engineering*", "*education*" and the "*Metaverse*" which were grouped into sets and their synonyms were considered to formulate the search string, as shown in Table 3.2.

Sets	Keywords
Population	software engineering
Intervention	education, learning, teaching, training, immersive learning, and immersive education
Comparison	not applicable
Outcomes	metaverse, virtual world, 3D virtual world, virtual environment, and 3D virtual environment, virtual reality, augmented reality, mixed reality, and extended reality

Table 3.2: Keywords identified from PICO

Each set of searches was performed on the databases of ACM[1], Engineering

[1]https://dl.acm.org/

Village[2], IEEE Xplore[3], Scopus[4], and Web of Science[5]. The search strings used for each database can be found in Table 3.3, and have been used on all fields, with the exception of Scopus. According to DYBA *et al.* (2007), Scopus indexes works from several bibliographic databases (e.g., ACM, IEE Xplore, and Engineering Village), and thus has been used on title, abstract, and keywords fields to return works with more relevance. A spreadsheet was used to remove duplicates and to manage the large number of references. This study was conducted in December 2022.

Database	Search string
ACM	[All: "software engineering"] AND [[All: learn] OR [All: teach] OR [All: edu] OR [All: train] OR [All: "immersive learning"] OR [All: "immersive education"]] AND [[All: metaverse] OR [All: "virtual reality"] OR [All: "augmented reality"] OR [All: "mixed reality"] OR [All: "extended reality"] OR [All: "virtual world"] OR [All: "3d virtual world"] OR [All: "virtual environment"] OR [All: "3d virtual environment"]]
Engineering Village	(English, conference article, journal article, conferencing proceeding, book chapter) (((("software engineering") WN ALL) AND ((learn OR teach OR edu OR train OR "immersive learning" OR "immersive education") WN ALL)) AND ((metaverse OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "virtual world" OR "3D virtual world" OR "virtual environment" OR "3D virtual environment") WN ALL)) + ((ca OR ja OR cp OR ch) WN DT) AND (english WN LA)
IEEE Xplore	("All Metadata":"software engineering") AND ("All Metadata":learn OR "All Metadata":teach OR "All Metadata":edu OR "All Metadata":train OR "All Metadata":"immersive learning" OR "intadata":"immersive education") AND ("All Metadata":metaverse OR "All Metadata":"virtual reality" OR "All Metadata":"augmented reality" OR "All Metadata":"mixed reality" OR "All Metadata":"extended reality" OR "All Metadata":"virtual world" OR "All Metadata":"3D virtual world" OR "All Metadata":"virtual environment" OR "All Metadata":"3D virtual environment")
Scopus	(TITLE-ABS-KEY ("software engineering") AND TITLE-ABS-KEY (learn OR teach OR edu OR train OR "immersive learning" OR "immersive education") AND TITLE-ABS-KEY (metaverse OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "virtual world" OR "3D virtual world" OR "virtual environment" OR "3D virtual environment")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English"))
Web of Science	"software engineering" (All fields) AND learn OR teach OR edu OR train OR "immersive learning" OR "immersive education" (All fields) AND metaverse OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "virtual world" OR "3D virtual world" OR "virtual environment" OR "3D virtual environment" (All fields)

Table 3.3: Search strings in databases

[2]https://www.engineeringvillage.com/
[3]https://ieeexplore.ieee.org/
[4]https://www.scopus.com/
[5]https://www.webofscience.com/

3.3.3 Selection Criteria and Procedure

Based on the research questions and focus of the research, we defined an inclusion criteria list. Articles should be included when attending all the following criteria:

- being a primary study;
- accessible for download;
- answers at least one research question;
- published in journal, conference or book chapter;
- article reports the latest author's work; and
- full text written in English.

Works that did not report XR applied in SEE were excluded, that is, XR apps developed that did not fit in the improvement of soft and hard SE skills, according to Guide to the Software Engineering Body of Knowledge (SWEBOK). In addition, duplicate studies were also excluded. Figure 3.4 presents an overview of the number of articles during the selection and screening procedure, as well as the final set of articles selected for data extraction (PAGE *et al.*, 2021). In general, the articles selection procedure has been divided into 4 steps. In *Step 1*, 3,316 registers have been identified from 5 databases through search strings (see Table 3.3). Posteriorly, 981 duplicated records have been removed in *Step 2*. Therefore, 2,335 records have been screened to start the screening process. In *Step 3*, when applying the selection criteria on the title and abstract, 2,295 records have been excluded, resulting in 40 works for eligibility. Finally, in *Step 4*, when reading the full text for each article, 23 records have been excluded (i.e., 13 papers were out of scope, 2 papers were not written in English, 6 papers were not accessible for download, and 2 papers were excluded because authors had more recent studies). As result, 17 studies have been included in this review (see Table 3.4).

3.3.4 Threats to Validity

We present some possible threats to the validity of the review and future work. Studies that mentioned the word "software engineering", mainly in the title, abstract and keywords were returned. Other related words, such as "requirement engineering", "programming", "software development process", among others, could have been used, but it could return a large number of articles out of scope. Thus, it is possible for the search procedure to have missed a limited number of studies that refer to software engineering, but this is not referenced to its title, abstract or keywords.

Primary Studies
SU & CHENG (2013)
WANG & ZHU (2009b)
BESSA & SANTOS (2017a)
NG & TANG (2012a)
GULEC *et al.* (2021a)
SITTIYUNO & CHAIPAH (2019)
CHEN *et al.* (2010a)
SHARMA *et al.* (2019)
YE *et al.* (2007)
OCHOA & BABBIT (2019b)
AKBULUT *et al.* (2018a)
NAZLIGUL *et al.* (2017)
MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
INAYAT *et al.* (2016b)
RODRIGUEZ *et al.* (2015)
RODRIGUES *et al.* (2016b)
FERNANDES & WERNER (2021b)

Table 3.4: Final set of selected primary studies

Moreover, the inclusion of work-in-progress and workshop papers in the review might have altered the results of the review due to the nature of these studies, in comparison to journals and conferences. In addition, the number of researchers is too low to validate the review protocol.

3.4 Results

In this section, we present the results obtained from 17 studies screened for this review.

3.4.1 SE topics (RQ1.1)

From an educational point of view, we are interested in what SE topics XR apps address, what are the target audiences, as well as the main motivation for adopting XR apps to support SEE.

In order to obtain a standard in the categorization of the SE topics covered by the works, the SWEBOK (ÉCOLE P. BOURQUE & FAIRLY, 2014) has been adopted to classify the area of operation of XR apps. SWEBOK was established to promote a consistent view of software engineering worldwide, specify its scope, characterize contents, provide access to the knowledge in SE, and provide a foundation for curriculum development and certifications.

Therefore, in response to RQ1.1, Figure 3.5 presents the topics covered in relation to the number of studies. Most of them focus on *software project planning* and *agile methods*. According to SWEBOK (ÉCOLE P. BOURQUE & FAIRLY, 2014), software project planning should be the selection of an appropriate software

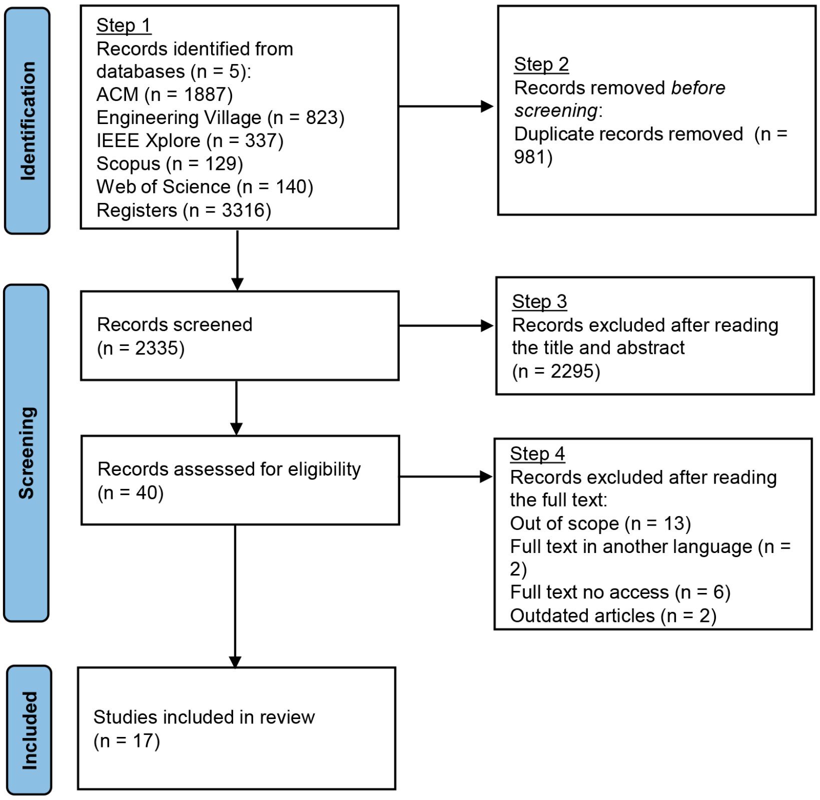


Figure 3.4: Overview of the filtering process

development life cycle model and perhaps tailoring it based on project scope, software requirements, and a risk assessment. Agile methods are considered lightweight methods in that they are characterized by short, iterative development cycles, self-organizing teams, simpler designs, code refactoring, test-driven development, frequent customer involvement, and an emphasis on creating a demonstrable working product with each development cycle.

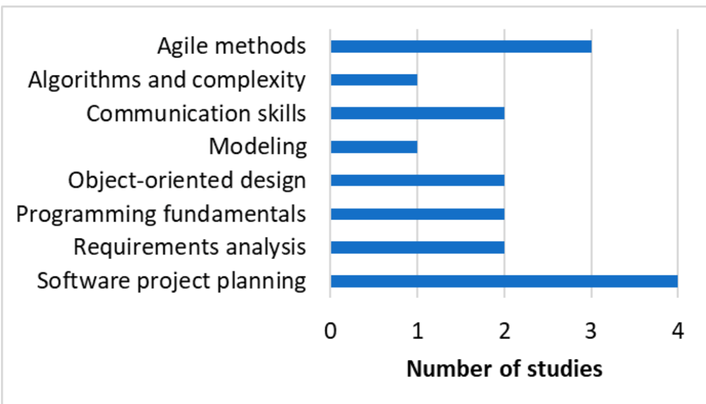


Figure 3.5: Number of studies by SE topics

Both studies in these two categories simulate real environments in which software engineers need to interact among teams and customers, as well as manage all or part of the software development process. Studies classified as *software project* *planning* aim to increase the level of knowledge and experience about the software development process (independent of process model) in an environment similar to a real environment. On the other hand, studies that specifically addressed *agile methods* were categorized separately. Table 3.5 presents the primary studies grouped by SE topic.

Topics	Primary studies
Agile methods	BESSA & SANTOS (2017a); RODRIGUEZ *et al.* (2015); SU & CHENG (2013)
Algorithms and complexity	AKBULUT *et al.* (2018a)
Communication skills	CHEN *et al.* (2010a) and NAZLIGUL *et al.* (2017)
Modeling	RODRIGUES *et al.* (2016b)
Object-oriented design	INAYAT *et al.* (2016b) and FERNANDES & WERNER (2021b)
Programming fundamentals	SITTIYUNO & CHAIPAH (2019) and SHARMA *et al.* (2019)
Requirements analysis	OCHOA & BABBIT (2019b) and SU & CHENG (2013)
Software project planning	NG & TANG (2012a); WANG & ZHU (2009b); YE *et al.* (2007); and GULEC *et al.* (2021a)

Table 3.5: Primary studies classified by SE topics

Considering the other topics, AKBULUT *et al.* (2018a) focused on sorting *algorithms* such as selection sort, bubble sort, insertions sort, and merge sort, which are relatively hard to be understood by the students.

Primary studies CHEN *et al.* (2010a) and NAZLIGUL *et al.* (2017) are approaches to improve and train *soft skills*. Problem and Task-Based Learning (PTBL) (CHEN *et al.*, 2010a) combines with Web 3D technologies to augment the teamwork skills in software engineering. Virtual Auditorium (NAZLIGUL *et al.*, 2017) is an approach to construct a practice environment for improving novice software engineers' public speaking experiences.

Regarding *modeling*, VisAr3D (RODRIGUES *et al.*, 2016b) provides a new way to visualize and understand UML models by combining the technologies of AVR. It is an environment that has been developed as an innovative proposal to be introduced in the classroom.

Studies FERNANDES & WERNER (2021b) and INAYAT *et al.* (2016b) developed XR apps to support understanding of concepts related to *object-oriented design*. More specifically, INAYAT *et al.* (2016b) basically emulates the real-world projects handed over to students as a part of object oriented analysis and design course. FERNANDES & WERNER (2021b) proposes the Immersive Software Engineering Education (iSEE), a theoretical framework to support the development of XR apps in the context of SE teaching, as well as an architecture to promote an immersive SE learning ecosystem. As proof of concept, an evaluation of a game named OO Game VR was carried out. This game is aimed at building three-dimensional drawings from primitive cube and sphere visuals based on basic object-oriented concepts.

Regarding the *programming fundamentals*, SHARMA *et al.* (2019) and SITTIYUNO & CHAIPAH (2019) are AR games to increase the motivation and reduce the fear of learning programming.

Finally, from the point of view of *requirements analysis*, OCHOA & BABBIT (2019b) allows creating a link of multiple perspectives from the separate analysis models to be viewed in three dimensions, and SU & CHENG (2013) developed a game that allows students to execute tasks according to story situation, and learn system analysis process via different characters corresponding to different situations.

3.4.2 Target Audiences (RQ1.2)

Considering the scope of XR apps in SEE, we hypothesized that most of the works focus on engagement and improvement of student learning outcomes. However, it is important to verify if the studies also contribute to the activities of the teachers, in order to assist in the preparation of classes, allowing the adaptation of the contents, as well as in the management and monitoring of the students' performance, among other resources. Therefore, in order to obtain evidence in relation to the target audience, below we respond RQ1.2.

We have identified three types of target audience: students, teachers and developers. According to Figure 3.6, a small part of the studies, in addition to facilitating student learning, supports activities by teachers as well as developers of XR apps.

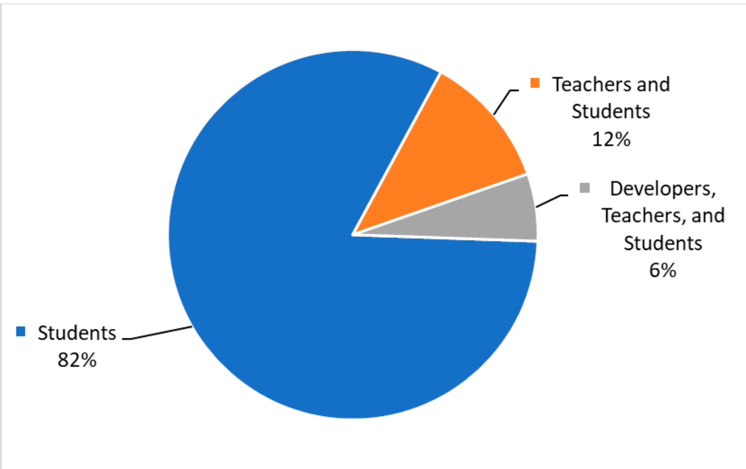


Figure 3.6: Target audience of XR apps

In terms of support for teachers, GULEC *et al.* (2021a) and RODRIGUES *et al.* (2016b) proposed mechanisms to facilitate the planning and personalization of SE content.

Virtual Reality Based Software Development Framework (VR-SODEF) (GULEC *et al.*, 2021a) provides an interactive VR experience for individuals learning about the tasks of software development starting from requirement analysis through software testing. The aim is to increase the level of knowledge and experience of the novice software engineers about the software development process in an environment similar to a real environment. Two complementary applications were developed: Scenario Generator and 3D Virtual Office Environment. Scenario generator is a desktop application for generating project scenarios used by teachers. This program enables to enter the information, tasks and items that are related to the whole project development processes. It is necessary to generate a software project scenario that contains the several different assignments related to each task of software development life cycle for participants to experience the entire software development process. The 3D virtual office environment was designed to teach the basis of software engineering concepts to novice software engineers. The inputs is provided by the "Scenario Generator" program as an Extensible Markup Language (XML) file, which contains a scenario of a software project. After parsing the XML file, the novice software engineer starts the simulation.

VisAr3D (RODRIGUES *et al.*, 2016b) facilitates the teacher's task, the students' learning, and the communication among them, being an important resource. Its target audience is the teacher and graduate students. On a regular course, the teacher exhibits a small part of a large and complex system diagram projected on the wall or on a printed folder. It details the features, components and connectors, in different levels of abstraction, possibly using various architectural styles. Before using VisAr3D, the software model in study must had been created and documented within a software model editor. All types of UML diagrams (class diagrams, use cases, sequence diagrams, etc.) must had been built using an external editor and exported as an XML Metadata Interchange (XMI) file. VisAr3D is able to read this stored UML diagram. Furthermore, it uses the 3D technology to capture and recognize the two-dimensional (2D) projection (teacher's diagram), helping the teacher and students in identifying and quickly accessing the model.

In addition to supporting teachers and students, iSEE approach (FERNANDES & WERNER, 2021b) also helps developers of XR apps. The approach has two contributions: an immersive platform in order to contribute to the SEE community, more precisely to be a platform in the provision of immersive educational applications of SE; and a theoretical framework to support the planning of the development of immersive educational applications, considering characteristics of the technologies, skills and competences of SE and pedagogical approaches. iSEE framework groups the main concepts of SEE through immersive experiences in two factors: objective and subjective. Objective factors are concepts that can be quantified (e.g., immersive devices, the immersive virtual environment itself and methods of interaction), and subjective factors are related to qualitative issues (e.g., feeling of being present in the virtual environment, engagement, the pedagogical theory and learning outcomes). In practice, when planning and developing an immersive educational application for teaching SE, one must establish and be constantly reviewing these factors, which can be identified through questions.

In this way, framework supports teachers in analyzing the adherence between the instructional objectives and the characteristics of the existing immersive platforms, in addition to being able to be used by developers in order to systematically establish the necessary requirements for the development of XR apps for SEE.

3.4.3 Features of XR apps (RQ1.3)

This section presents the features that motivate and engage the use of XR apps in SEE. In other words, we are interested in discovering what are the approaches that underlie the proposals of immersive experiences in SE learning.

During data extraction, we identified four types of features: 3D visualization, ecosystem, game, and social VR. Table 3.6 shows the classification of studies in relation to features.

Features	Primary studies
3D visualization	AKBULUT *et al.* (2018a); BESSA & SANTOS (2017a); NAZLIGUL *et al.* (2017); OCHOA & BABBIT (2019b); RODRIGUES *et al.* (2016b); and GULEC *et al.* (2021a)
Ecosystem	FERNANDES & WERNER (2021b)
Game	INAYAT *et al.* (2016b); SHARMA *et al.* (2019); SITTIYUNO & CHAIPAH (2019); SU & CHENG (2013); and MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
Game and Social VR	YE *et al.* (2007) and WANG & ZHU (2009b)
Social VR	CHEN *et al.* (2010a); NG & TANG (2012a); and RODRIGUEZ *et al.* (2015)

Table 3.6: Primary studies classified by features

XR apps that presented a new dimension to visualization and interaction with software artifacts have been classified as *3D visualization*. In addition, we also consider in this category environments that do not support the collaboration of other participants simultaneously, that is, single user. For example, VisAr3D (RODRIGUES *et al.*, 2016b) builds 3D views from UML models, but does not have mechanisms that allow users to enter the same view of the models in real time. VR-SODEF (GULEC *et al.*, 2021a) allows the student to navigate through an environment that simulates an office, in which the objective is to obtain the necessary requirements through interaction with Non-Player Character (NPC), in order to be able to perform the software design. NPC is a video game character that can not be controlled by a player. NPC is part of the story and setting of a game, and the user can interact with them to complete quests, buy, sell items or learn about the history of the environment (WARPEFELT, 2016).

The study reported in FERNANDES & WERNER (2021b) was classified as *ecosystem*, because iSEE approach establishes an architecture with the purpose of facilitating the use of XR apps of SEE developed by a community of actors (students, teachers and developers).

Most studies support *game*-based SEE (see Table 3.6). For instance, CODAR (SHARMA *et al.*, 2019) and ARCode SITTIYUNO & CHAIPAH (2019) are AR applications that create a playful environment to support the teaching of programming fundamentals. Through markers, virtual objects increase reality and provide a new way of interacting and defining basic programming commands. Particularly, SITTIYUNO & CHAIPAH (2019) checks whether the order of code is correct and provides rewards and feedbacks to a user. In addition, INAYAT *et al.* (2016b); SU & CHENG (2013); and MAYOR & LÓPEZ-FERNÁNDEZ (2021a) also allow students to develop their cognitive activities in a playful universe, where there is no force and weight of reality, that is, when entering the game world, the player can feel, even if temporarily, away from the reality in which they live, and to "live" safely in another world that gives you pleasure.

We classified as *social VR* the primary studies that afford more social interaction than video conferencing, such as the ability to organically break off into small groups, or interact with virtual objects in the scene (LI *et al.*, 2021). Therefore, CHEN *et al.* (2010a); NG & TANG (2012a); and RODRIGUEZ *et al.* (2015) fit into this category.

Finally, WANG & ZHU (2009b) and YE *et al.* (2007) are game proposals that allow collaboration and communication between students.

3.4.4 XR Technologies (RQ2.1)

In this research question, we are interested in finding out which technologies are adopted for the development of approaches, that is, which programming languages, frameworks, game engines and existing platforms were chosen for implementation.

With the purpose of meeting instructional objectives through experiences in XR apps, the use and adaptation of existing platforms are common in iL research (FERNANDES *et al.*, 2021), such as Second Life[6] and Open Wonderland[7]. In this sense, we want to obtain evidence regarding the adaptation of existing platforms for SEE.

[6]https://secondlife.com/

[7]http://www.openwonderland.org/

Table 3.7 presents evidence that most studies did not use existing platforms. On the other hand, we identified that some studies adopted the Second Life and Open Wonderland (see Table 3.7). In the studies INAYAT *et al.* (2016b); RODRIGUEZ *et al.* (2015); and BESSA & SANTOS (2017a) it was not possible to extract from the text what the development strategies were adopted, that is, the text does not report enough data on the implementation of the approach.

Platforms	Primary studies
Not used	AKBULUT *et al.* (2018a); FERNANDES & WERNER (2021b); GULEC *et al.* (2021a); NAZLIGUL *et al.* (2017); OCHOA & BABBIT (2019b); RODRIGUES *et al.* (2016b); SHARMA *et al.* (2019); SITTIYUNO & CHAIPAH (2019); SU & CHENG (2013); and MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
Open Wonderland	CHEN *et al.* (2010a)
Second Life	WANG & ZHU (2009b); YE *et al.* (2007); and NG & TANG (2012a)
Uninformed	INAYAT *et al.* (2016b); RODRIGUEZ *et al.* (2015); and BESSA & SANTOS (2017a)

Table 3.7: Existing platforms adopted by primary studies

In addition, Table 3.8 presents the programming and markup languages, frameworks, game engines, among other technologies reported in the studies for the implementation of the approaches.

Development technologies	Primary studies
Artificial Intelligence Markup Language (AIML)	NG & TANG (2012a)
iOS's MultiPeer Connectivity Framework, Apple's Core Motion Framework, SceneKit, Xcode IDE, and Swift 3	AKBULUT *et al.* (2018a)
Second Life's scripting language WANG & ZHU (2009b)	
Uninformed	BESSA & SANTOS (2017a); CHEN *et al.* (2010a); INAYAT *et al.* (2016b); NAZLIGUL *et al.* (2017); RODRIGUEZ *et al.* (2015); YE *et al.* (2007); and SHARMA *et al.* (2019)
Unity	OCHOA & BABBIT (2019b)
Unity and C#	MAYOR & LÓPEZ-FERNÁNDEZ (2021a) and FERNANDES & WERNER (2021b)
Vuforia AR	SITTIYUNO & CHAIPAH (2019)
WSDL, XML, and SOAP	SU & CHENG (2013)
XML	GULEC *et al.* (2021a)
XML, ARToolKit libraries, C++, OpenGL, Java, X3D, and Xj3D	RODRIGUES *et al.* (2016b)

Table 3.8: Development technologies adopted by primary studies

3.4.5 XR Modalities (RQ2.2)

In this research question we categorize studies in relation to Milgram's Reality-Virtuality (RV) continuum (MILGRAM *et al.*, 1995). MILGRAM *et al.* (1995) proposed a classification from the point of view of what appears in XR headsets (i.e., Head-Mounted Display) and defines three situations: environments composed only of real objects (reality); environments composed only of virtual objects (virtual environment); and environments composed of real and virtual objects MR. In other words, according to Figure 3.7, RV continuum works as a kind of "slider" that starts from the left (real environment), and as it moves to the other end (virtual environment), the real and/or virtual elements are presented.

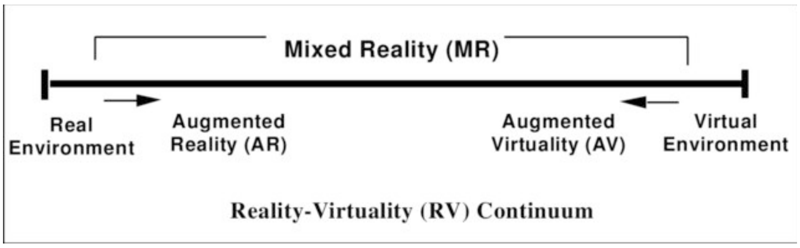


Figure 3.7: RV Continuum (MILGRAM *et al.*, 1995)

In our categorization, we analyzed the authors' classifications of each study, as well as the relationship with the RV continuum. In this way, we consider the studies self classified as AVR and AR as MR, and the environments that are composed only of virtual objects were classified as VR.

XR modalities	Primary studies
MR	RODRIGUES *et al.* (2016b); SHARMA *et al.* (2019); and SITTIYUNO & CHAIPAH (2019)
VR	AKBULUT *et al.* (2018a); BESSA & SANTOS (2017a); CHEN *et al.* (2010a); GULEC *et al.* (2021a); INAYAT *et al.* (2016b); MAYOR & LÓPEZ-FERNÁNDEZ (2021a); NAZLIGUL *et al.* (2017); NG & TANG (2012a); OCHOA & BABBIT (2019b); RODRIGUEZ *et al.* (2015); SU & CHENG (2013); WANG & ZHU (2009b); YE *et al.* (2007); and FERNANDES & WERNER (2021b)

Table 3.9: Primary studies classified by XR modalities

3.4.6 XR Devices (RQ2.3)

In this research question, we answered which devices users used to interact with XR apps. Figure 3.8 presents the distribution of devices identified in the studies.

As it can be seen, most environments are accessed via desktop (35%); mobile (smartphone/tablet) are used by 20% of the studies; immersive devices, such as

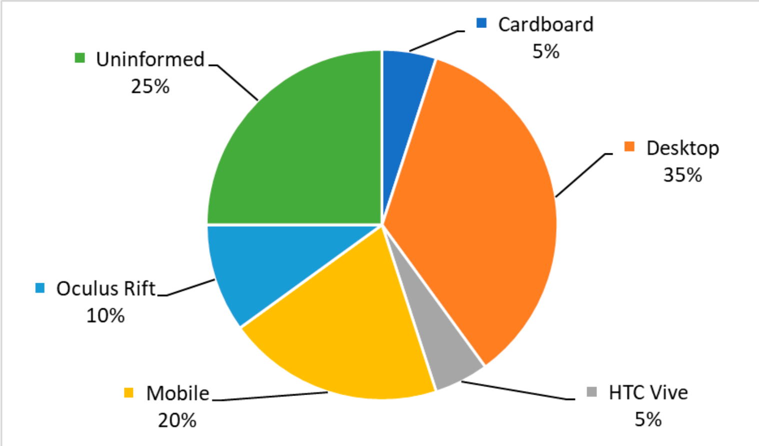


Figure 3.8: XR devices used by XR apps

Oculus Rift, HTC Vive, and Cardboard correspond to 20%; and 25% of the studies did not inform which devices are used to interact with the environments. Table 3.10 presents the relationship between XR devices and primary studies.

XR devices	Primary studies
Cardboard	MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
Desktop	CHEN *et al.* (2010a); NG & TANG (2012a); RODRIGUES *et al.* (2016b); SHARMA *et al.* (2019); WANG & ZHU (2009b); YE *et al.* (2007); and GULEC *et al.* (2021a)
HTC Vive	GULEC *et al.* (2021a)
Mobile	AKBULUT *et al.* (2018a); SITTIYUNO & CHAIPAH (2019,?); and MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
Oculus Rift	NAZLIGUL *et al.* (2017) and FERNANDES & WERNER (2021b)
Uninformed	BESSA & SANTOS (2017a); INAYAT *et al.* (2016b); RODRIGUEZ *et al.* (2015); SU & CHENG (2013); and OCHOA & BABBIT (2019b)

Table 3.10: Primary studies classified by XR devices

3.4.7 Evaluation Design (RQ3.1)

In this section we present how assessments are designed in studies. As shown in Table 3.11, for each study, the total number of participants, the number of participants in the experimental and control groups, the profile of the participants, as well as the main outcome metrics used in the evaluations were extracted. We emphasize that studies NG & TANG (2012a), MT163 do not report the number of participants and SHARMA *et al.* (2019) did not perform an evaluation, therefore, they were not included in the analysis.

Primary studies	Total of participants	Total number of groups	Experimental group	Control group	Type of participants	Outcomes
RODRIGUES *et al.* (2016b)	18	1	18	0	Graduate students	Effectiveness of the tool
WANG & ZHU (2009b)	52	1	52	0	Undergraduate students	Performance of the students
NAZLIGUL *et al.* (2017)	6	1	6	0	Students	Effectiveness of the tool
RODRIGUEZ *et al.* (2015)	45	1	45	0	Undergraduate students	Performance of the students
BESSA & SANTOS (2017a)	16	1	16	0	Undergraduate students	Usability of the tool
INAYAT *et al.* (2016b)	36	2	18	18	Undergraduate students	Performance of the students
YE *et al.* (2007)	29	1	29	0	Students	Performance of the students
SITTIYUNO & CHAIPAH (2019)	28	2	14	14	Undergraduate students	User satisfaction
CHEN *et al.* (2010a)	50	1	50	0	Students	Effectiveness of the tool
GULEC *et al.* (2021a)	32	2	16	16	Undergraduate students	Effectiveness of the tool
MAYOR & LÓPEZ-FERNÁNDEZ (2021a)	27	1	27	0	Students and Teachers	Effectiveness of the tool
FERNANDES & WERNER (2021b)	6	1	6	0	Students	Usability of the tool
AKBULUT *et al.* (2018a)	36	2	18	18	Undergraduate students	Performance of the students
SU & CHENG (2013)	63	2	33	30	Undergraduate students	Effectiveness of the tool

Table 3.11: Evaluation design of the primary studies

3.4.8 Evaluation Materials (RQ3.2)

Finally, we present the main materials used to obtain the results from the metrics (see Table 3.11). Thus, as shown in Table 3.12, all studies adopted questionnaires that were applied to participants. Most of the questionnaires were prepared by the authors of the studies. In some evaluations, questionnaires consolidated in the literature were adopted, such as TAM (DAVIS, 1985), Presence Questionnaire (PQ) (WITMER & SINGER, 1998a), Immersive Tendencies Questionnaire (ITQ) (WITMER & SINGER, 1998a), among others. In addition, some questionnaires were adapted to suit the purpose of the studies. For example, BESSA & SANTOS (2017a) made adaptations from TAM (DAVIS, 1985) and SU & CHENG (2013) adapted from ELY (1983); LIU & CHU (2010); SU *et al.* (2010).

Questionnaires	Primary studies
SUTCLIFFE & GAULT (2004)	FERNANDES & WERNER (2021b)
Authors' questionnaire	AKBULUT *et al.* (2018a); CHEN *et al.* (2010a); INAYAT *et al.* (2016b); NAZLIGUL *et al.* (2017); NG & TANG (2012a); RODRIGUES *et al.* (2016b); RODRIGUEZ *et al.* (2015); WANG & ZHU (2009b); YE *et al.* (2007); MAYOR & LÓPEZ-FERNÁNDEZ (2021a)
ITQ (WITMER & SINGER, 1998a)	GULEC *et al.* (2021a)
Interaction Anxiousness Scale (IAS) (LEARY & KOWALSKI, 1993)	NAZLIGUL *et al.* (2017)
Liebowitz Social Anxiety Scale (LSAS) (LIEBOWITZ & PHARMACOPSYCHIATRY, 1987)	NAZLIGUL *et al.* (2017)
PQ (WITMER & SINGER, 1998a)	GULEC *et al.* (2021a)
Questionnaire adapted	BESSA & SANTOS (2017a); SU & CHENG (2013); BESSA & SANTOS (2017a)
Subjective Units of Distress Scale (SUDs) (WOLPE, 1968)	NAZLIGUL *et al.* (2017)
TAM (DAVIS, 1985)	SITTIYUNO & CHAIPAH (2019)

Table 3.12: Questionnaires used by primary studies

3.5 Discussions

3.5.1 Coverage of SE topics

It is possible to notice that the coverage of XR apps in SE topics is low, in relation to the SWEBOK (BOURQUE & FAIRLEY, 2014). We believe that Metaverse has great potential to explore other SE topics and support in this area.

For example, from the point of view of software construction and testing (ÉCOLE P. BOURQUE & FAIRLY, 2014), an XR app can be developed to explore other forms of coding, such as the one based on low-code. Low-code is a technique that allows the creation of software solutions without requiring much programming or coding. Instead of writing many lines of code, it is more practical and faster to use visual interfaces to create applications. An example of low-code is Scratch (MALONEY *et al.*, 2010). Scratch is a graphical programming language that was developed by the Massachusetts Institute of Technology (MIT), inspired by the constructivist principles of the Logo language (SOLOMON *et al.*, 2020). Its objective is to help programming learning in a playful and creative way, and can be used by children from 8 years old and people who do not have any programming knowledge. The activities are developed from blocks that fit together and are divided into 8 categories: Movement, Appearance, Sound, Pen, Sensors, Control, Operators and Variables.

In this sense, we imagine that the student, wearing an XR headset (e.g., Meta Quest (META, 2022)) and immersed in the virtual world, can "grab" the code blocks with his/her hands and build the algorithm as if they were real LEGO bricks (LAWHEAD *et al.*, 2002) joining one piece to another. In addition, this construction process can be carried out collaboratively, that is, several students at the same time interacting with each other and modifying the construction of the blocks in order to solve the problem together in the form of algorithms. Therefore, students can develop programming skills more easily compared to the traditional way, especially considering aspects of object-oriented programming, as proposed in (FERNANDES & WERNER, 2021b).

From a motivation point of view, students can feel more engaged when programming. From a 3D visualization point of view, we believe that this feature has great potential for understanding the various "layers" when building software. Although FERNANDES *et al.* (2017) did not focus on teaching, the authors proposed the VisAr3D-Dynamic tool, whose objective is to create a new 3D representation of code execution based on the object-oriented paradigm in order to support the understanding of behavior dynamics of complex systems. Through the "timeline" function of the tool, the user can visualize the behavior of the software in several perspectives at the same time. For each piece of code executed, a representation is created in each perspective (diagram of classes, of sequence and of packages), in addition to maintaining code traceability between perspectives. In general, the tool works similarly to a video player, as it allows the user to control which moments he/she wants to see during the execution of the code. In addition, 3D visualization is also leveraged to add the dynamic coupling metric (YACOUB *et al.*, 2000). Figure 3.9 presents the instantiation of execution from various perspectives.

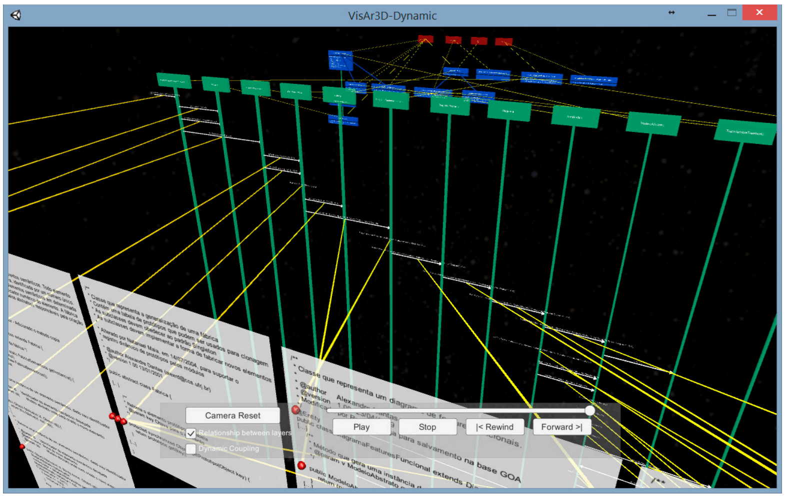


Figure 3.9: Perspectives visualization of VisAr3D-Dynamic FERNANDES *et al.* (2017)

3.5.2 Ways of Interacting and Visualizing Software Artifacts

New ways of interacting and visualizing software artifacts can be explored, as it has been used by software engineers to support software understanding. The use of 3D visualization is already a well-known method in SE.

Software visualization is a specialized area of information visualization that can be defined as "a representation of computer programs, associated documentation and data, that enhances, simplifies and clarifies the mental representation the software engineer has of the operation of a computer system" (GALLAGHER *et al.*, 2005). TEYSEYRE & CAMPO (2009) present an overview of works that use 3D visualization to support software comprehension. One of the main motivations for using the third dimension in software visualization is the use of metaphors known by human beings. This technique use well-understood elements of the world to provide insights about software. For example, some works are based on a city abstraction. CodeCity (WETTEL & LANZA, 2007) represents classes as buildings located in city districts, which, in turn, represent packages. TELEA & VOINEA (2004) help to gain an overview of a software system based on a 3D landscape technique called Theme Scapes (WISE *et al.*, 1995). Moreover, there exist several other systems based on real-world metaphors, such as ScenarioML, a requirements engineering tool for validating use cases using social interactions (ALSPAUGH & ANTÓN, 2008), and Metaballs, a 3D modeling technique commonly used to represent complex organic shapes and structural relationships in biology and chemistry (RILLING & MUDUR, 2002), among others. In addition to 3D visualization, some works have explored new forms of interaction through XR. MERINO *et al.* (2018) present a list of works. For example, CityVR an interactive software visualization tool that implements the city metaphor technique using VR in an immersive 3D environment medium to boost developer engagement in software comprehension tasks. KAPEC *et al.* (2015) present a visualization system that allows visual analysis of graph structures representing software systems in both AR. SkyscrapAR (SOUZA *et al.*, 2012) use AR to visualize software evolution using a metaphor of an evolving city. The packages are visualized as a rectangular city lots with the buildings on top of it, representing classes, where the area that a building occupies represents the size of a particular class measured in lines of code. Therefore, we reinforce the exploration of new forms of representation and interaction of software artifacts in order to support the improvement of SE learning outcomes.

According to the studies analyzed, we observed that all, with the exception of FERNANDES & WERNER (2021b), do not explore the third dimension to provide new ways of visualizing and informing software artifacts. For example, OO Game VR (FERNANDES & WERNER, 2021b), provides another way of representing objects besides traditional UML diagrams. Essentially, the studies focus on the potential that XR apps have to simulate interaction scenarios between users. According to Figure 3.10, most studies simulate scenarios of interaction between people in the context of software development.

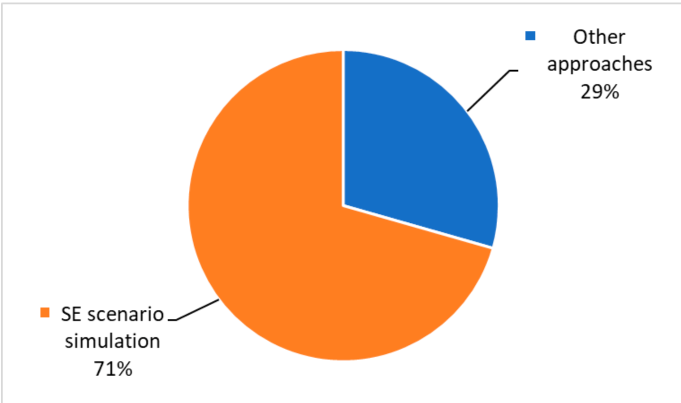


Figure 3.10: Approaches for using XR apps in SEE

We carry out this analysis because we intend to understand why the studies focused on scenario simulation. One hypothesis that we elaborate is the use of Second Life and Open Wonderland by most applications, since they are platforms that implement basic functions of virtual worlds (e.g., multi-user, avatar, chat, mouse/keyboard interactions, etc.) and allow the customization of environments.

However, according to the analysis of the relationship between the studies and the adaptation of the platforms for SEE, we do not have enough data to confirm or refute our hypothesis. According to Figure 3.11, disregarding the studies that did not provide information concerning the development of XR apps, 50% of the studies used platforms. Therefore, we can not understand why most studies only propose XR apps to simulate human interactions in the context of SE.

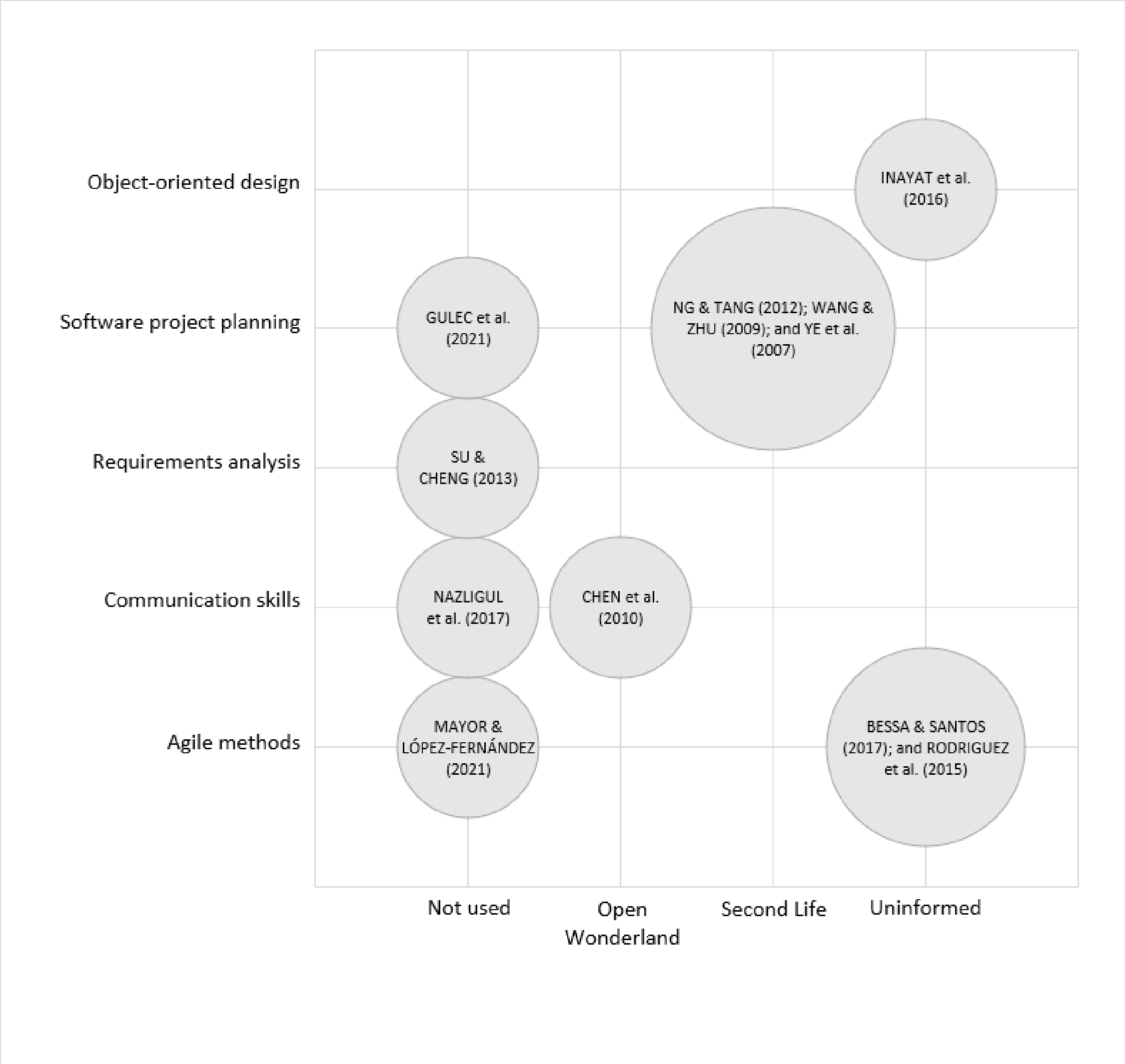


Figure 3.11: Mapping between primary studies, SE topics, and platforms

3.5.3 Learning Performance Analysis

Another feature perceived in the studies is the lack of integration of learning data between virtual environments. No study reported obtaining data from students while interacting with the XR app, in order to support decision-making by teachers based on academic performance indicators. XR apps identified by this review are stand-alone apps that do not integrate or support learning process tracking. Mechanisms for collecting data can be implemented for the purpose of tracking improvement to achieve better performance, as well as obtaining user experience data.

Applying LA is a strategy that can solve this problem. LA area aims to collect and analyze educational data from students' activities and to identify patterns of teacher behavior, improve the understanding of the teaching-learning process and provide useful information and tools that can help improve the environments in which these processes occur (HARMELEN & WORKMAN, 2012). LA applies Statistics, Machine Learning (ML), Natural Language Processing (NLP), and Exploratory Data Analysis (EDA), among other approaches, to education problems such as students' performance prediction, identifying misconceptions, slip detection, to mention a few (PEÑA-AYALA, 2018). Some works applied LA to improve the teaching-learning process in XR apps. For instance, HSIAO *et al.* (2017) developed a visualization analytic method to examine the recorded learner paths within a virtual world while second language learning occurred. KICKMEIER-RUST & ALBERT (2013) developed a tool to support teachers in the assessment process that retrieves performance data (e.g., the results of a test or the activities in a virtual environment) and updates the probabilities of the competencies and competence states in a domain. When a task is mastered, all associated competencies are increased in their probability, vice versa, failing in a task decreases the probabilities of the associated competencies.

3.5.4 Support to the XR apps Development

Another limitation that we highlight is the support of tools and technologies for the development of XR apps. As shown in Table 3.8, many XR apps for SEE are developed from technologies that require specific programming knowledge, such as Unity, Vuforia AR, Java, ARToolkit, C#, C++, among others. This is a challenge that should be considered by the SEE community, as the development of XR apps in other SE topics depends on people having specific skills and knowledge in XR development. In other words, teachers and other stakeholders who do not have this knowledge are limited in applying immersive experiences to SEE.

Some studies have been implemented to support XR development. For example, FERNANDES *et al.* (2017) adopted a software reuse strategy to develop VisAr3D-Dynamic, whose objective is to support the understanding of the dynamic behavior of the software. Authors developed Application Programming Interface (API) ThreeDUML[8] for the purpose of creating 3D models of class, sequence, and package created from any UML modeling tool that exports to XMI. XMI is a standard from Object Management Group (OMG)[9] that uses UML information to create XML documents. Through the use of XML, UML information can be more readily transferred between tools. Therefore, through this API the development process of other XR apps for SEE can be facilitated. In addition, FERNANDES & WERNER (2022) developed a Software Product Line-based approach to create instances of Web XR apps from a core of reusable assets that define a series of variables involved in the development of applications for the Metaverse. The approach consists of three phases: domain analysis defined a features model, it represents the features of an XR app

[8]https://github.com/filran/VisAr3D-Dynamic-Ultimate/tree/master/Assets/Scripts/ThreeDUMLAPI
[9]https://www.omg.org/

family, their commonalities and variabilities, and the relationships among them; domain design conceived a core of generic and reusable software artifacts based on the A-Frame as Domain Specific Language (DSL); and in the domain implementation an interface prototype for instantiating an XR app family was developed. This interface, named MetaSEE Features Model Editor, allows the developer to select which features the application will have and a code skeleton is generated in accordance with the selected features.

3.5.5 Biometric and Physiological Measures

From the point of view of validation of XR apps for SEE, all evaluations were carried out through questionnaires. One of the main limitations of this method is the non-guarantee of accuracy of the answers, as well as the ambiguity in the interpretation of questions by the participants.

Biometric and physiological measures should be explored in the evaluations of future studies in order to increase the reliability of the results and reduce the invalidity bias of the answers to the questionnaires. Biometric and physiological metrics can enrich data analysis, in addition to applying only questionnaires. These measures are one possible alternative to circumvent the questionnaires' limitations and can be monitored during and after immersion, such as heart rate, salivary cortisol levels, and postural stability (REBELO *et al.*, 2012). In this sense, biometric and physiological measures can be useful indicators to study human behavior and performance in XR apps in order to highlight what physiological data monitoring can bring to the understanding of user experience (MARTINEZ *et al.*, 2020), which is difficult to obtain through questionnaires.

3.6 Final Remarks

This review has two main contributions: to characterize the state-of-the-art of the Metaverse for SEE and to propose a set of components to enable it to be grouped into 5 layers.

We characterize the state-of-the-art from a scoping review of the literature. We analyzed 17 out of 3316 studies retrieved from 5 databases. As a result, we identified some limitations: (i) there is little coverage in SE topics by the applications; (ii) applications do not provide means for analysis of learning data in order to improve the immersive experience, as well as provide (iii) learning performance indicators to support decision making; (iv) no mechanisms were proposed to support the development of Metaverse for SEE digital assets; (v) there is no interoperability between the applications, in addition to having a centralized and non-scalable architecture; (vi) in the primary studies, biometric data were not used to validate the proposals for immersive experiences SEE. Furthermore, the evidence that supports the proposal of our approach, which is presented in this review, is expounded upon in Chapter 5.

Chapter 4

Experience Report

4.1 Introduction

This section has as its main objective to describe the experiences acquired during the research and how they contributed to the evolution and definition of the proposed approach. As presented in Chapter 1, MetaSEE is an approach with the purpose of supporting an ecosystem through the Metaverse, that is, the approach proposes to facilitate the adhesion of the Metaverse by professors and students, providing mechanisms to support the design and development of XR apps, as well as establishing an interoperable framework focused on SEE through the Metaverse.

Through the systematic review of iL frameworks (Chapter 2), we were able to verify mainly that the proposed frameworks focus more on theoretical than technological aspects. In addition, we identified some gaps, such as lack of development tools that facilitate the construction of immersive environments without requiring skills in programming or 3D design; techniques to reduce motion sickness, immersive and assistive technologies, tools to facilitate the instantiation of XR apps from the parameterization of variability; mechanisms that can integrate student data between different XR apps and allow monitoring of learning evolution, among others.

Additionally, we carried out a review of works that propose to support SEE through the Metaverse. As already explained in Chapter 3, we understand the Metaverse as a new paradigm of human-computer interface. In other words, the Metaverse must allow users to interact with computational mechanisms in an intuitive, realistic, and ubiquitous manner. For example, *intuitive* for providing interactions and feedback through multimodal channels, such as gestures instead of mouse clicks, and feedback through smell; *realistic* by providing views that come close to reality (e.g. quality, FPS, 3D), stereo audio, as well as financial transactions; it is ubiquitous because it is present and available in all places and contexts, such as equipment maintenance, surgery assistance, and teaching support, among others.

Therefore, XR apps are one of the main elements that make up the Metaverse, as they are applications that operate in the spectrum of the Reality-Virtuality Continuum (MILGRAM *et al.*, 1995) and enable interaction through multimodal channels and are mainly composed of VWs. As a result, one of our main findings is the lack of interoperability between XR apps, as well as limitations in visualization and interaction. Identified XR apps do not allow data interoperability, which hinders the monitoring by professors regarding the evolution of students' learning in certain topics of SE. XR apps does not exploit the potential of immersive visualization and interaction technologies. In other words, most applications focus on simulating interaction between users in the context of software process routines, such as the use of tools based on agile methodologies, such as Kanban. A few other applications resignified the use of UML diagrams and explored the third dimension to insert new information, as well as the exploration of new views in the VW.

Based on the evidence acquired as presented above, we carried out two case studies: the first we applied it in the design of an XR app focused on SEE, and in the second case we carried out three evaluations of a VW focused on supporting SEE.

The purpose of this chapter is to present the evidence and experiences gained during our research in providing mechanisms that bridge the SEE gap through the Metaverse. In Sections 4.2 and 4.3, we describe our experience applying the framework and evaluations of a VW, respectively. In Section 4.4, we highlight our main findings and experiences.

4.2 Case 1

As described in Chapter 1, we produced the first version of our framework from a RR. As a Proof of Concept (PoC), we used it to assist in the design of an XR app focused on SEE. The details of the framework, named iSEE, and its guidelines are described in (FERNANDES & WERNER, 2021a).

iSEE framework was presented in an online session for a team composed of a doctor professor specialized in SEE, a doctor specialized in AVR; and a doctoral student specialized in serious games.

The team's objective was to establish the main aspects of the development of a VW for SEE, named as virtual classroom prototype. During the definition of requirements, opportunities for improvement in the framework guidelines were identified, such as the reformulation of some terms, and the addition of some guidelines, among others. In addition, we also checked during development that the framework did not yet address key issues to assist in the construction of the virtual classroom prototype. As a result of the defined requirements, the FRAME VR[1] tool was chosen for the development of the environment. The virtual classroom prototype was developed by students in a postgraduate course in advanced topics in SE (FERNANDES *et al.*, 2022a).

4.3 Case 2

Once the prototype was developed, we designed three evaluations, each with a specific objective: the first focused on usability; the second focused on the UX; and, finally, the third focused on learning outcomes in SEE. The evaluations involved different participant's profiles depending on the defined objectives.

4.3.1 Usability Evaluation

This evaluation was conducted with one usability specialist in order to verify the usability of the virtual classroom prototype. We should emphasize that the only specialist who participated in the evaluation did not work in the development and was completely unaware of the environment developed. The specialist has a master's degree in computing; is familiar with devices such as computers and mobile devices, including immersive devices, and has experience with AVR; but rarely has contact with games.

Materials and Methods

The study consisted of three stages: initial familiarization with the prototype, task execution, and usability evaluation. During the first stage, the specialist was given up to 30 minutes to explore the environment freely. After exploration, the specialist completed a set of tasks designed collaboratively by the environment designers. For each task, the specialist rated its difficulty on a 5-point Likert scale and provided a justification for the score. Subsequently, the specialist evaluated the prototype's usability through a questionnaire.

Usability questionnaire was elaborated based on SUS (BROOKE, 1996b), Igroup Presence Questionnaire (IPQ) (SCHUBERT *et al.*, 2001), PQ (WITMER & SINGER, 1998b) and Motion Sickness Assessment Questionnaire (MSAQ) (GIANAROS *et al.*, 2001) because they comply with the purpose of the assessment and it was defined the utilization of only 13 out of the 32 questions from Witmer and Singer's Presence Questionnaire (PQ) (WITMER & SINGER, 1998b) with a 7-point Likert scale for each question. More details are described in FERNANDES *et al.* (2022b).

[1]https://framevr.io/

Analysis

The evaluation was carried out in two rounds, the first being interrupted by technical problems, and the second the evaluation was completely carried out.

In January 2022, the prototype evaluation was conducted. During the exploration phase, the environment did not experience issues with the slow loading of items, which had occurred during the first round. Following the exploration phase, the specialist successfully completed the assigned tasks. The specialist rated 34% of the tasks as easy to perform, 8% as neutral, and 58% as very easy.

Subsequently, the specialist completed the usability questionnaire. Overall, the environment was evaluated positively, with most of the usability questions receiving favorable scores. However, two questions were identified as critical aspects that require improvement in the prototype. These critical aspects were related to the issues encountered during the initial evaluation session. Upon a detailed analysis of the situation, it was discovered that the equipment utilized interfered with the execution performance of the environment, resulting in a poor interaction experience characterized by delays in the response time of the interaction with the virtual classroom prototype.

Regarding the evaluation feedback applied after the usability questionnaire, the specialist agrees that the time for exploration was sufficient. Regarding the understanding of usability issues, the participant states that "*depending on the degree of knowledge of the English language and even the concepts and definitions of technical terms, this may result in difficulties for users to answer the usability questionnaire*". When asked how virtual environments can support education, the specialist stated: "*I believe it is a new way of not only disseminating content but also for people to interact with each other and with the content*". About virtual environments, the specialist stated that the advantages are "*being able to explore interactive content such as multimedia, videos, audios, webcam, in addition to simulating real-world scenarios and environments*" and the disadvantage "*at the moment, the need to have an infrastructure (machine, internet) that supports the execution of the technology and perhaps the lack of knowledge on how it works by a group of people*".

Lastly, the specialist identified certain areas in the questionnaires that require improvement. Specifically, these areas include the need to reformulate certain questions to enhance their clarity and reduce ambiguities, incorporating a visual element to enable users to monitor their progress in completing the questionnaire, and providing information about the total number of questions that must be answered.

4.3.2 User Experience Evaluation

This evaluation was conducted in July 2022 to assess the user's level of satisfaction when interacting with the prototype. The contribution of this work is to verify if the virtual classroom has minimum conditions to provide experiences in VR.

Materials and Methods

The profile questionnaire was used to collect demographic data, as well as device and browser information from the participants. On the other hand, the tasks questionnaire identified 12 tasks (FERNANDES *et al.*, 2022a) to be performed by the participants and obtained their level of difficulty through a 5-point Likert scale, along with justifications for their scores. Finally, the UX questionnaire was used to assess the participants' interaction experience with the virtual classroom prototype.

Prior to the start of each session, participants completed the profile questionnaire via email, providing their demographic and equipment information. The researcher then explained that the session was divided into three phases. The first phase involved participants freely exploring the virtual classroom for a maximum of 30 minutes while verbalizing their thoughts through the think-aloud protocol. Participants were also informed that the researcher would not be able to intervene or assist them during this phase.

After the free exploration, the second phase involved carrying out tasks in the prototype, with participants rating the difficulty level of each task using the 5-point Likert scale and providing justifications for their scores. Finally, the UX questionnaire was administered to obtain the participants' feedback on their overall experience with the virtual classroom prototype.

Analysis

Following our strategy, we chose participants who are experts in VR and active in the industry, regardless of academic background. XR specialists members of the Brazilian Association of Extended Reality (XRBR)[2] were randomly invited to participate in the experiment.

A pilot study aimed to validate and improve the experiment protocol by conducting a pilot study with two participants. Some changes were implemented to reduce threats to the validity of the experiment and enhance its reliability.

The study recruited four participants, consisting of a mix of males and females with varying educational backgrounds and experience in immersive environments. Participants' profiles reflect individuals who are directly involved in the XR market, creating content and managing teams of programmers who develop immersive

[2]https://xrbr.com.br/

environments, with an average industry experience of 5 years and 3 months. Thus, the participants possess a practical understanding of the minimum requirements for immersive environments to deliver a satisfying user experience.

The study found that most participants were able to discover common avatar movements features, such as A, S, D, and W keys, arrow keys, and teleport, which are typically found in virtual environments and games. Most desktop-based games allow interaction with these keys. Additionally, common interaction features, such as click-to-access items, were also easily discovered by participants.

Although FRAME VR provides a tutorial of basic commands, no participant was able to access it. Half of the participants in the study identified the absence of a tutorial as a major difficulty. Overall, the main difficulties encountered by the participants were related to the design of the environment, such as improving visual aspects to facilitate location understanding, using self-explanatory descriptions and eye-catching signs, avoiding visual clutter, and placing objects away from the avatar's head. There were also issues related to the FRAME VR software, such as operational instability, difficulty accessing the tutorial, and unfriendly interaction buttons.

After free exploration, the participants were led to perform 12 tasks in the environment, which were designed in order to observe if the participants would be able to access the main functionalities and project contents for VW. Most participants were able to successfully perform most of the tasks, highlighting P5, who achieved 92% of success in carrying out the tasks. One of the reasons that explain this result is the programmer profile and interaction with games. On the other hand, P6 has a high failure rate in performing tasks. The fact of finding some difficulties in the locomotion of the avatar can substantiate its performance. At the same time, the participants indicated the degree of difficulty in performing each task. More details can be found in (FERNANDES *et al.*, 2022a).

After completing the tasks, the participants answered the 27 questions of the UX questionnaire. In general, most of the evaluated characteristics of the environment had positive levels of satisfaction. However, some questions are more critical because they are considered, by at least half of the participants, as harmful aspects to the user experience. These aspects correspond to immersion, flow, presence, and expectation.

After the questions, the participants informed which were the positive and negative aspects and opportunities for improvement. From the point of view of positive aspects, P3 stated that *"the environment was similar to others, which made the experience easy to master"*. For P4, *"it is a simple way for many people to have experiences in virtual environments, regardless of more sophisticated or expensive hardware"*. For P5, the environment has *"good performance and everything seems to work well, such as whiteboard and pointer. The environment is satisfactory for* *laptop users"*. For P6, the *"environment is pleasant and has inviting elements for interaction"*.

Regarding the negative aspects, P3 highlighted that *"audio is not standardized and very loud; the avatar rotation sensitivity is low (I didn't find an option to change this); the teleportation system doesn't match the speed I prefer to interact in this environment and there is no way to regulate it; viewing the videos is uninteresting because it offers the same experience that I would have outside this virtual environment; the option to open other tabs and take me out of the virtual environment is discouraging and breaks the little immersion. I got dizzy and a little nauseous after a while of exploring the space"*. For P4, it stated that the *environment "lacks a command tutorial and a step-by-step path indicator"*. For P5, the main difficulty lies in moving the camera with the laptop's touchpad. Finally, P6 stated that had *"difficulty in recognizing movement and content exit commands"*.

Finally, as the main suggestions for improvement for a better user experience, according to P3, the environment should *"enjoy more 3D animations; fewer 2D screens and offer interaction with other users"*. For P4, it is important *"to present a step-by-step tutorial of commands and waypoint"*. For P5, *"the possibility to use VR headset while other users use desktop/laptop"*. And for P6, *"to provide commands for moving around and more visible icons for interacting with content"*. More details can be found in (FERNANDES *et al.*, 2022a).

4.3.3 Learning Outcomes Evaluation

Finally, after the increments made in the virtual classroom prototype based on the previously reported evaluations, the objective of this evaluation was to verify the learning gain in SE through the prototype.

Materials and Methods

In this evaluation, we elaborate five materials. The profile questionnaire aims to obtain demographics, professionals, and game experience, as well as experiences in learning SE. The pre-and post-test questionnaires were designed to measure the learning before and after the intervention (use of the virtual classroom).

A set of tasks was designed so that participants can explore the prototype features. The participants were divided into two teams and the members of each had to perform activities collaboratively. The final objective is the elaboration of a document of requirements based on the simulated interviews with the avatars of the VW.

Finally, in the feedback questionnaire, the experience of each participant when interacting with the virtual classroom prototype is obtained from the point of view of usability. The ten questions from SUS (BROOKE, 1996a) were incorporated into this form, as well as four questions prepared by the researcher.

Analysis

We carried out this third evaluation in November 2022 in the context of a course on advanced topics in SE in the graduate course at Federal University of Rio de Janeiro (UFRJ). The study was carried out in Lab3D at COPPE/UFRJ with four students of the discipline. Each one used a computer individually.

The average age among them is 25 years old, half men and half women, all master's students. From the point of view of gaming experience, two reported playing up to 5 hours a week, one playing up to 10 hours a week, and one playing up to one hour a week. Among the types of games reported by participants are First Person Shooter (FPS), Role Playing Game (RPG), fantasy and adventure games, and multiplayer. In addition, the main devices used by participants to play are desktop and mobile. We also looked at whether participants had ever had contact with immersive devices. Among the four participants, three reported that they had already had contact with immersive applications through the XR headset, such as Samsung VR and Oculus Quest.

From the point of view of SEE, all participants reported that they developed some project during the undergraduate course. However, three reported that the project did not add much to their knowledge of the practice. One reported that the project he participated in went into production. Regarding the practical activities of SE, half of the participants reported that they did not obtain considerable gains, while the other two agree that they acquired positive experiences. When investigating the SE topics that were most difficult to learn, they all reported software testing and maintenance. To finalize the profile analysis, three participants reported that they consider themselves able to act as software engineers considering the knowledge acquired in undergraduation. However, only one declared to be unprepared to work in the industry.

In order to be able to measure learning after the intervention, pre-and post-test questionnaires were applied. Both are composed of the same three questions, which are related to the contents of the virtual classroom. In the VW of the prototype, concepts of software requirements are presented, as well as mechanisms for simulating interviews with stakeholders in order to approximate real scenarios of software requirements elicitation. When comparing each participant's pre-and post-test responses, three participants got the same result. However, one participant obtained a lower result in the post-test.

Finally, we analyze the prototype from a usability point of view. It was possible to obtain an average acceptability score of 81.25 points for the prototype, as shown

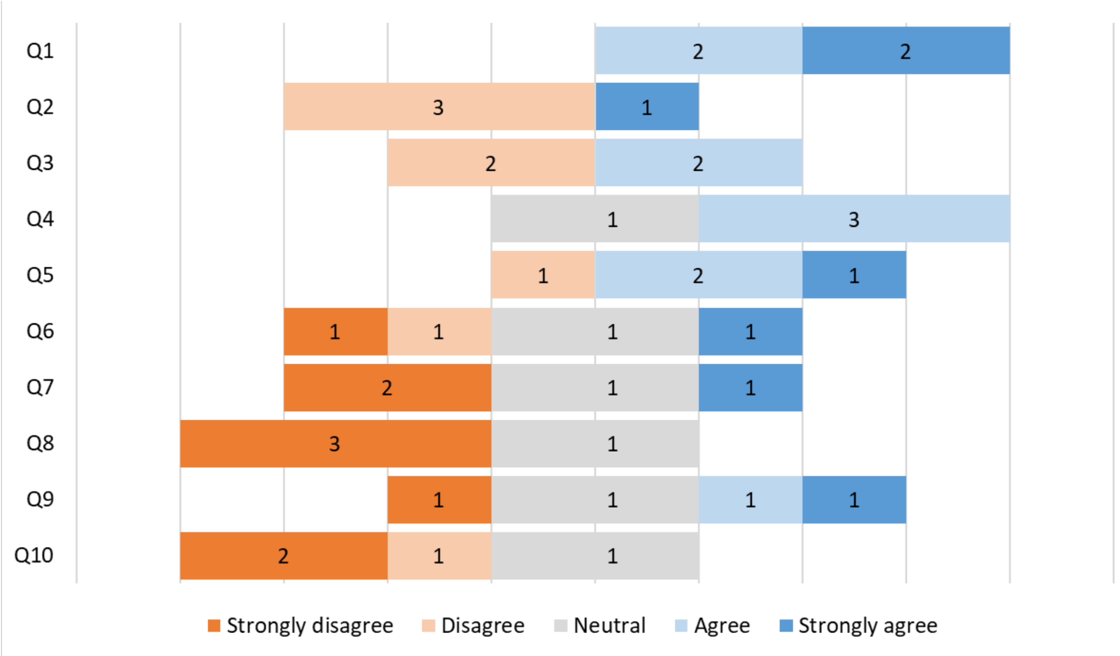


Figure 4.1: Analysis of feedback questionnaire responses

in Figure 4.1. The obtained score indicates that the system meets the acceptable threshold in usability, as evidenced by its score surpassing the referenced baseline average of 68 points, thus allowing for the conclusion that the prototype is deemed acceptable in terms of usability (BROOKE, 1996a).

In addition to usability issues, we got everyone's feedback on:

1. understanding of software requirements through the prototype;
2. benefits of VWs for teaching requirements engineering;
3. features that should be added to improve the experience; and
4. if they believe that in the future, immersive devices will be used to support SE activities.

Three participants reported that the use of the virtual classroom prototype during graduation would facilitate the understanding of software requirements.

From the perspective of the advantages of VWs, all participants reported that the main advantage is the simulation and interaction in a controlled environment. Specifically, one participant reported "*being able to have a hands-on activity for requirements elicitation in a controlled, risk-free environment is the biggest benefit. In this way, it is possible to simulate conversations with interested parties without, effectively, taking the time of a person who could not possibly help and, thus, assemble the requirements for the software, having the freedom to make mistakes without being afraid of having consequences for someone or some company.*" Another participant reported "*the experience of talking with stakeholders helped to see how things work in practice, a test or list of exercises does not require the ability to extract information in the face of unnecessary information that common users usually pass in the process of gathering requirements, the process in this environment, in turn, it was closer to reality and required skills such as the perception that are normally not worked on in the discipline. The way the content is passed is more immersive, motivating me to know more details about each content for a longer time than what happens in the classroom.*"

Participants also reported some features that could improve the experience, such as tutorials for moving and accessing features, design and visualization aspects (e.g., color, positioning of 3D objects), a kind of virtual map to facilitate self-location and relationship to the VW and better organization of contents.

Finally, three of the participants believe that immersed devices will be common in the future and that they can contribute to SE activities. For example, one participant reported that "*immersive devices will become commonplace in the daily life of software engineers, which can facilitate remote work, improve interaction with customers and allow for more realistic software testing without the need for physical displacement*". Another participant reported that "*with the advancement of technologies, the software can be generated from verbal commands or through gestures*". Another participant described that "*a space can be created where people do interviews and immersive meetings, without the need for a monitor, keyboard and mouse*". However, one participant believes that it is unlikely that SE activities will be aided by immersive devices. He reported that "*replacing the use of the computer by VR in the SE process is unlikely, due to high costs and technology limitations. Furthermore, software engineers are highly accustomed to the use of computers, which are already considered an extension of the human body*".

Although the post-test results indicate a decline in knowledge of SE, the analysis of the participants' feedback indicates the advantages of the use of virtual environments for SEE.

A possible threat to the validity of the results, especially in the assessment of knowledge through the pre-and post-test, resides in the fact that it was not possible to guarantee the consultation of materials when completing the pre-test questionnaire. In this sense, the participant could have consulted some material, which was not used when completing the post-test questionnaire. In addition, perhaps the participant did not really learn and chose a random answer in the pre-test and got it right, or it could even be due to fatigue or loss of focus during the assessment session.

4.4 Final Remarks

In this chapter, part of the trajectory of the research in carrying out PoC through the two cases described above was reported.

This stage of the research helped to evolve the framework, as well as to better design the experiments, as in the definition of instruments, such as software, questionnaires, and indicators.

The evidence and experiences obtained allowed for testing the first version of the framework in a real scenario regarding the definition of requirements for the use of VWs for SEE. Additionally, from this point of the thesis, the research has all the necessary evidence to define the fundamental requirements (Chapter 5) and establish our approach to enable the Metaverse-based SEE.

Chapter 5

Fundamental Requirements

5.1 Introduction

In SE, requirement engineering plays a vital role as the whole success of software depends on the correctness of requirements gathered requirement (OCHODEK & KOPCZYŃSKA, 2018). If requirements are not collected properly, projects can fail (PACHECO & GARCIA, 2012). Therefore, in order to define our approach, first, we have established a comparative analysis of iL frameworks aspects from primary studies found from SLR (Chapter 2). Second, we have established fundamental requirements to compose an interoperable structure and ensure data integration between XR apps for SEE based on results found in Chapter 3. Finally, we performed a PoC (Chapter 4) in order to evolve the approach.

5.2 Comparative Analysis of iL Frameworks

Considering findings from Chapter 2, we grouped all framework elements in order to support understanding and analysis. Table 5.1 presents each framework element according to each work.

Table 5.1: iL Framework Element Descriptions

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
Practical Framework	Guideline	[PS7]	E1	Learning context	Pedagogical	A set of principles that educational context
			E2	Learning objectives	Pedagogical	A set of instructional objectives that students should achieve
			E3	Pedagogy/ heutagogy	Pedagogical	A set of principles that consider pedagogical aspects
			E4	Mobile learning considerations	Technological	A set of principles for mobile learning design
		[PS15]	E5	Physical space	Technological	Components that are essential for capturing the physical environment
			E6	User space	Technological	It includes all components required by the student to access the virtual space
			E7	Virtual space	Technological	It is virtual world of the environment
	Model Development	[PS2]	E8	Distributed Learning	Technological	It considers adopting next generation networking techniques which enable distributed participants to learn from distributed locations
			E9	Information-Centric Systems Engineering (ISCE) principles	Technological	It emphasizes the adoption of information centric principles while supporting systems engineering approaches
			E10	Role of Experts	Technological	They help create the information models and use-case diagrams (outlined earlier)

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E11	Technology based Mediums and Environments	Technological	It refers to immersive devices and technological support
			E12	User Centric Design	Technological	Use of software design tools, such as class, communication and sequence diagrams (based on the Unified Modeling Language UML)
		[PS3]	E13	Prototyping stage	Technological	It measures motivation and enjoyment
			E14	Planning and design stage	Technological and Pedagogical	It refers to four-dimensional framework for designing and evaluating immersive learning experience proposed by De Freitas et al. (2010)
			E15	Post-launch stage	Technological and Pedagogical	It analyses the learners' comments on the platform
		[PS8]	E16	Educational services	Pedagogical	They complement the virtual content offering support to academic institutions processes
			E17	User roles	Pedagogical	The roles define the actions of the user and their learning process, in the reverse part of virtual reality determines the type of interaction and content available and its associated educational services
			E18	Platform	Technological	The platform selection determines the degree of interaction and content that can be presented to the user within in virtual reality learning environments

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E19	VR learning environments features	Technological and Pedagogical	The objective is that users achieve their learning objectives through immersive learning
Theoretical Framework	Design of Learning Activities	[PS6]	E20	Acting Engagement	Pedagogical	It is the personal roadmap to build meaningful understanding of course materials
			E21	Pro-Acting Engagement	Pedagogical	It is to stimulate students' mind and emotion to be self-regulated and self-determined learner
			E22	Re-Act Engagement	Pedagogical	Learners will develop personal mental models
			E23	Reflecting Engagement	Pedagogical	Learners practice a sense-making process in which they assess the value of their own perspectives and other learners' perspectives
		[PS12]	E24	Context	Pedagogical	It may impact upon the place where learning is undertaken
			E25	Learning specifics	Pedagogical	This dimension involves a process of profiling and modelling the learner and their requirements
			E26	Pedagody	Pedagogical	This dimension analyses the pedagogic perspective of the learning activities, and includes a consideration of the kinds of learning and teaching models adopted alongside the methods for supporting the learning processes
			E27	Representation	Technological	This dimension outlines the representation itself, how interactive the learning experience needs to be, what levels of fidelity are required and how immersive the experience needs to be

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
	Influences Learning Outcomes	[PS1]	E28	Context	Pedagogical	The context is related to learner's family, educational environment and his/her cultural
			E29	Learning Activities	Pedagogical	Theses activities precede the learning outcomes and they describe the leaner's active use of the supplied learning material
			E30	Learning Outcomes	Pedagogical	It is the construction of knowledge in the mind of the learner
			E31	Teacher	Pedagogical	Teacher's role impacts on the learning potential
			E32	Learning Potential	Psychological	It defines that motivational factors, cognitive factors, emotional factors and previous experience are connected and influence the learning
			E33	Perception & Interpretation	Psychological	It is related to learners' presence
			E34	Instructional Media	Technological	It is related to quality of the learning and teaching material and to medium that represents the instructional information
		[PS4]	E35	Immersive Virtual Field Trips Taxonomy	Technological	It has three components that have guided our design of iVFTs and their evaluation
			E36	SENsing-ScAlability Trade-off contInuUM (SENSATIUM)	Technological	It reflects the sensing capabilities and resulting interaction opportunities of different immersive technologies and, more importantly, the associated costs

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
		[PS5]	E37	Complexity	Pedagogical	Complexity of what is studied
			E38	Interaction	Pedagogical	Interaction with teachers and other learners
			E39	Sense of immersion	Psychological	Learner feels embedded in a specific situational and geographical context
		[PS9]	E40	Learning outcomes	Pedagogical	Users' academic performance because it is a direct and relatively objective indicator for evaluating the effect of employing IVS for collaborative learning
			E41	Aesthetic experience	Psychological	It refers to users' awareness on how to proceed and of what counts as the fulfillment of the purposes and objectives being pursued within a system
			E42	Imagination affordance	Psychological	It refers to the capacity to creatively picture in one's mind something nonexistent
			E43	Immersion affordance	Psychological	It refers to the mental state of total absorption in the virtual environment enabled by, in addition to a high degree of real-time interaction, the rich information perceived through multiple sensory channels
			E44	System satisfaction	Psychological	It is defined as their overall affective and cognitive evaluation of the pleasurable level of fulfillment experienced with Immersive Visualization System
			E45	Interaction affordance	Technological	The extent to which users can participate in modifying the form and content of a mediated environment in real time
		[PS10]	E46	Afforded learning tasks	Pedagogical	These are tasks offered (afforded) by 3D virtual learning environments

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E47	Learning benefits	Pedagogical	They are the affordances resulting from tasks learning performed within 3D virtual learning environments
			E48	Construction of identity	Psychological	It is characteristics of the learner's experience as a result of these environment characteristics
			E49	Co-presence	Psychological	It is defined as the sense of "being there together" with other geographically dispersed users
			E50	Sense of presence	Psychological	It refers to a user's perception of "being there"
			E51	Learner interaction	Technological	It consists of embodied actions including view control, navigation and object manipulation, embodied verbal and non-verbal communication, control of environment attributes and behaviour and construction of objects and scripting of object behaviours
			E52	Representational fidelity	Technological	It consists of realistic display of environment, smooth display of view changes and object motion, consistency of object behaviour, user representation, spatial audio and kinaesthetic and tactile force feedback
		[PS11]	E53	Achieved learning outcomes	Pedagogical	Student's performance
			E54	Designing for learning	Pedagogical	Learning requirement, task affordances and learning specification
			E55	Learning stages	Pedagogical	The stages are conceptualisation, construction and dialogue

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E56	Dalgarno and Lee's model	Technological and Psychological	It is composed by representational fidelity, learner interaction, construction of identity, sense of presence, co-presence, afforded learning tasks, learning benefits
			E57	Types different of immersion	Technological, Psychological and Pedagogical	Empathy, reification and identification
		[PS14]	E58	Cognitive benefits	Pedagogical	It refers to better memorization, understanding, application and overall view of the lesson learned
			E59	Learning outcomes	Pedagogical	They are measured by performance achievement, perceived learning effectiveness and satisfaction
			E60	Reflective thinking	Pedagogical	It defined as active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it and the conclusion to which it tends
			E61	Student characteristics	Pedagogical	Student factors that could affect the learning outcomes include demographics, language, communication skills, learning styles, spatial abilities, problem solving styles, attitudes toward technology, cognitive styles, cognitive needs, computer anxiety and technology experience
			E62	Control and active learning	Psychological	They are akin to involvement in a psychological state experienced as a consequence of focusing one's attention on a coherent set of related activities and stimuli

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E63	Motivation	Psychological	Student motivation is a potentially important but understudied factor in virtual reality-based learning environment
			E64	Presence	Psychological	It refers to the user's subjective psychological response to a system
			E65	Usability	Technological	It is measured by perceived usefulness and ease of use
			E66	VR features	Technological	They are measured by representational fidelity and immediacy of control
	Influences Teacher's Intention	[PS13]	E67	Intention	Pedagogical	The degree to which a person believes that using a particular system would enhance his or her job performance
			E68	Attitude	Psychological	It refers to the degree to which a person believes that using a particular system would be free from effort
			E69	Perceived ease of use	Psychological	It is the degree to which a person believes that the use of an information system will be effortless
			E70	Perceived enjoyment	Psychological	The extent to which the activity of using the computer is perceived to be enjoyable in its own right, apart from any performance consequences that may be anticipated
			E71	Perceived relative advantage	Psychological	It refers to the degree to which an innovation is seen as better than the idea, program, or product it replaces
			E72	Perceived usefulness	Psychological	The degree to which a person believes that using the system will improve their performance

Continued on next page

Table 5.1 – *Continued from previous page*

Categories	Subcategories	Primary studies	ID	Framework elements	Element aspects	Element descriptions
			E73	Facilitating conditions	Technological	It refers to the degree to which an individual believes that an organizational and technical infrastructure exists to support the use of the system
			E74	Mobile self-efficacy	Technological	An individual's perceptions of his or her ability to use mobile devices in order to accomplish particular tasks

Considering the framework elements presented in Table 5.1, we started the analysis of the main elements to compose our framework to support XR apps design for SEE. First, we disregard elements focused only on psychological aspects. These aspects require model analysis based on psychological theories, which are not within our scope. For this reason, we consider technological and pedagogical aspects because they are related to our scope to support XR apps design for SEE. After iL framework elements analysis, we define a set of main affordances essentials to support XR app design, as shown in Table 5.2.

Although Chapter 2 demonstrated divergent definitions between immersion and a sense of presence, we consider immersion to be a qualitative characteristic of immersive experiences. In other words, *Immersion* affordance is related to which human senses will be involved during the immersive experience, the type of reality (e.g. VR or MR), as well as the devices that will be used to allow the stimulation of senses.

A good UX design in XR apps can make the user feel more immersed in the environment, facilitate easy navigation and interactions, and make the experience more intuitive and enjoyable. A bad UX design can lead to frustration, disengagement, and ultimately abandonment of the platform. XR apps often have complex interfaces with many features and options. Then, a good UX design is essential to help users easily navigate and understand the various functions available to them. Additionally, XR apps often rely on social interaction between users, and a UX design should also facilitate communication and collaboration between users. Therefore, *User Experience* affordance is related to HCI techniques, as well as mechanisms to ensure a comfortable immersive experience.

According to DIEHL (2005), software visualization can help developers, architects, and stakeholders better understand the complexity and functionality of a software system, identify potential problems or improvements, and communicate information about the system to others. Metaphors are one of the strategies to improve comprehension of software systems, such as the universe, solar system, trees, branches, maps, among others. For this reason, *software visualization* affordance is related to defining visualization strategies to represent software artifacts in VWs.

Adequate development tools have a significant impact on the efficiency, quality, and effectiveness of the development process. Especially for XR apps, these tools should be adherent to the characteristics provided by immersive experiences. For this reason, *development tools* affordance is related to mechanisms to help developers deploy XR apps.

Application features affordance is related to some XR app characteristics, such as if the XR app will support single or multi-users, necessary space around, language, and system requirements.

Type	Affordance	iL framework elements
Technological	Immersion	E11, E57, E68, E69, E72
	User Experience	E7, E18, E36, E45, E51, E52, E56, E57, E65, E66, E67, E68, E69, E72
	Software Visualization	E27, E34, E52, E56, E66
	Development Tools	E4, E9, E12, E74
	Application Features	E5, E6, E38, E61, E73
	Learning Indicators	E13, E15, E33, E39, E40, E44, E46, E47, E48, E50, E53, E59, E64, E70
Pedagogical	Learning Outcomes	E2, E19, E30
	Pedagogical Approaches	E3, E17, E26
	Student Profile	E61, E63
	Context	E24, E28, E63

Table 5.2: iL framework elements analysis

Providing feedback to students and helping them understand their progress and performance is very important in applications for education. For this reason, *learning indicators* affordance is related to indicators to provide motivation, feedback, personalization, assessment, and engagement.

Educational applications should define instructional objectives, i.e., what subjects should be addressed to learning improvement. Therefore, *learning outcomes* affordance is related to what SE topics and skills should be addressed in XR apps.

Pedagogical approaches can support different learning styles. By incorporating a variety of instructional methods and techniques within the XR app, developers can cater to the needs of different learners and provide a more inclusive learning experience. For this reason, *pedagogical approaches* affordance is related to approaches to aid immersive experiences.

Understanding the student profile can help to improve learning. By aligning the XR app with the learning outcomes affordance, developers can ensure that the XR app is effective at promoting learning and supporting skill development. Therefore, *student profile* affordance is related to student characteristics to personalize the learning experience, ensure accessibility, increase learner engagement, and improve learning outcomes.

Finally, *context* affordance is related to the context in which the XR app will be used. For example, classroom, training in a professional environment, anywhere the experience is not interrupted, anywhere that meets physical space requirements, etc.

5.3 Metaverse for SEE Requirements

Based on the discussions presented in Chapter 3, we identified three fundamental requirements to create a structure for the Metaverse for SEE: (FR1) software engineering education; (FR2) feasibility factors; and (FR3) components and technologies. According to discussions, the main limitations for SEE's progress in the Metaverse and to FR1, a Metaverse for SEE should:

- **FR1.1**: cover SE topics;
- **FR1.2**: support the analysis of learning performance data;
- **FR1.3**: implement new forms of visualization and interaction;
- **FR1.4**: facilitate development for the Metaverse;
- **FR1.5**: perform analyses using biometric data;
- **FR1.6**: provide data interoperability.

According to DIONISIO *et al.* (2013), the Metaverse needs four factors to make it viable. Therefore, in compliance with FR2, the Metaverse for SEE should consider the following factors:

- **FR2.1**: *realism* enables users to feel fully immersed in an alternative universe;
- **FR2.2**: *ubiquity* establishes access to the system via all existing digital devices and maintains the user's virtual identity throughout transitions within the system;
- **FR2.3**: *interoperability* is a connected collection of information, format, and data standards, most of which focus on the transfer of 3D models across virtual worlds, in addition to involving communication protocol, identity, and currency standards; and
- **FR2.4**: *scalability* allows concurrent efficient use of the system by massive numbers of users.

Finally, with the purpose of establishing the main components and technologies (FR3), we carried out a comparative analysis of the related works presented in Section 3.2. We extract information from studies that report the main components and technologies of the Metaverse in a structured and organized way, that is, in the form of architecture, overview, taxonomy and/or abstract and conceptual layers:

- **FR3.1**: *authoring tools* corresponds to tools and technologies to support the creation of content and virtual assets for the Metaverse;
- **FR3.2**: *devices* allow users to interact with the Metaverse through multimodal interfaces (e.g., XR headsets, haptic devices, brain-computer interface) were considered, as well as devices that provide data indirectly from the immersive experience (e.g., actuators, sensors, IoT);

- **FR3.3**: *economy* aspect addresses e-commerce issues and technologies as well as digital currencies;
- **FR3.4**: *infrastructure* encompasses aspects of architectures and infrastructures decentralized, as well as a set of technologies that involve data processing in different types of networks (e.g., 6G, data center, cloud computing, edge computing, etc.);
- **FR3.5**: *interaction* aspect is related to immersive experiences in the Metaverse, as well as multimodal and multisensory interaction methods and technologies;
- **FR3.6**: *physical world* is external and important real-world entities, such as users and service providers;
- **FR3.7**: *security* corresponds to implementing technologies to ensure financial transactions in XR apps, and issues such as user interaction moderation policies and laws are one of the great challenges;
- **FR3.8**: *storage* is related to the persistence of data, in which they originate from different sources (e.g., users, devices, economy) and are registered in a decentralized database, such as Blockchain;
- **FR3.9**: *technology* grouped computational methods and techniques for the development and support of XR apps, such as computer vision, spatial computing, digital twin, AI, among others;
- **FR3.10**: *virtual world* is virtual elements that make up XR apps and allow interaction between users and with virtual objects, such as avatars, virtual environments, scenarios, virtual services, among others.

For each element identified, we grouped it into general aspects and made a comparison between the studies, as shown in Table 5.3.

5.4 SE-specific Features

From the experience gained with the PoC (see Chapter 4), in addition to evolving the framework, we identified that XR apps for SEE needs to provide specific functionality to support SE activities. FRAME VR, Mozilla Hubs, Spatial.io and other virtual spaces are a kind of social network in which users interact and communicate with each other through VWs. In this way, virtual spaces do not have functionalities to support SE activities, such as coding, modeling, versioning, among others.

Works / Aspects	**FR3.1**: Authoring Tools	**FR3.2**: Devices	**FR3.3**: Economy	**FR3.4**: Infrastructure	**FR3.5**: Interaction	**FR3.6**: Physical World	**FR3.7**: Security	**FR3.8**: Storage	**FR3.9**: Technology	**FR3.10**: Virtual World
AKS *et al.* (2022)							✓			
GIANG BARRERA & SHAH (2023)				✓	✓				✓	
CHANG *et al.* (2022)		✓		✓		✓			✓	✓
CHEN *et al.* (2022b)				✓	✓				✓	✓
CHENGODEN *et al.* (2022)				✓	✓			✓	✓	
FU *et al.* (2022)									✓	✓
GADEKALLU *et al.* (2022)		✓					✓	✓		
AL-GHAILI *et al.* (2022)				✓	✓				✓	
HUANG *et al.* (2022b)					✓	✓			✓	
HUANG *et al.* (2022a)									✓	
HUYNH-THE *et al.* (2022)		✓	✓	✓		✓			✓	✓
KUSUMA & SUPANGKAT (2022)				✓					✓	
LEE *et al.* (2021a)	✓	✓	✓	✓	✓		✓		✓	✓
NJOKU *et al.* (2022)		✓	✓	✓	✓				✓	
PARK & KIM (2022)	✓	✓			✓				✓	✓
SETIAWAN *et al.* (2022)		✓	✓	✓					✓	✓
SUN *et al.* (2022a)				✓	✓				✓	✓
SUN *et al.* (2022b)				✓	✓					✓
WANG & ZHAO (2022)									✓	✓
WANG *et al.* (2022b)		✓		✓				✓	✓	✓
XU *et al.* (2022)		✓	✓	✓		✓			✓	✓
YANG *et al.* (2022a)				✓	✓				✓	
YANG *et al.* (2022b)	✓		✓	✓				✓	✓	✓

Table 5.3: Comparative analysis of key components and technologies for the Metaverse

Considering our experience with PoC, the MetaSEE approach should allow the use of SE-specific features. As a strategy, the MetaSEE architecture should enable the development of these features by a community interested in the Metaverse-based SEE and that they are reusable so that they can be added and adapted to any XR app.

5.5 Final Remarks

In this chapter, we performed a comparative analysis of iL framework elements and XR apps for SEE. After our analysis, we defined a set of affordances to help XR apps design for SEE, as well as we also established fundamental requirements to enable the Metaverse for SEE. In addition, we performed a PoCin order to evolve our approach. Considering these findings, Table 5.4 presents the traceability of the fundamental requirements that we based to define the approach, which is presented in Chapter 6.

Requirements	Physical Layer			Virtual Layer				Metaverse Engine Layer			MetaSEE Layer			Infrastructure Layer	
	User	Devices	Physical Enviroment	Avatar	Multimodal Interactions	XR App	Mulsemedia	Technologies	Economy	Security	Development Tools	Integration Tools	Learning Analytics	Network	Decentralized Storage
FR1.1													✓		
FR1.2													✓		
FR1.3					✓										
FR1.4											✓	✓			
FR1.5		✓											✓		
FR1.6													✓		✓
FR2.1		✓		✓	✓	✓	✓								
FR2.2		✓		✓	✓	✓									
FR2.3				✓		✓	✓		✓				✓		✓
FR2.4	✓			✓	✓	✓	✓	✓					✓		✓
FR3.1											✓	✓			
FR3.2		✓													
FR3.3									✓						
FR3.4														✓	✓
FR3.5					✓										
FR3.6	✓		✓												
FR3.7										✓					
FR3.8															✓
FR3.9								✓							
FR3.10				✓		✓	✓								

Table 5.4: Fundamental requirements traceability

Chapter 6

MetaSEE Approach

6.1 Introduction

Metaverse-based Software Engineering Education (MetaSEE) approach was defined in order to answer the main research question of this thesis (see Chapter 1): *How to support immersive learning in Software Engineering through the Metaverse?* For this reason, MetaSEE approach enables the Metaverse-based SEE by providing guidelines to support XR apps design based on technological and pedagogical affordances, as well as defining an interoperable and scalable structure composed of the Metaverse's main concepts and technologies grouped in layers that support both XR apps development based on software reuse techniques and mechanisms to improve learning outcomes in SE, allowing educators and students to have immersive experiences and increasing adoption of iL in SEE.

In other words, the main objective of the MetaSEE approach is to encourage the adoption of immersive experiences in SEE by educators and students. For this reason, firstly, the approach establishes mechanisms to facilitate the development of XR apps and provides a Metaverse structure to allow access and interoperability between XR apps for SEE. In this way, MetaSEE approach serves both developers in the use of mechanisms that assist in the development of XR apps, as well as educators and students, in the interoperable access of XR apps to engage learning outcomes in SE.

MetaSEE approach was conceived through four phases, as shown Figure 6.1. In the first phase (Section 6.2), it was elaborated a structure composed of main concepts and technologies grouped in layers that enable the Metaverse, adding SEE specific features in *MetaSEE Layer*. In the second phase (Section 6.3), *MetaSEE Layer* was designed providing three abstract components: *Development Tools*, *Integration Tools*, and *Learning Analytics*. According to Figure 6.1, *MetaSEE Framework*, *MetaLine*, *MetaSEE Extensions*, and

MetaSEE Analytics are concrete components that implement the *MetaSEE Layer*. In the third phase (Section 6.4), we describe an architecture to aid XR apps development, allowing immersive experiences and supporting the improvement of learning outcomes in SE. Finally, in the fourth phase (Section 6.5), *MetaSEE platform* was deployed in order to enable immersive experiences in SE through the Metaverse. The following sections detail each phase of the MetaSEE approach.

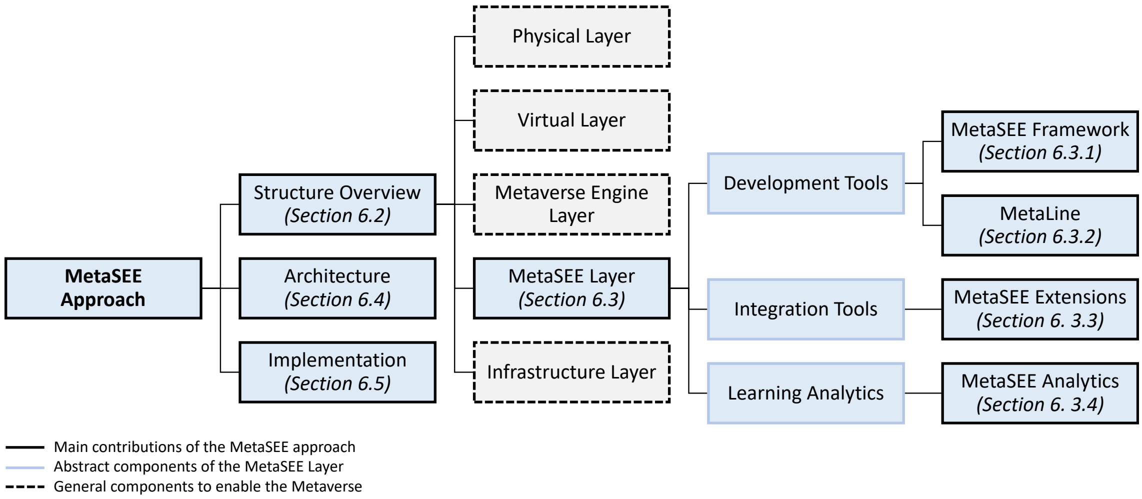


Figure 6.1: MetaSEE approach overview

6.2 MetaSEE Structure Overview

After analyzing the Metaverse's main requirements in Section 5.3, we established an overview of the main components to enable the Metaverse-based SEE. These conceptual components are grouped into five layers: *physical*, *virtual*, *Metaverse engine*, *MetaSEE*, and *infrastructure layer*. Figure 6.2 presents the relationship between layers and we describe each of them.

6.2.1 Physical Layer

Physical Layer corresponds to the main entities external to the Metaverse and that belong to the physical and real world. In the SEE context, *User* represents the student, teacher, or anyone interested in immersive experiences. *Devices* correspond to a range of devices that users use or wear to interact with XR apps. *Physical Environment* is also an important element, as it may be necessary to obtain data from the environment around the user in order to provide pleasant XR experiences.

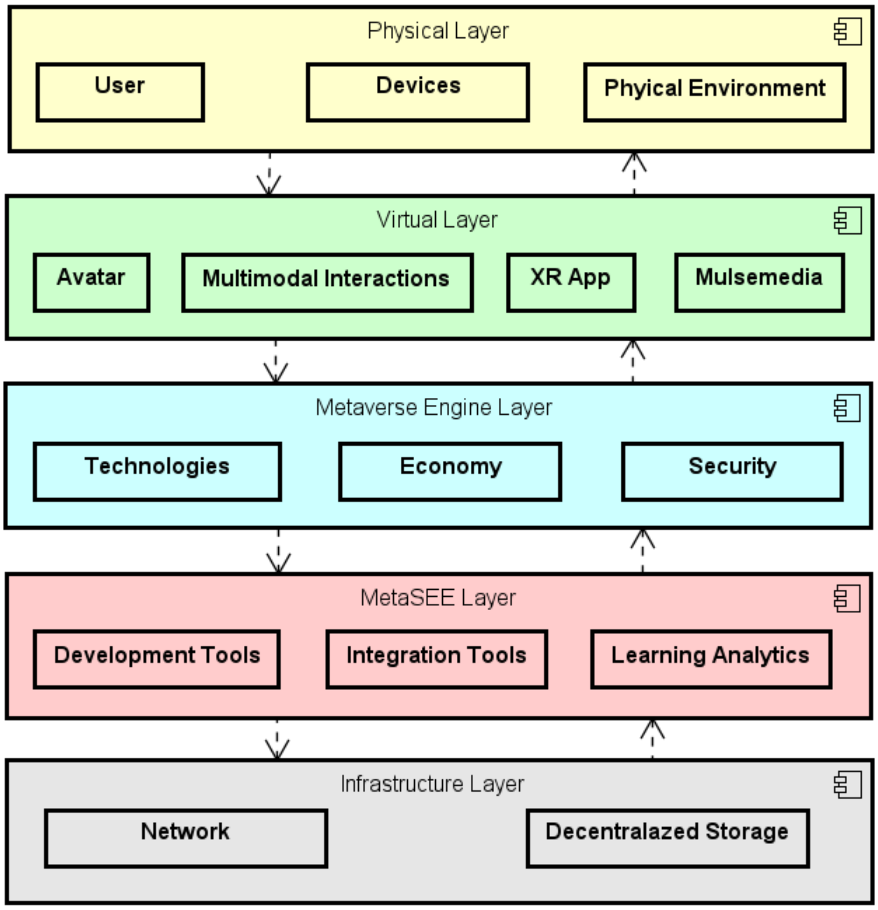


Figure 6.2: MetaSEE approach overview

6.2.2 Virtual Layer

This layer establishes the main components of the "virtualization" of physical layer elements. For example, user is represented through *Avatar*, which is his/her virtual appearance in the Metaverse. Just as the avatar is the representation of an entity in the physical world, *Multimodal Interactions* is the recognition of data from the devices on which the user uses to interact in a multimodal way with the Metaverse. *XR app* is the main component of the Metaverse. Much of the technical literature classifies it as a VW or VE. We use this nomenclature as we consider elements of Milgram's continuum (MILGRAM *et al.*, 1995). For example, a MR application is not necessarily composed of a fully synthetic VW. There is a mixture of virtual and real elements.

In this way, XR app is a classification that encompasses any type of application for the Metaverse. XR apps are made up of virtual objects that give meaning to the application. For example, in a surgery training simulation, the stretcher, the operating apparatus and instruments, the patient as well as the avatar are 3D models that give meaning to the application context. In addition, some 3D models can represent sensory stimuli, that is, when picking up a scalpel (3D model), the user can feel its weight when manipulating it. Therefore, we consider 3D models as a new type of media, that is, *mulsemedia*, which involves both virtual 3D and multisensory representation (olfactory, haptic, etc.). According to COVACI *et al.* (2018), MulSeMedia makes possible the inclusion of layered sensory stimulation and interaction through multiple sensory channels.

6.2.3 Metaverse Engine Layer

In *Metaverse Engine Layer* we have grouped the general *Technologies*, as well as *Economics* and *Security* of the Metaverse. This layer takes inputs as user data, and XR apps are generated, maintained, and enhanced with these inputs. Therefore, *Technologies* are represented to manipulate these data and meaning to the user and adapted to the mulsemedia that affects XR app. Computer Vision, Digital Twin, Spatial Computing, AI are some of these technologies.

Economy is an aspect that critically differentiates the Metaverse from other applications. The Metaverse offers its users the opportunity to create assets like NFTs and trade them. Furthermore, the economic system is the engine that encourages the continuous development of digital assets for the sustainable development of the Metaverse. The Metaverse can make physiological responses and movements in users' bodies. Information and therefore their personal characteristics, such as user's habits, are physical characteristics to third parties. Also, since in the Metaverse users will have their avatars more realistic, some users can commit crimes in relation to the interaction, as for example, sexual harassment.

Additionally, financial transactions are also carried out in the Metaverse. Therefore, *Security* considers policies and technologies so that they can work to ensure data protection, good relationships, and financial transactions.

6.2.4 MetaSEE Layer

MetaSEE Layer is our main contribution to support the Metaverse-based SEE. According to the established fundamental requirements (see Table 5.3), we have defined *Development Tools*, *Integration Tools*, and *Learning Analytics* as the components of this layer.

Development Tools should provide a set of mechanisms to facilitate the development of XR apps for SEE. From the point of view of SE, software reuse is an approach that starts from the principle of enhancing the use of existing software, aiming to reduce production and maintenance costs, guarantee more agile deliveries, try to add more quality and maximize the return on investment of software (WERNER *et al.*, 1997). Therefore, the adoption of software reuse techniques as a development strategy has the potential to allow the reuse of assets involved in immersive experiences, as well as improve the quality of XR apps. For example, Software Product Line (SPL) can be used to map the features of XR apps and generate a code skeleton (MARINHO *et al.*, 2010).

In addition, *Integration Tools* should provide reusable functionality for SEE. For example, rendering UML models, coding in XR, and virtual Integrated Development Environment (IDE), among others, are some of the features that can be integrated into other XR apps. That is, instead of creating these solutions, developers will be able to reuse these features for their XR apps and promote Metaverse-based SEE.

Learning Analytics is the component that must guarantee the maintenance of the learning performance of the Metaverse for SEE users. As the name suggests, this component is responsible for performing the learning analysis. According to DAWSON (2000), LA addresses the measurement, collection, analysis, and reporting of data about students and their contexts, with the aim of understanding and optimizing learning and the environments in which it takes place. According to CHATTI *et al.* (2013), the general process of LA is often an iterative cycle and generally performed in three main steps: (i) data collection and pre-processing, (ii) analysis and action, and (iii) post-processing. LA is a field that involves AI, machine learning, information retrieval, statistics, and visualization.

6.2.5 Infrastructure Layer

Finally, *Infrastructure Layer* deals with network and decentralization aspects of the Metaverse. In order to allow the user to be uninterrupted in his/her experience and to be aware of the real-world configuration, XR devices have stringent requirements for rate, reliability, and latency (PARK & KIM, 2022).

Due to the expected explosive growth in data traffic, ultra-dense networks deployed on edge networks can potentially alleviate constrained system capacity. Therefore, edge computing and cloud computing are some of the technologies that support the *Network* component. Distributed edge technologies are key to preserving the value and universality of virtual goods, as well as establishing the economic ecosystem within the Metaverse. It is difficult for today's virtual goods to have value outside the platforms on which they are traded or created. For example, an NFT serves as a mark of the uniqueness of a virtual asset and authenticates ownership of the asset (WANG *et al.*, 2021). This mechanism protects the value of virtual goods and facilitates peer-to-peer commerce in a decentralized environment.

As XR apps in Metaverse are developed by different parties, user data can also be managed separately. To allow seamless traversal between them, multiple parties will need to access and operate on the user data. Therefore, *Decentralized Storage* plays an essential role in reducing dependence on centralization in order to promote decentralization. For example, blockchain technologies offer an open and decentralized solution for building a sustainable virtual economy, as well as building the value system in the Metaverse.

6.3 MetaSEE Layer

Considering MetaSEE structure presented previously, in this section we describe the *MetaSEE Layer* implementation through *MetaSEE Framework*, *MetaLine*, *MetaSEE Extensions*, and *MetaSEE Analytics* components. Figure 6.3 presents the implementation relationship between each component and layer element.

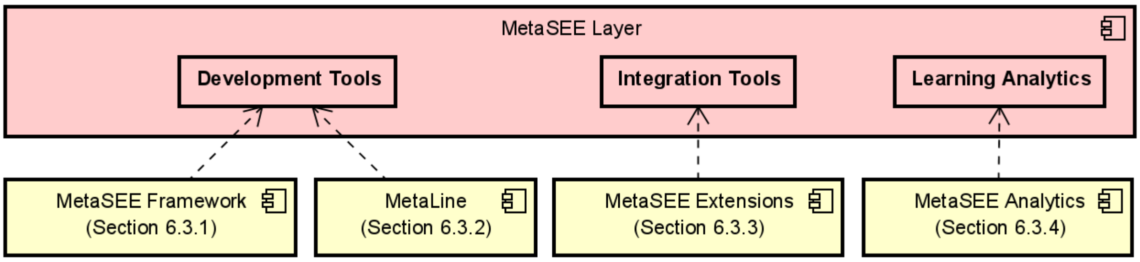


Figure 6.3: MetaSEE Layer implementation

6.3.1 MetaSEE Framework

MetaSEE framework aims to support the XR app design providing essential technological and pedagogical affordances through guidelines in order to aid learning outcomes improving in SE. Technological affordances are concepts that can be quantified (e.g., immersive devices, the immersive VW itself and methods of interaction). Pedagogical Affordances are related to pedagogical aspects and qualitative issues (e.g., feeling of being present in the XR app, engagement, the pedagogical theory and learning outcomes). In practice, when designing an XR app for teaching SE, one must establish and be constantly reviewing these affordances, which can be identified through guidelines.

From the comparative analysis presented in Table 5.2, we defined questions that must be answered to support the design of XR apps, in order to support the improvement of SE learning outcomes. These questions are addressed in this thesis as guidelines. The following sections describe each guideline in detail.

Immersion

This affordance is directly related to the quality and characteristics of immersive devices used to interact with the VW. The greater the use of the human senses through immersive devices, the greater the degree of immersion. Thus, the following questions must be answered:

- **IM1**: Which sensory stimuli will be used during the immersive experience?
  - Example: human senses with combinations (vision, hearing, smell, taste and touch) and/or body movements (hands, body etc.)
- **IM2**: Which kind of reality will be used during the immersive experiences?
  - Example: VR, MR, and XR.
- **IM3**: Which immersive devices will be used during the immersive experiences and that are adherent to IM2?
  - Example: Oculus family, HTC VIVE family, PICO family, HoloLens, Windows MR family etc.

User Experience

User experience is crucial for XR apps as it directly impacts the level of engagement, satisfaction, and enjoyment of the users. XR apps are immersive and interactive environments that allow users to explore, socialize, learn, and play in a virtual setting. A positive user experience can enhance the user's sense of presence, emotional connection, and overall enjoyment of the XR app. On the other hand, a poor user experience can lead to frustration, disengagement, and negative feedback. Therefore, optimizing the user experience through intuitive interface design, responsive performance, engaging content, and social interaction is essential for the success of XR apps. For these reasons, the following questions must be answered:

- **UX1**: What human-computer interface techniques will be used to support user interaction with the XR app?
  - Example: vector-based pointing techniques (ray-casting, fishing reel, image-plane pointing. . .), volume-based pointing techniques (flashlight, aperture selection, sphere-casting) etc.
- **UX2**: What mechanisms will be adopted to provide the user's perception of the VW of the XR app?
  - Example: field of view, frames per second, 360º audio, occlusion etc.
- **UX3**: What mechanisms will be adopted to mitigate the problem of motion sickness?
  - Example: movement through teleportation, rendering rate, etc.

Software Visualization

Appropriate software visualization is essential for XR apps as it can improve user understanding, engagement, and interaction with the VW. VWs are rich in information, from the layout of the world to the behavior of other users and objects within it. Effective information visualization can help users make sense of this information by presenting it in a clear, intuitive, and interactive manner. Choosing appropriate software visualization can also improve user experience, reduce cognitive load, and increase engagement and retention in the VW. This affordance intend to represent graphically, in an appropriate way, the elements related to SE according to the learning objective of the immersive educational applications. Therefore, the following question must be answered:

- **SV1**: What metaphors will adequately represent aspects of software during the immersive experiences?
  - Example: visual metaphors (graphs, trees, abstract geometrical shapes, cities, solar system), technical notations, such as UML, Business Process Modeling Notation (BPMN), flowchart, etc.

Developing Tools

Choosing the right developing tools and SDK for XR apps for each platform, such as desktop, mobile, and wearable, is crucial for ensuring optimal performance, compatibility, and user experience. Each platform has its unique hardware and software specifications, and the developing tools and SDK must be tailored to meet these specific requirements. For instance, developing tools and SDK for mobile platforms must take into account the limited processing power, memory, and battery life of mobile devices. On the other hand, developing tools and SDK for desktop platforms can take advantage of more powerful hardware and provide more sophisticated features and functionalities. Moreover, developing tools and SDK for wearables must optimize performance and compatibility with the specific XR hardware and software. Choosing the right developing tools and SDK for each platform can also facilitate cross-platform compatibility, enabling users to access the VW from different devices and platforms seamlessly. Therefore, selecting the appropriate developing tools and SDK for each platform is crucial for optimizing performance, ensuring compatibility, and enhancing the overall user experience in XR apps. Therefore, the following questions must be answered:

- **DT1**: What SDK and/or API will be used to implement communication between the application and the immersive devices?

  - Example: Oculus Integration SDK, Steam VR SDK, OpenXR, OpenVR, etc.

- **DT2**: What development environments will be used to build the immersive applications?
  - Example: Unity, Unreal, Android, iOS, Web, etc.

Application Features

Application features such as the number of users the XR app can support, the required space around the user, the supported languages, and the system requirements are essential for XR apps as they directly impact the user experience and the overall success of the platform. The number of users the application can support determines the scalability and capacity of the VW, and whether it can accommodate a large and active user base. The required space around the user can affect the user's sense of presence and immersion in the VW, and whether they can interact with objects and other users freely. The supported languages can broaden the reach of the VW and attract a more diverse user base. Finally, the system requirements can determine the performance and quality of the immersive experience, and whether it can run smoothly and without glitches. Therefore, taking into account these application features, the following questions must be answered:

- **AF1**: How many users will the XR app support?
  - Example: single user and multi users.
- **AF2**: Which space around the user is needed for the immersive experience?
  - Example: seated, standing or room-scale.
- **AF3**: What languages will the XR app be developed?
  - Example: Portuguese, English, among others.
- **AF4**: What system requirements must be met in order to guarantee a good performance of the immersive experience?
  - Example: processor, memory, system operation, disk space, etc.

Learning Indicators

Learning indicators for VWs are important because they provide measurable evidence of the effectiveness and impact of educational or training programs conducted within the VW. VWs offer a unique and immersive platform for learning, where users can engage with complex simulations, interactive scenarios, and collaborative learning activities. However, without reliable and valid learning indicators, it can be challenging to assess the learning outcomes and determine whether the VW experience has been successful. Learning indicators can include a variety of measures, such as knowledge acquisition, skills development, task completion, engagement, and satisfaction. These indicators can be collected through different methods, such as pre and post-tests, surveys, observations, and performance metrics. Analyzing and interpreting these learning indicators can provide valuable insights into the effectiveness of VW-based learning, identify areas for improvement, and inform future instructional design and development. Therefore, the following question must be answered:

- **LI1**: What indicators will be used to track student performance during the immersive experience?
  - Example: tokens, scores, ranking, rewards, time of use, etc.

Learning Outcomes

SE topics should be covered by XR apps as they provide essential knowledge and skills for designing, developing, and maintaining systems. Based on the SWEBOK, it is possible to indicate which topics will be covered by the application according to the areas of knowledge (GAROUSI *et al.*, 2019). In addition, the SWECOM presents the skills of a software engineer separated by areas of skill and activities, classified according to the professional's technical level of competence (SOCIETY, 2014). In this sense, the purpose of this affordance is to establish the topics of SE, as well as the competences and skills, which must be acquired. The questions that make up this affordance are:

- **LO1**: What Software Engineering topics will be covered?
  - Example: based on SWEBOK skill areas (software requirements, software design, software construction, software testing etc.)
- **LO2**: What skills and competencies must be achieved?
  - Example: based on SWECOM skills and activities (software requirements elicitation, integrating and collaborating, software test planning etc.)

Pedagogical Approaches

Theories and pedagogical approaches provide a solid foundation for designing and developing effective and engaging educational experiences within the VW. XR app offer a unique and immersive platform for learning, where students can engage with complex simulations, interactive scenarios, and collaborative learning activities. However, to ensure that these experiences are effective, it is essential to use theories and pedagogical approaches that are appropriate for the learning goals, objectives, and audience. Theories and pedagogical approaches can provide guidance on how to structure the learning content, scaffold the learning activities, and promote learner engagement and motivation. The appropriate selection of theories and learning approaches positively impacts the expected learning results. Therefore, this affordance aims to select the theory and pedagogical approaches that are adequate to the expected learning results and is guided by the following question:

- **PA1**: Which theories and pedagogical approaches are adherent to the expected learning outcomes?
  - Example: game-based learning, problem-based learning, project-based learning, experiential learning, etc.

Student Profile

The student profile is important for XR apps because it helps to personalize the learning experience and meet the individual needs and preferences of students. Students have different backgrounds, prior knowledge, learning styles, and preferences, which can influence their engagement and performance within the virtual environment. By creating a student profile, XR apps can tailor the learning content and activities to the individual needs and characteristics of the student. This affordance aims to establish for which type of student profile the XR app is most suitable. For this affordance, the following question was established:

- **SP1**: What is the profile of the student who will use the XR app?
  - Example: degree of knowledge in an area (beginner, median or advanced), age range, familiarity with XR/games, etc.

Context

In addition to establishing the affordance presented previously, it is also important to define in which context the XR app will be used. Therefore, this affordance aims to establish the place where the XR app will be used through the following question:

- **CO1**: What is the context in which the XR app will be used?

  – Example: classroom, training in a professional environment, anywhere the experience is not interrupted, anywhere that meets physical space requirements, etc.

6.3.2 MetaLine

MetaLine is a component that supports XR apps development based on SPL, generating code skeleton considering a range of XR app variabilities. Nevertheless, in order to generate this component, firstly we defined a SPL-based approach for Metaverse to instantiate a XR app family. This approach, also named as MetaLine, is composed of the following phases: (i) *domain analysis*; (ii) *domain design*; and (iii) *domain implementation*. Domain analysis defines the scope of the SPL. The domain design describes the main elements in a generic way. The domain implementation provides model-based parameters to generate code skeleton to be reused by Web XR apps.

Domain Analysis

Domain analysis was performed on existing Web XR apps for defining the scope of the developed SPL and considering MetaSEE framework guidelines (Section 6.3.1). This phase basically resulted in three products:

- a list of general requirements for Web XR apps;
- the list of functionalities for the end user, classified according to their presence in existing applications and the possibility of reuse; and
- modeling the characteristics of the SPL, based on these requirements and functionalities, represented by a features model.

General requirements for existing Web XR apps are:

- work in web browsers;
- allow the use of traditional (e.g., desktop and smartphone) and non-traditional devices (e.g., XR headset and data glove);
- use the human senses to engage in immersive experiences; and
- allow various ways of interaction.

These requirements, together with the point functionalities, were classified in terms of their presence in the applications. A common functionality is one that is or could be present in more than one family member, while a specific functionality is present in only one application and can not be included in the others. This mapping resulted in the definition of the characteristics of the SPL, presented in Figure 6.4. For the modeling, the Odyssey-FEX notation (BLOIS *et al.*, 2006) provided by the Odyssey environment (BRAGA *et al.*, 1999) was used.

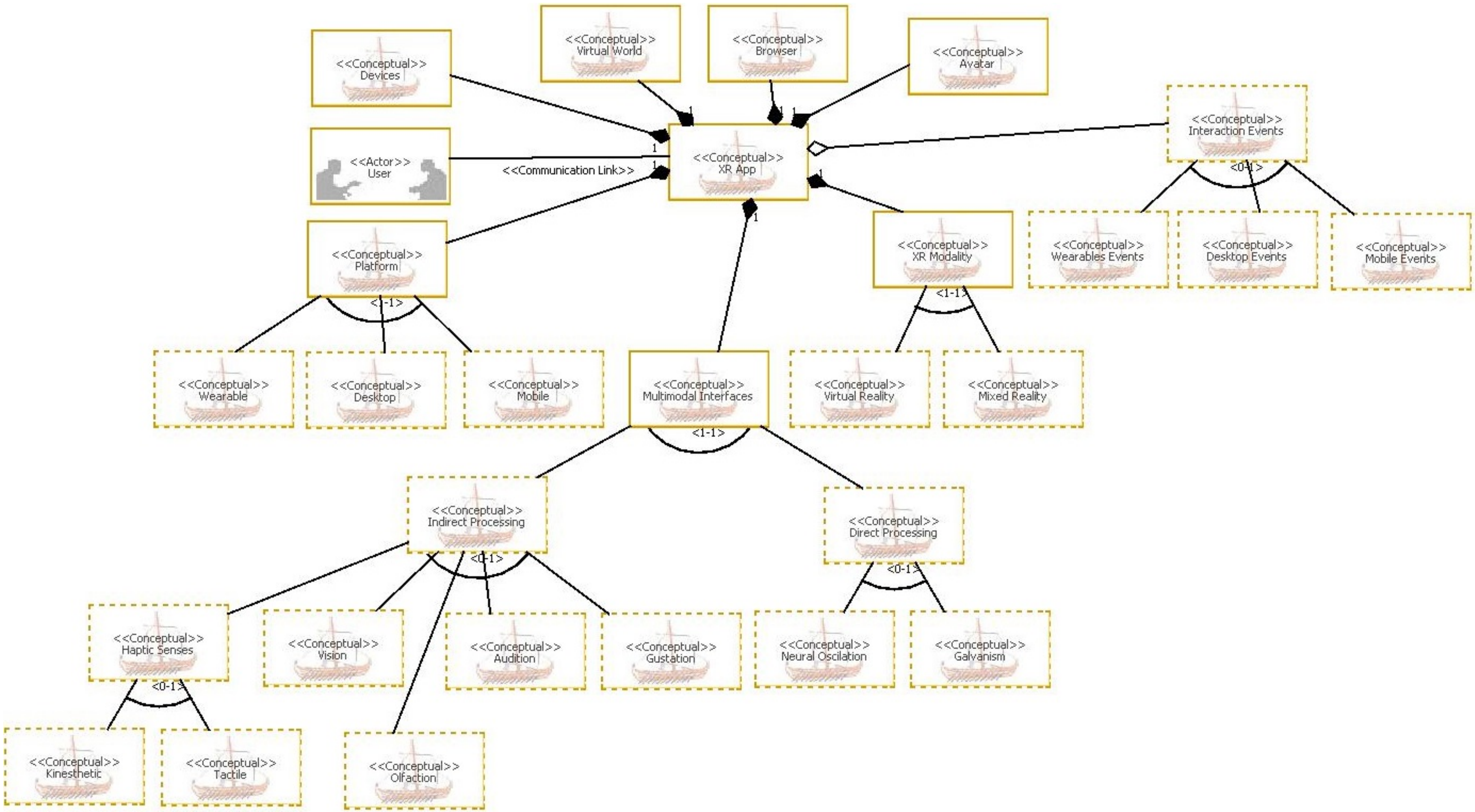


Figure 6.4: Features model for Web XR apps

In the model, a Web XR app is described by the mandatory features *Platform*, *Multimodal Interfaces*, *XR Modality*, *Devices*, *Browser*, *Avatar*, and *Virtual World*.

Platform is a variation point that establishes variants of the type of device the application will run on. Wearable represents immersive devices (non-traditional), such as XR headsets, haptic devices, motion sensors, etc. Desktop and Mobile represent the common interaction devices between the user and computer.

Multimodal Interfaces is a variation point that establishes which modalities (i.e., human senses) that may be present in the applications in order to enable the engagement of immersive experiences. The modeling of this variability is based on the taxonomy of interaction modalities for XR (AUGSTEIN & NEUMAYR, 2019). Direct processing works directly between a computer and the brain or muscles. Indirect processing refers to the multi-stage process where an output stimulus is perceived by a human receptor and then the information is delivered via electrical signals for further processing to the brain. The flow is similar for input stimulus from a human via sensors to the computer.

We used Milgram's RV continuum (MILGRAM *et al.*, 1995) to define the *XR Modality* variants. Virtual Reality considers only virtual objects to compose the application's VW and Mixed Reality combines real-world elements and virtual objects to compose the VW.

Devices correspond to the devices that will be used for both interaction and feedback (e.g. Meta Quest, HTC Vive, HoloLens); *Browser* is the web browser that will be compatible with the application, *Avatar* is the representation of the user, and *Virtual World* is the virtual space in which the user is inserted to interact with virtual objects.

The only optional characteristic of modeling is *Interaction Events*. It establishes interaction events for each type of device. For example, the implementation of the "click" event considering the execution of an application on the desktop is different on a XR headset. On the desktop, this event is fired through the mouse button, but in XR headset it can be through any button of the user controls. This characteristic is optional because an application can only display virtual objects without requiring any kind of interaction and/or feedback.

Domain Design

The purpose of this phase is to specify a structure to be followed by applications from the modeled domain (NORTHROP, 2002), i.e., software artifacts that belong to a particular domain and composed of a standard structure for the construction of applications.

For the design, we considered the features model built in the previous phase and the documentation of the A-Frame framework (A-FRAME, 2022). Therefore, the code skeleton generation will be based on this framework. The core of A-Frame is defined by the Entity-Component-System (ECS) architecture:

- **Entities** are container objects into which components can be attached, and are represented by the *a-entity* element and prototype;
- **Components** are reusable modules or data containers that can be attached to entities to provide appearance, behavior, and/or functionality, and are represented by HTML attributes on *a-entity*'s; and
- **Systems** provide global scope, management, and services for classes of components, and are represented by *a-scene*'s HTML attributes.

Figure 6.5 shows an example of A-Frame code. All the elements that will compose the virtual world must be contained in the entity *a-scene*. Therefore, the entities *a-box* and *a-sky* are inside the tag *a-scene*. These three tags are entities that are composed of components or systems. In line 1, *a-scene* has the system *physics* with its defined value as *gravity:0*. From line 2, *a-box* is composed of the *position*, *rotation*, and *color* components. Both *a-box* and *a-sky*, defined in line 5, have the *color* component, but with different values.

```
1 <a-scene physics="gravity: 0">
2   <a-box position="-1 0.5 -3"
3     rotation="0 45 0"
4     color="#4CC3D9"></a-box>
5   <a-sky color="#ECECEC"></a-sky>
6 </a-scene>
```

Figure 6.5: Example of A-Frame code

From its ECS architecture, components can be developed by the community and implement specific features in order to reduce complexity in application development as well as promote code reuse. For example, *aframe-event-set-component* provides a high-level API to facilitate the definition of mouse events or by gaze point. To change the behavior of an entity when clicking, the component "*event-set__click*" must be assigned.

As a result of this phase, we defined a comprehensive code template to define the inner workings of a Web XR app independently of the specific features of each application. Furthermore, we model the ECS architecture of the A-Frame based on the *Composite* design pattern (GAMMA *et al.*, 1995) in order to support the domain implementation.

According to Figure 6.6, an *Entity* can contain other entities (*Composite* class), and each *Entity* can be composed by *Components*.

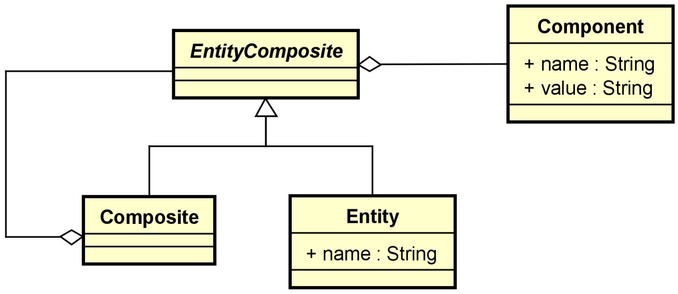


Figure 6.6: Abstraction of ECS architecture

Domain Implementation

Finally, in this phase of domain implementation we build, through source code, reusable artifacts, based on modeling and domain design, as well as the interface for applications instantiation, named Software Product Line for Metaverse (MetaLine) Features Model Editor. This tool consists of three components:

- **Features**: comprises the modeled features in the domain analysis phase;
- **XR Component**: corresponds to A-Frame components that will be required for the implementation of features; and
- **Template Generator**: generates the source code based on the selected features for the Web XR app instantiation.

Figure 6.7 shows the dependency relationship between the components. The generated code skeleton must conform to the features as well as the A-Frame components.

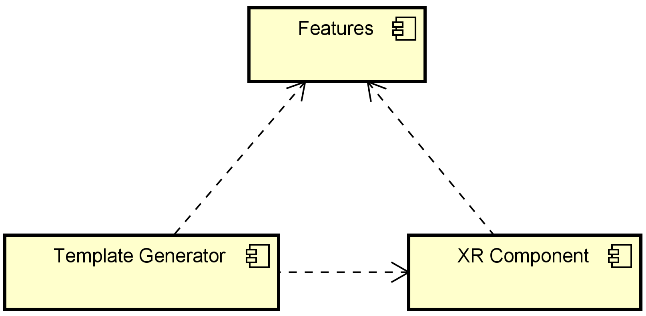


Figure 6.7: MetaLine Features Model Editor components

Figure 6.8 shows the relationship between the features and the generated source code. The editor's web interface presents the features that must be configured. The user on each screen must select which features will compose his/her application. In this example, the Web XR app must work on wearable, mobile, and Personal Computer-based Virtual Reality (PCVR) platforms; the VW will consist only of

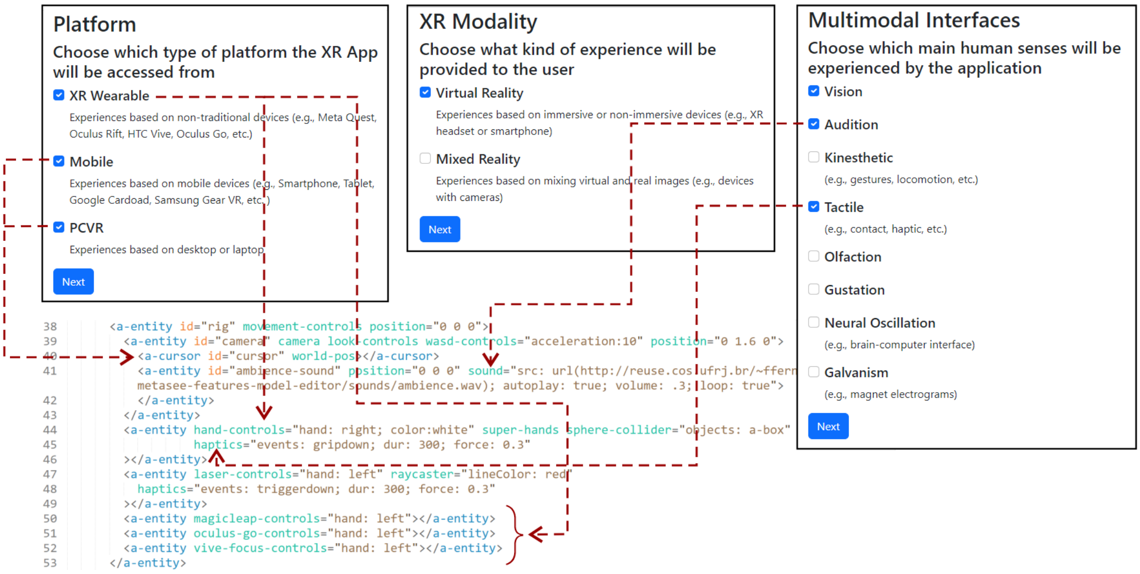


Figure 6.8: Relationship between features and generated source code

virtual objects VR; and the vision, audition, and tactile senses will be used during the immersive experience.

The piece of code is a cut of the source code skeleton generated. Considering that the three platforms were selected, the application must ensure the different forms of interaction. For example, if the application is accessed by a mobile device or desktop/laptop, the *a-cursor* entity is implemented. It allows basic interactivity with a scene. The standard appearance is a ring geometry. If accessed by an XR headset (Wearable), the tracked-controls component are implemented. According to the piece of code, line 44 implements the right hand and lines 50, 51 and 52 implement the left hand.

According to Figure 6.9, the left hand represented in the VW by a control and the right hand by a virtual hand. The difference between the two implementations is that *hand-controls* is device independent, and for each type of XR headset a component is implemented (*magicleap-controls*, *oculus-go-controls*, *live-focus-controls*).

The virtual representation of each hand was based on the selection of the *tactile* feature. By default, the code implements the *haptics* component with the *gripdown* event. A-Frame documentation (A-FRAME, 2022) lists other events that can be used. *Gripdown* is the hand closed into a fist without thumb raised. The *dur* property defines the control vibration time in milliseconds, and *force* is the vibration intensity. Therefore, the virtual hand induces the user "to grab" the virtual objects, and the left hand (virtual control) with the actions of walking and clicking. Finally, the component *sound* implements the hearing in the application.

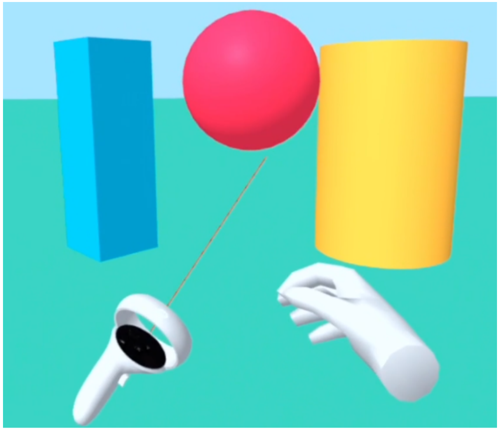


Figure 6.9: Example of an application generated through the MetaLine Features Model Editor

6.3.3 MetaSEE Extensions

MetaSEE Extensions aims to provide SE-specific features to XR apps. Currently, virtual spaces do not allow SE functionalities to engage students in immersive experiences during learning. There is no possibility to edit code, create UML diagrams, manage repositories, among other features based on IDEs. Therefore, this component integrates SE functionalities into XR apps. This component was designed based on two requirements: importation of A-Frame components and integration with MetaSEE platform (Section 6.5).

As presented in Figure 6.10, each extension from MetaSEE Extensions imports an A-Frame component and integrates some MetaSEE platform functionalities through *MetaSEE Integration*. This design decision ensures reuse for any application because an A-Frame component does not deploy any database connection or interaction interface with any platform or application.

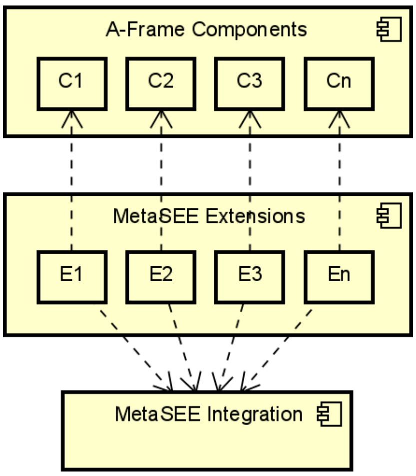


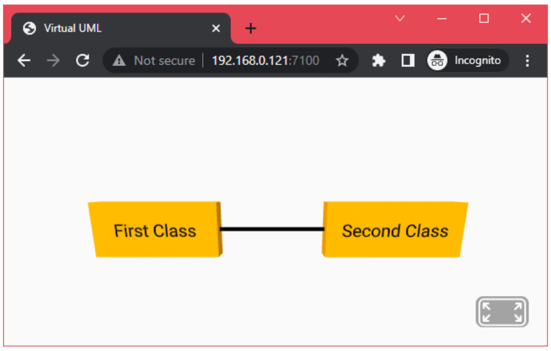
Figure 6.10: MetaSEE Extensions overview

Some pieces of the *Virtual UML* code are presented to clarify our design decision.

Virtual UML is an A-Frame component developed in this work. As shown in Figure 6.11a, Virtual UML provides customized Hypertext Markup Language (HTML) tags: *a-umlclass* and *a-association*, respectively, to create a class and association in VW. The class properties *classname* (lines 3 and 9) sets a class name and *position* (lines 4 and 10) sets a position class in VW. The association properties *start* and *end* (lines 14 and 15) set a relationship between the classes from class *id* (lines 2 and 8). Figure 6.11b presents the 3D elements on the browser.

```
1  <a-umlclass
2    id="firstclass"
3    classname="First Class"
4    position="-1.5 0 0"
5  ></a-umlclass>
6
7  <a-umlclass
8    id="secondclass"
9    classname="Second Class"
10   position="1.5 0 0"
11 ></a-umlclass>
12
13 <a-association
14   start="#firstclass"
15   end="#secondclass"
16 ></a-association>
```

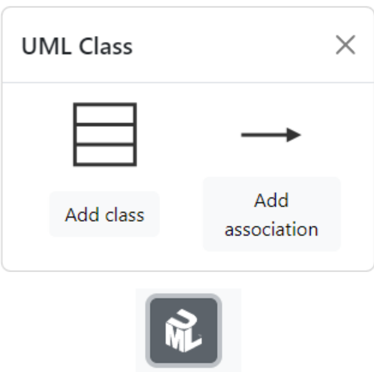
(a) A-Frame Virtual UML component code



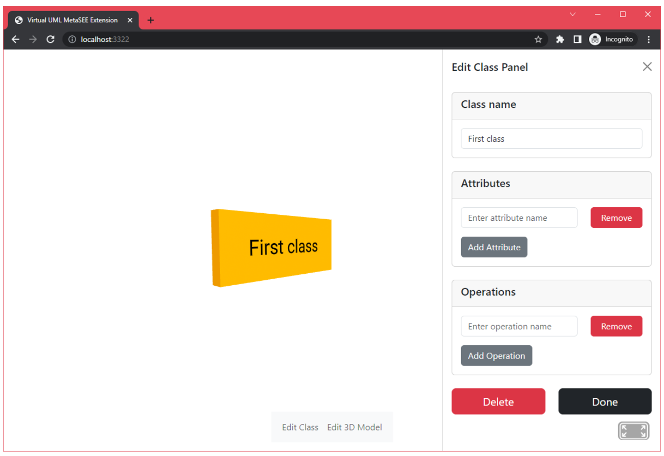
(b) Result of previous code

Figure 6.11: Example of the A-Frame Virtual UML component

Therefore, in order to facilitate the creation of UML class diagrams, Virtual UML extension implements a user interface. As shown in Figure 6.12a, a menu supports the user to create classes or associations, and for each element, there is a panel for custom information. Figure 6.12b presents a sidebar to change class information. In addition, Virtual UML extension makes calls to MetaSEE Integration to integrate data into the platform.



(a) Virtual UML extension menu



(b) Vitual UML extension interface

Figure 6.12: Example of the Virtual UML extension

6.3.4 MetaSEE Analytics

LA aims to comprehend and enhance the learning process. However, learning does not always transpire through or with the assistance of a technological system that can gather digital data. To enable the examination of learning in such settings, various indicators, such as video and audio, need to be captured, processed, and scrutinized to generate traces of the activities and interactions of the participants in the learning procedure. The utilization and merging of diverse modalities contained in these signals are referred to as Multimodal Learning Analytics (MMLA) (OCHOA & WORSLEY, 2016).

MMLA seeks to take advantage of advances in capturing and processing multimodal data to tackle the challenges involved in analyzing various complex constructs related to learning, as observed in intricate learning environments. Examples of multimodal data include speech, video, electrocardiology, and eye tracking (OUHAICHI *et al.*, 2023). Although the fields of educational data mining and LA have greatly benefited from the ability to collect trace data from an individual student's work in computer-mediated learning environments, MMLA aims to collect, synchronize and analyze data from different communication modalities, to provide on-time feedback (ECHEVERRÍA *et al.*, 2016).

Based on SHANKAR *et al.* (2018), we define the MetaSEE Analytics module considering three main components: *Data Discovery*, *Data Integration*, and *Data Exploitation*. Figure 6.13 presents an overview of this module.

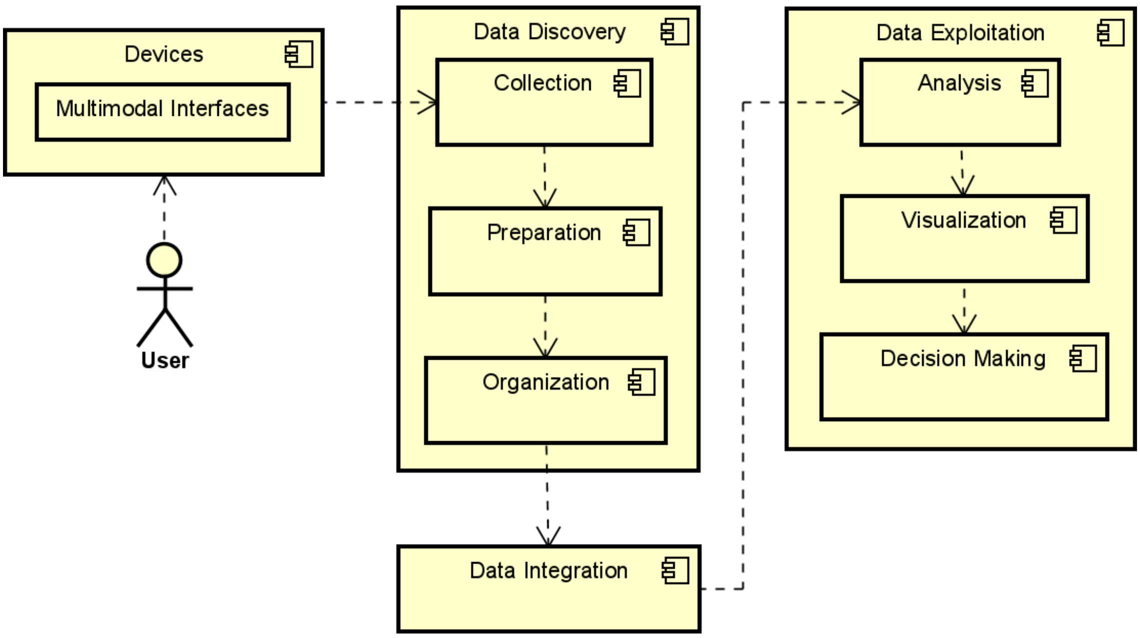


Figure 6.13: MetaSEE Analytics overview

By the user using any *Multimodal Interfaces*, such as XR wearables, mobile, PCVR, eye tracking, microphone, camera, etc., *collection* captures from one or more data sources. Then, *preparation* can apply techniques, such as data reduction, pre-transformation, extraction of basic features, data sharing, and pre-processing, in order to prepare data for the following step. *Organization* provides an organization with the data according to the design decisions and the affordances of the learning context.

Data Integration (also known as data fusion, referring to the alignment of all the data sources which can reveal learning information) is one of the most crucial activities in multimodal analytics. Different solutions can be used regarding the storage of integrated data, e.g., My Structured Query Language (MySQL) databases, Learning Record Stores (LRSs), or more generic data warehouses.

In *analysis*, various statistical analysis methods can be used, such as descriptive, inferential, and multivariate analyses. In addition, ML, Linear Mixed Effect Models (LMEM), and Random Forests are common techniques used in this phase. Analytical results are provided to different stakeholders (e.g., teachers, students, educators, and parents) by means of visualizations. Applying *visualization* techniques, such as dashboards, indicators using color coding, or warnings, helps to get insights into the learning process. Finally, *decision making* provides mechanisms for students' awareness of their individual learning process, and the teachers get information about the progress of the students.

6.4 MetaSEE Architecture

In this thesis, the C4 model was adopted to represent our proposed architecture. C4 model[1] is a model composed of four layers, each one progressively more detailed than the last: *context*, *container*, *component*, and *code*. The first layer, context is the most superficial and aims to illustrate the application as a black box that interacts with users and external systems by receiving inputs and returning outputs. The second layer, in turn, is the container layer, in which the functional modules of the system are represented as containers and illustrated at a high level, together with the communications established between them. Component, the third layer, details the individual aspects of each container represented in the previous layer and shows the components that make it up. Finally, the code layer is composed of diagrams that can be used to detail the components and show their implementation.

Figure 6.14 presents the architecture from the point of view of the context layer and how its elements (MetaLine, MetaSEE Extensions, and MetaSEE Analytics) integrate the architecture. It is composed of two external systems and two roles that interact with a platform, named *MetaSEE platform*, which allows *users* to have immersive experiences and create XR apps. Each XR app integrates SE-

[1] https://c4model.com/

specific features from *MetaSEE Extensions* built by *developers*. These extensions, based on A-Frame components, can be UML diagrams editing, software artifact 3D visualization, repositories, code editing, among others. In addition, the platform provides mechanisms to support XR apps development based on software reuse. These XR apps can be adapted, hosted and linked with the platform through an API.

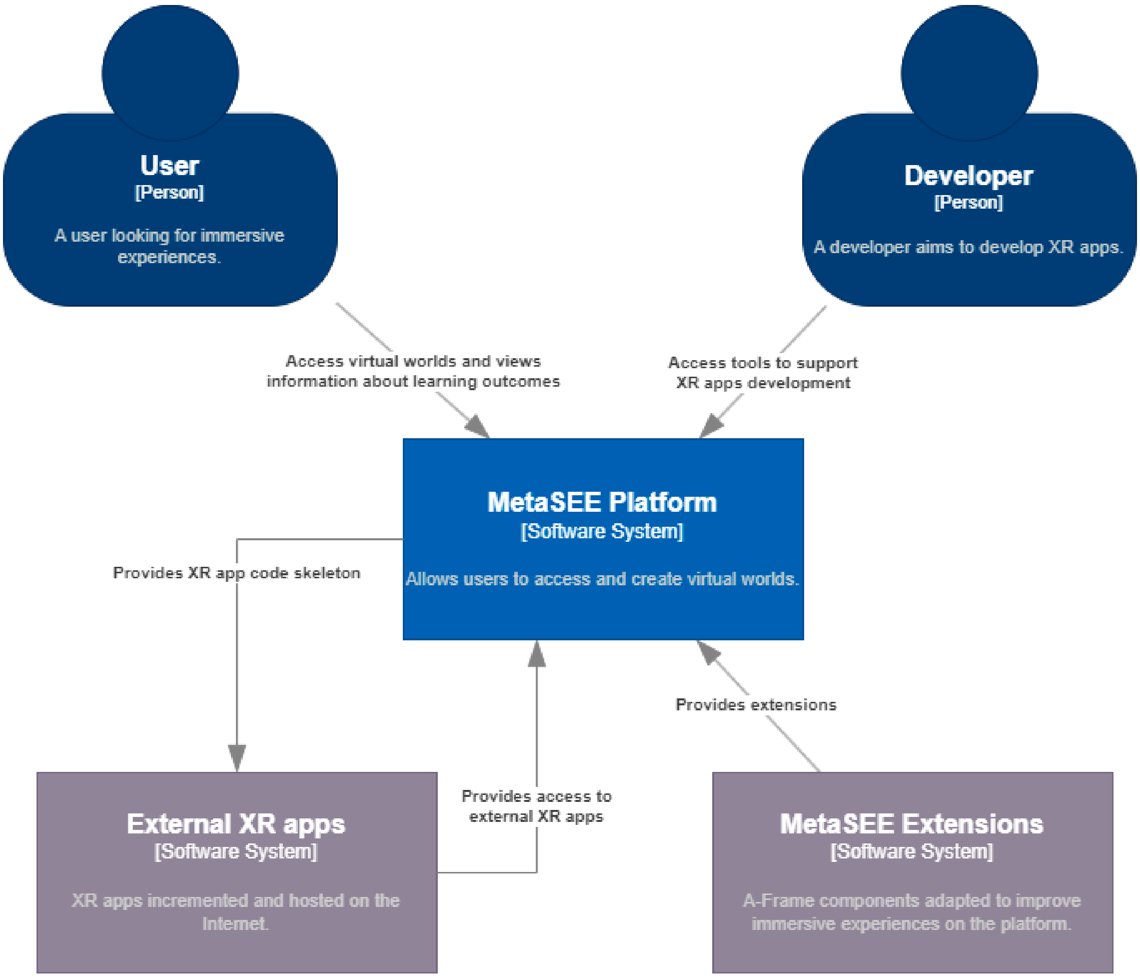


Figure 6.14: MetaSEE architecture context diagram

From the point of view of the container layer, Figure 6.15 presents the platform's main containers (modules). User accesses a *web application* that provides an interface with basic functionalities in order to maintain XR apps and user register. One of the main purposes of the web application is to ensure users can *"enter"* and *"exit"* a range of XR apps with different learning goals addressing SE topics. *XR app* is the main content with which the user interacts. XR app is composed of a computer-generated three-dimensional space where users interact with each other or with other virtual objects (i.e. VW) and functionalities to enable interaction with SE-specific features (e.g. UML diagrams and code editing). These features are integrated from *MetaSEE Integration*, which provides mechanisms to connect XR apps to the *MetaSEE Extensions* designed by *developers* community. As presented in Section (6.3.3), a MetaSEE extension is based on an A-Frame component (stand-alone application) and provides SE-specific features. For example, an A-Frame component provides a structure based on HTML, JavaScript (JS) and A-Frame for building a 3D Kanban. However, database integration, user interface, and other features should be deployed as a MetaSEE extension.

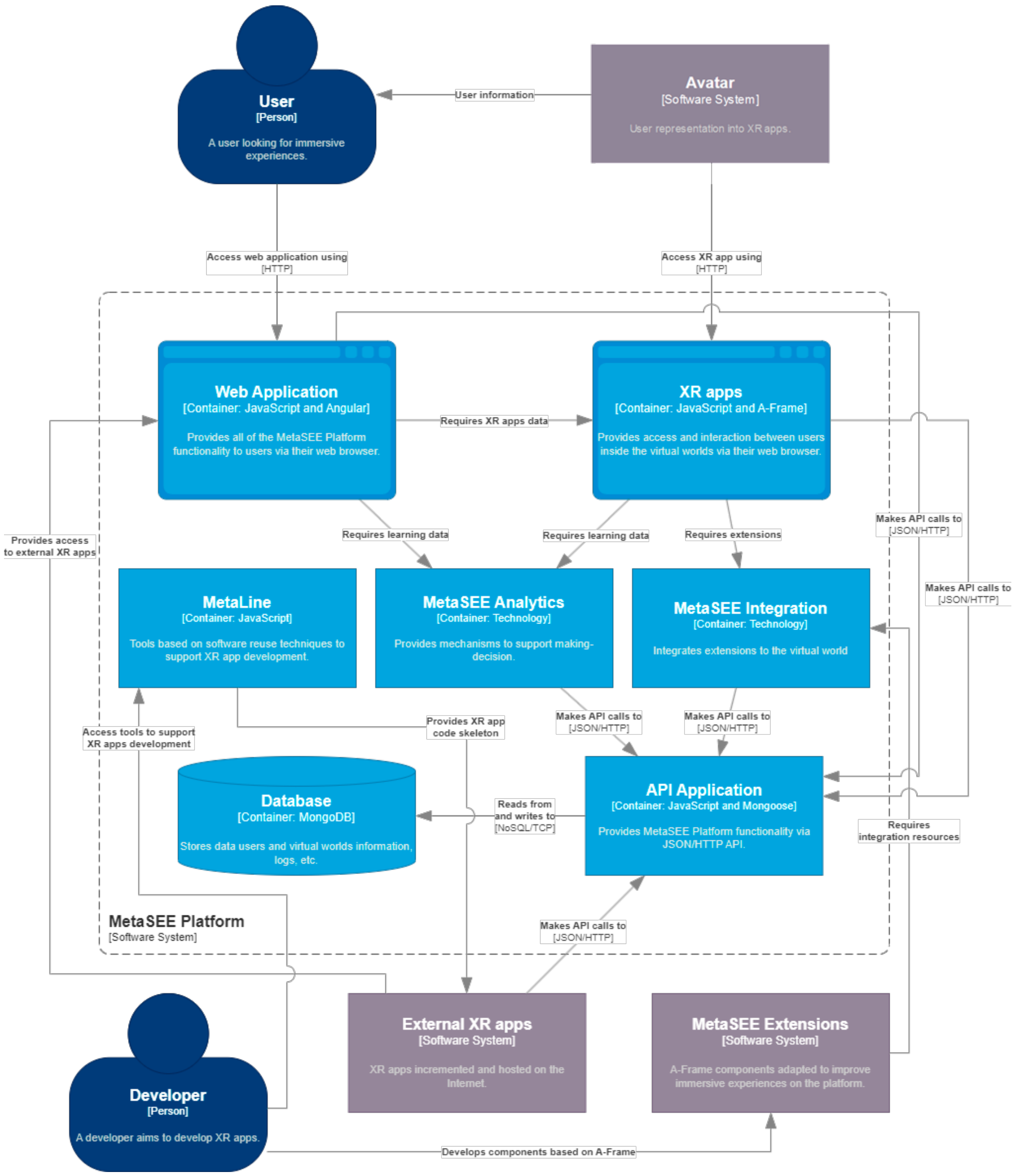


Figure 6.15: MetaSEE architecture container diagram

In addition, the platform provides advanced tools from *MetaLine* container in order to support the complexity XR apps development (see Section 6.3). *External XR apps* hosted on other servers can be accessed by users through the platform and integrating data via *API Application* container. *MetaSEE Analytics* container aims to provide mechanisms in order to support making decisions based on multimodal data (see Section 6.3.4). In practice, educators will be able to follow the evolution of learning and engagement of students on various topics of SE, independent of internal or external XR apps. Finally, containers make calls to *API Application*, which provides JavaScript Object Notation (JSON) data from the non-relational *Database*.

Figure 6.16 presents a components overview of XR apps container. *Virtual World* is accessed by *avatars* and allowing interaction with other users and 3D objects. All functionalities based on the network (e.g. communication between multiple avatars) are managed through *Network Manager* component. Menus, panels, and other interface resources are provided by *Interface Manager* component. *Extentions Manager* allow users adding extensions to custom VWs and improving learning experiences.

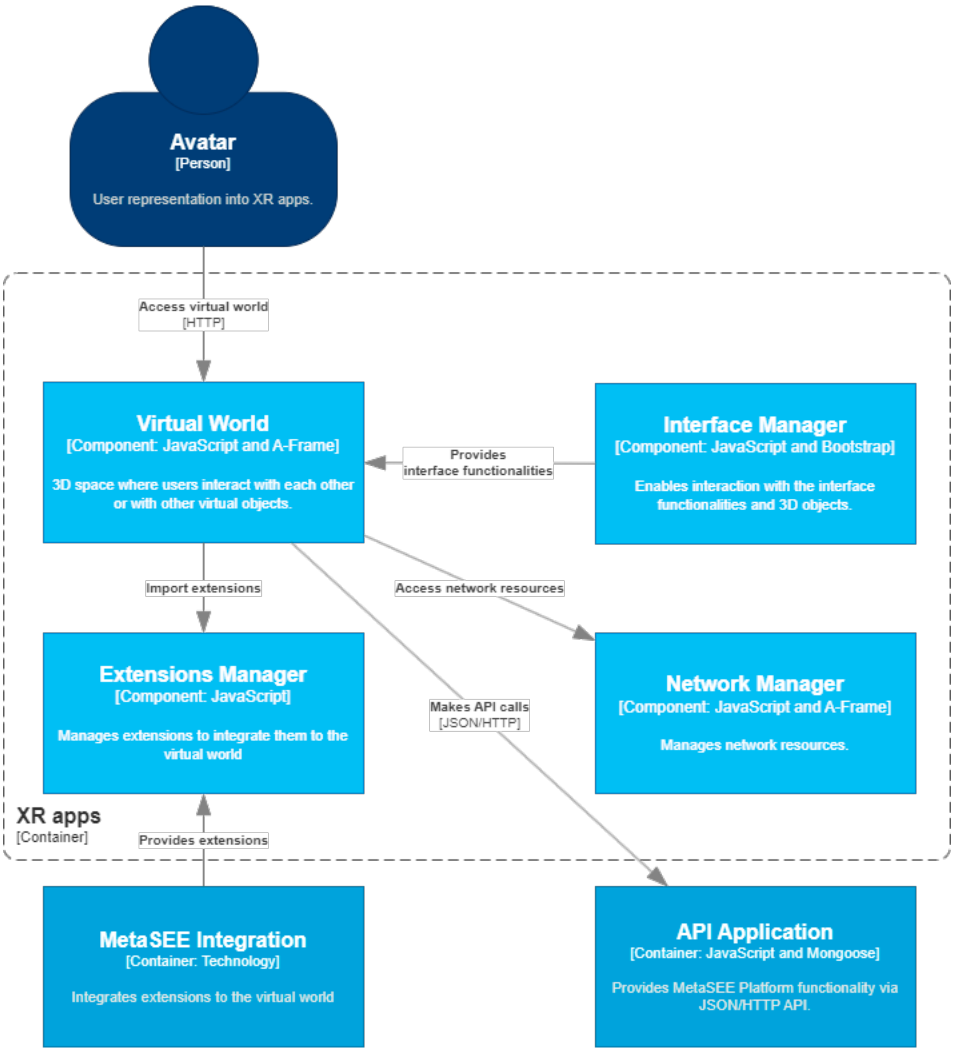


Figure 6.16: Components of XR apps container

Finally, Figure 6.17 presents the *Web Application* composed of two main components. *XR apps Manager* has the responsibility of providing mechanisms to the users creating, searching, and managing XR apps. *User Manager* controls all access into XR apps and manages all user information, such as creating, reading, updating, and deleting accounts.

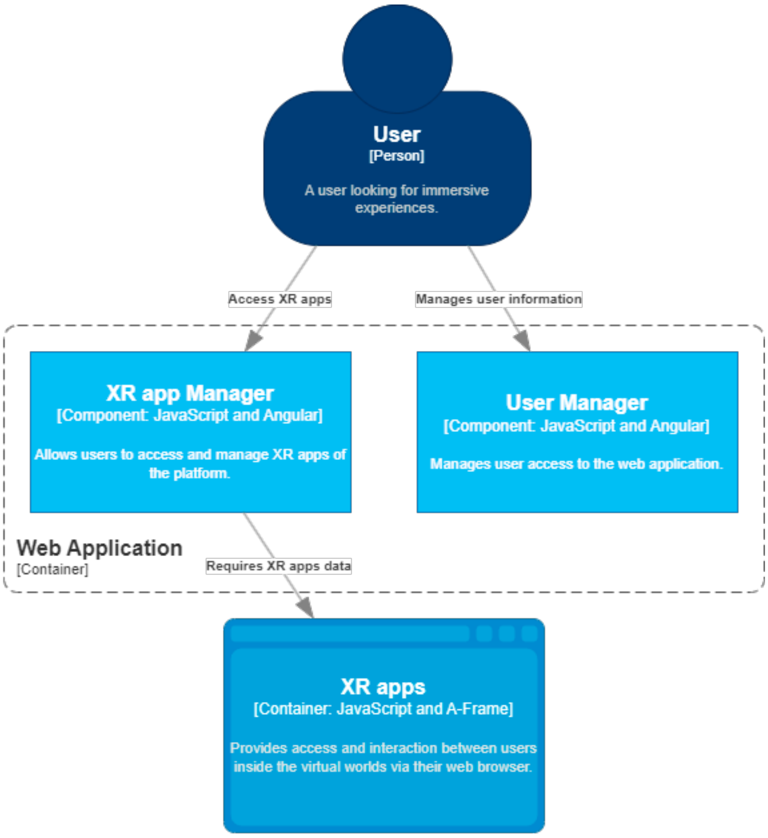


Figure 6.17: Components of the Web Application container

6.5 Implementation

Implementing the Metaverse involves all elements defined in MetaSEE structure (Section 6.2), such as Metaverse technologies, economy system, security rules, network aspects, decentralized storage, among others. In this thesis, we deployed basic functions to enable the Metaverse-based SEE, allowing users creating and acessing VWs based on interoperability mechanisms, which are described below.

Figure 6.18 presents the homepage of the *Web Application* container. This application was developed as a Single Page Application (SPA). SPAs are web applications that dynamically update the content of a single web page, rather than loading multiple pages from the server. In a SPA, the user interacts with the application through a single HTML page that is loaded into the browser, and subsequent interactions with the application result in new content being loaded dynamically onto that same

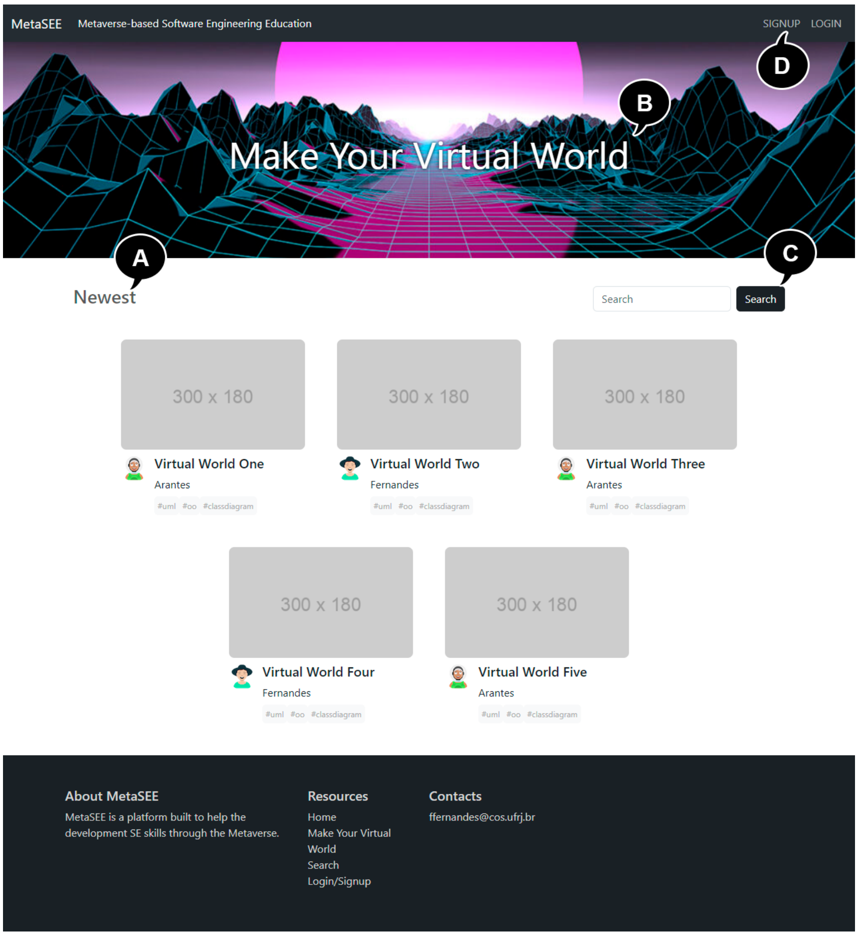


Figure 6.18: Web application homepage

page. Angular[2] framework was selected to render content on the client side, and communicate with the server through APIs.

This homepage is composed of the newest VWs created on the web application, as shown in Figure 6.18(a). For each VW a thumbnail, name, creator user, and SE topics are addressed as hashtags are presented. It is also possible to search by VWs, as presented in Figure 6.18(b). In the page header, there is a link to create a new VW, as shown in Figure 6.18(c), as well as registering and logging into the application, as presented in Figure 6.18(d). This project is available in the github repository[3].

When the user clicks on the VW link, the web application communicates with *XR apps* container via *API Application*, according to Figure 6.15. Figure 6.19 presents the VW accessed from the web application, in this case, composed of three UML classes. Each VW has a link to share with other users in order to access it. For example, *http://metasee.com/[id]*, where *[id]* refers to a unique identification of the VW. XR apps container implementation was based on Node.js, Bootstrap[4]

[2]https://angular.io/
[3]https://github.com/MetaSEE/metasee-app
[4]https://getbootstrap.com/

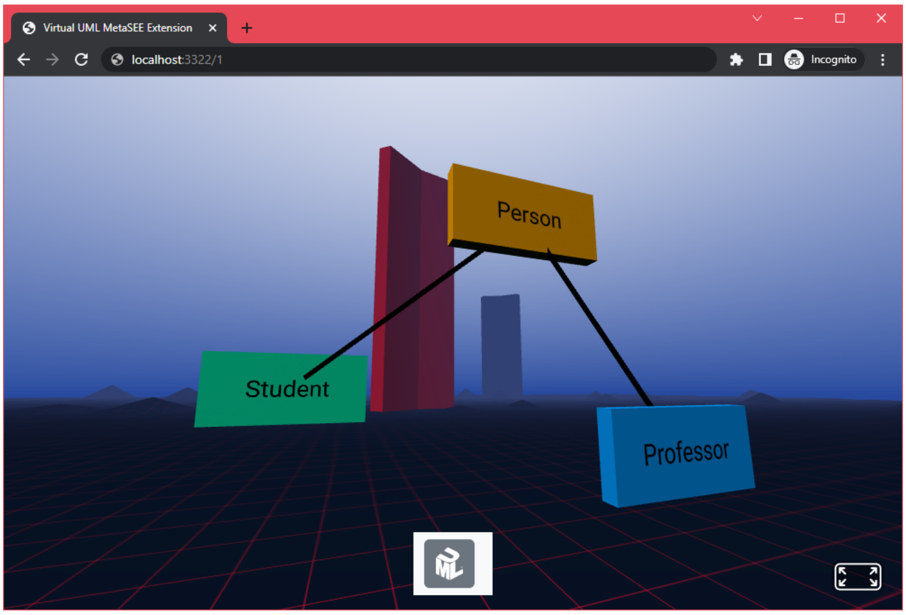


Figure 6.19: VW accessed from web application

framework, A-frame framework, and A-Frame components. These components are modular pieces of code that encapsulate a specific behavior or functionality that can be added to an A-Frame entity, such as a 3D object or a VR scene. For example, we adopted the *Networked A-Frame*[5] to enable network functionalities, such as multi-users and collaboration. *A-Frame Randomize*[6] supports randomizing vectors, numbers, or colors, and can randomly select from a list of possible values. *A-Frame Environment*[7] is a simple way of setting up a whole basic environment in a scene. *VirtualUML*[8] itself is an A-frame component that allows to create UML diagrams. XR apps project is available in the github repository[9].

All *XR apps* and *Web Application* containers data are stored in the MongoDB[10] database. MongoDB is a popular open-source not only SQL (NoSQL) document database. MongoDB's flexible schema, combined with its ability to handle large amounts of data, makes it a popular choice for modern web applications that need to store and retrieve large amounts of unstructured data quickly and efficiently.

API Application is a RESTful API, because it exposes a set of resources and allows clients to perform operations on these resources using Hypertext Transfer Protocol (HTTP) verbs, such as GET, POST, PUT, and DELETE. Each resource is identified by a unique Uniform Resource Identifier (URI) and can be represented in various formats, including JSON, XML, or plain text. This API was developed

[5]https://github.com/networked-aframe/networked-aframe
[6]https://github.com/harlyq/aframe-randomize-component
[7]https://github.com/supermedium/aframe-environment-component
[8]https://github.com/MetaSEE/aframe-virtualuml-component
[9]https://github.com/MetaSEE/metasee-virtualworld
[10]https://www.mongodb.com/

```
let mongoose = require("mongoose");

const umlclassShema = new mongoose.Schema({
  classname: {type:String},
  owner: {type:mongoose.Types.ObjectId, ref:'users', required:true},
  position: {
    x: {type: Number, required:true},
    y: {type: Number, required:true},
    z: {type: Number, required:true}
  },
  rotation:{
    x:{type:Number, required:true},
    y:{type:Number, required:true},
    z:{type:Number, required:true},
  },
  scale:{
    x:{type:Number, required:true},
    y:{type:Number, required:true},
    z:{type:Number, required:true},
  },
  color: {type:String},
});

const umlclass = mongoose.model('umlclasses' , umlclassShema);

module.exports = umlclass;
```

Figure 6.20: UML class schema defined

based on Node.js[11]. Node.js enables developers to write server-side applications in JS, making it possible to use a single language for both client-side and server-side programming. Through Mongoose[12] component, the process of connecting to MongoDB is simplified, in addition, it provides a straightforward way to define data models using schemas. Schemas define the structure of the documents that can be stored in a MongoDB collection and can also include validation rules to ensure that data are consistent and accurate.

Figure 6.20 presents an example of schema defined. It establishes a UML class schema with some properties, such as *classname*, *owner*, *position*, *rotation*, *scale*, and *color*. When accessing it via GET, JSON data are returned according to this schema, from the MongoBD database. Figure 6.21 presents data obtained when accessing the GET method.

API Application provides a list of endpoints in order to ensure a standardized way for client applications to access specific resources or services. Endpoints are essential components of RESTful APIs, which are designed to be stateless and use standard HTTP methods and status codes. By using standardized endpoints, developers can create more scalable and flexible APIs that can be accessed by a variety of client applications. Table 6.1 presents a list of UML class endpoints. This project is available in the github repository[13]. A platform demonstration video is available [14].

[11]https://nodejs.org/
[12]https://mongoosejs.com/
[13]https://github.com/MetaSEE/metasee-api
[14]https://youtu.be/TrJI5VLL3ho

```
[
    {
        "position": {
            "x": 0,
            "y": 1,
            "z": 0
        },
        "rotation": {
            "x": 0,
            "y": 0,
            "z": 0
        },
        "scale": {
            "x": 1,
            "y": 0.5,
            "z": 0.2
        },
        "_id": "63eec2c0d517af8a162f95ec",
        "classname": "Manager",
        "owner": {
            "_id": "63ee7b392ed75e8905e7feee",
            "login": "filran",
            "email": "filran@gmail.com",
            "name": "Arantes",
            "picture": "https://loremflickr.com/40/40"
        },
        "color": "blue",
        "__v": 0
```


Figure 6.21: Example of JSON data via GET verb

Verb	URI	Description
GET	/umlclasses	It returns all uml classes
GET	/umlclass/[id]	It returns a uml class by [id]
GET	/umlclass/search?user=[user]	It returns all uml classes by [user]
POST	/umlclass	It creates a uml class and it returns the new uml class created
PUT	/umlclass	It updates a uml class
DELETE	/umlclass/[id]	It deletes a uml class by [id]

Table 6.1: Example of endpoints

Chapter 7

Evaluation

7.1 Introduction

In Chapter 6, we presented our MetaSEE approach, which aims to support design, development, and integration of XR apps for SEE through a framework, SPL for Web XR apps, Metaverse structure for SEE, architecture and platform. In the present planning, we have utilized certain studies from the Software Reuse Lab (ALBERT, 2014; DE FRANÇA COSTA, 2019; DOS SANTOS, 2016; MAGDALENO, 2013; NUNES, 2014; VASCONCELOS, 2007), as well as other research groups in SE at COPPE/UFRJ, such as BARRETO (2011); TRAVASSOS *et al.* (2002), as exemplars. Adhering to the methodology prescribed by SHULL *et al.* (2001), our planning includes an initial investigation to ascertain the practicality of implementing a given solution. Feasibility studies are employed to delineate the features of a technology, verify its capabilities, and assess its worth for further development. According to SHULL *et al.* (2001), such assessments lead to significant modifications in nascent technologies and should therefore be conducted early in the evaluation process. Consequently, feasibility studies are typically utilized to evaluate new approaches or technologies.

Therefore, we planned 4 experiments with the purpose of verifying the feasibility of our approach. In Section 7.2, we present the experiments planning, the sample profiles of the participants, the types of instruments used, as well as an overview of the relationship between the goals, questions and metrics of the experiments, according to the paradigm Goal-Question-Metric (GQM). In Sections 7.3, 7.4, 7.5, and 7.6, we present the specificities of each of the experiments, as well as the analyses, respectively. In Section 7.7, we carried out a discussion based on the results of the experiments and ended this chapter with our final considerations in Section 7.9.

7.2 Experiments Planning

This section aims to clarify the process of experiment planning. As previously presented, this thesis proposed to carry out four experiments, each one with the purpose of validating aspects to which the MetaSEE approach aims to contribute. The experiments are: MetaSEE Framework (E1); MetaLine Features Model (E2); A-Frame VirtualUML Component (E3); and MetaSEE Platform (E4).

As a strategy, for experiments E1, E2, and E3 we focused on two types of sample participants: academics and developers. The opinion of professionals involved with scientific methods and the state of the art (academics), as well as industry professionals involved with the state of practice (developers), can bring significant gains in data analysis when focusing on the same object of study. However, we developed specific instruments for each type of profile per experiment. This decision was taken during the execution of a pilot study, as some Discord users reported that the average duration of the experiments was long and users would hardly have time available to help with the research (see Appendix A).

In this way, considering experiments E1, E2, and E3, the following types of instruments were developed for the academics:

- *Informed Consent Form*: this document serves to communicate the objective of the experiment, as well as outline the rights and responsibilities of experiment participants. Additionally, it emphasizes that the data collected will not be utilized to evaluate the performance of participants and elaborates on the terms of confidentiality. Prior to the commencement of the experiment, this form must be distributed to all participants, who are required to sign and return the document;

- *Characterization Form*: facilitates the researcher's ability to analyze the profiles of participants and subsequently categorize them into distinct groups. Such information is instrumental in conducting an accurate and comprehensive analysis of the experiment's results;

- *Execution Form*: presents a set of tasks based on the object of study; and

- *Evaluation Form*: consists of a questionnaire in which each participant should evaluate his/her experience after the experiment execution.

Considering user feedback on Discord, a compact version of the instruments for developers has been produced:

- *XR apps Aspects*: a form was produced, in which developers rated each MetaSEE Framework guideline in relation to its level of importance in the context of aspects that must be defined before starting the development of XR apps. Furthermore, in the same instrument, a question related to the MetaLine Features Model was added. In order to preserve the response time and enable the developer to validate the features model, it was completely described in statements and the developer informs the level of agreement. As a result, experiments E1 and E2 were compacted and included in this single instrument;

- *VirtualUML Documentation*: in this form, the developers evaluated the documentation of the A-Frame VirtualUML Component and answered four questions based on the evaluation form of the E3 experiment.

Regarding experiment E4, professors and students from Federal Institute of Southeast Minas Gerais (IF Sudeste MG) participated in the experiment, with professors selected for convenience and students as volunteers. The types of instruments used in this experiment are the same defined in experiments E1, E2, and E3 for academics.

For experiments E1, E2, and E3, the following strategies were adopted in order to obtain samples by profile:

- *Academics*: shared on Brazilian Computer Society (SBC - acronym in portuguese) email lists from specific areas[1], such as Virtual Reality and Education, Special Committee on Software Engineering, Special Committee on Virtual Reality, Special Committee on Multimedia and Hypermedia Systems, and Special Committee on Human-Computer Interaction; as well as on Discord Immersive Learning Research Network[2] and Educators in VR[3] servers;

- *Developers*: social media, such as LinkedIn[4], ResearchGate[5], Twitter[6], Slack, and Discord. The list of servers released on Slack and Discord is presented in Appendix B.

Each experiment was designed based on GQM paradigm (BASILI *et al.*, 1999) and it is composed of goals, and these goals are measured from 5 metrics through questions, as presented in Figure 7.1. Metrics are based on the number of participants who choose one from five options on a 5-point Likert scale, and SUS questionnaire score, as described in Table 7.1. Each experiment is presented in more detail in the following sections.

[1]https://www.sbc.org.br/22-destaques/34-listas-eletronicas
[2]https://discord.gg/TQvgrxWa
[3]https://discord.gg/xZtUetya
[4]https://www.linkedin.com
[5]https://www.researchgate.net/
[6]https://twitter.com/

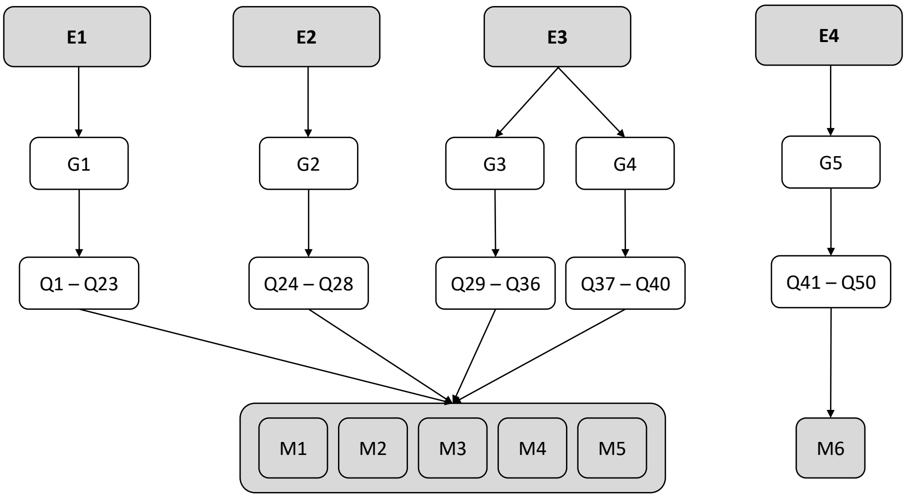


Figure 7.1: GQM model overview for MetaSEE approach evaluation

Metric	Description
M1	Number of participants who choose "Totally disagree"
M2	Number of participants who choose "Disagree"
M3	Number of participants who choose "Neither agree nor disagree"
M4	Number of participants who choose "Agree"
M5	Number of participants who choose "Totally agree"
M6	SUS score of participants

Table 7.1: Metrics for the approach evaluation

7.3 MetaSEE Framework Experiment

7.3.1 Planning

Goals, Questions, and Metrics

In this section, we planned the *MetaSEE Framework Experiment (E1)*. The main purpose of this experiment is to evaluate the importance of MetaSEE Framework guidelines to define the main affordances to design of XR apps for SEE. According to GQM paradigm (BASILI *et al.*, 1999), we designed the evaluation as described in Figure 7.2 and Table 7.2.

Analyze	the MetaSEE framework
With the purpose of	characterizing
With respect to	the impact of guidelines to define main affordances to design of XR apps for SEE
The point of view	XR app academics and developers
In the context of	design of XR apps for SEE

Table 7.2: Goal G1

In order to achieve goal G1, a set of questions was elaborated, as described in Table 7.3. Questions 1 to 4 were elaborated to the academics. Q1 verifies if the organization and structure of the guidelines are adequate. Q2 verifies if there is

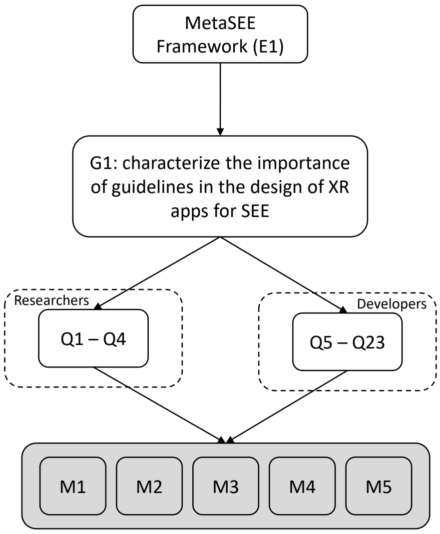


Figure 7.2: GQM model of the MetaSEE Framework experiment

any ambiguity that may impair the understanding of the guidelines. Q3 is intended to verify if the guidelines make sense in the XR apps development. Q4 verifies if the framework covers all the basic aspects of XR app design. Questions 5 to 23 were elaborated to developers. All 19 framework guidelines were converted into statements for developers to indicate the level of importance. Participants measured each question based on the metrics defined in Table 7.1.

Instruments

As presented in Section 7.2, the instruments used by the academics are described in Appendix C, and the instrument used by the developers are described in Appendix D.

Tasks

The academics' task was divided into two parts: the definition of requirements without the framework and the definition of requirements with the framework.

First, a hypothetical scenario is presented in which the project's objective is to develop an XR app that supports the teaching of any SE topic. Next, participants must list the main aspects that must be defined before starting the development of XR apps based on the presented scenario, that is, without the assistance of the MetaSEE Framework. After completing this part, participants are invited to redesign the application they have designed based on the MetaSEE Framework. For each guideline of the framework, some examples were presented to support the understanding.

Regarding the developers, tasks were not elaborated.

Profile	Question	Description
Academics	Q1	The questions are properly organized and structured
	Q2	The questions are objective and self-explanatory, that is, they are clear and easy to understand
	Q3	The questions are relevant and useful in defining key aspects of XR app design
	Q4	The framework addresses the basic aspects of XR app design
Developers	Q5	**IM1**: It is important to specify the sensory stimulus (vision, hearing, smell, taste, touch, etc.)
	Q6	**IM2**: It is important to specify the kind of reality (VR, MR or XR)
	Q7	**IM3**: It is important to specify the devices (XR headset, controllers, mouse, keyboard, etc.)
	Q8	**UX1**: It is important to specify interface-human computer techniques, such as gaze point, voice commands, detection of surfaces, etc
	Q9	**UX2**: It is important to specify mechanisms to provide the user's perception of the virtual world (visual overlays, space-aware sound, vibration, etc.)
	Q10	**UX3**: It is important to specify mechanisms to mitigate the problem of motion sickness
	Q11	**SV1**: It is important to specify the adequate graphical representation according to audience (metaphors, color scale, dimensions, etc.
	Q12	**DT1**: It is important to specify tools in order to integrate XR app and devices (Oculus Integration SDK, Steam VR SDK, OpenXR, etc.)
	Q13	**DT2**: It is important to specify development and design tools (SDK, API, engine, etc.)
	Q14	**AF1**: It is important to specify how many users will use the XR app (single or multi users)
	Q15	**AF2**: It is important to specify space around the user (seated, standing, room-scale, etc.)
	Q16	**AF3**: It is important to specify the XR app language
	Q17	**AF4**: It is important to specify the system requirements must be met in order to guarantee a good performance
	Q18	**LI1**: It is important to specify some indicators that will be used to track user performance (sequences of actions and time, etc.)
	Q19	**LO1**: Considering any XR app for education, it is important to specify the topics that will be covered (gravity, electromagnetic field, etc.)
	Q20	**LO2**: Considering any XR app for education, it is important to specify skills and competencies that must be achieved (understand how the force of gravity affects the motions of bodies, etc.)
	Q21	**PA1**: Considering any XR app for education, it is important to specify the theories and pedagogical approaches (project-based learning, game-based learning, experiential learning, etc.)
	Q22	**SP1**: Considering any XR app for education, it is important to specify the student profile (beginner, K-12, etc.)
	Q23	**CO1**: Considering any XR app for education, it is important to specify the context (online college, classroom in-person, distance learning, etc.)

Table 7.3: Questions elaborated to MetaSEE Framework evaluation

Pilot Study

A pilot study was conducted in April 2023. The participant selected for convenience has a postdoctoral degree and reported that he/she has approximately

16 years of experience with XR apps development, with 40 projects focused on supporting teaching through immersive technologies. After the evaluation, some adjustments were made, such as the organization of the instrument sections, as well as the reformulation of some questions.

7.3.2 Execution

After the adjustments made from the pilot study, the evaluation of the MetaSEE Framework was carried out in April 2023 with 4 academics and 12 developers. As presented in Section 7.2, the instruments for the evaluation were shared in the communication channels according to researcher and developer profiles.

7.3.3 Analysis

This section comprises an in-depth scrutiny of the data garnered from the study, entailing an exploration of the participants' profiles and an elaborate discourse of the dataset analysis. Initially, the academics' and developers' profiles were scrutinized independently, followed by a meticulous examination of the significance of the MetaSEE Framework.

Academics' Profile

By means of analyzing the academics' profiles, significant facets were able to be discerned. With regard to academic education, 2 academics reported having a PhD degree, one is a postdoctoral fellow, and the other a doctoral student. The participants informed experience degree according to the scale in Table 7.4.

Degree	Description
0	"none" (no experience)
1	"I studied in class or in a book" (very low experience degree)
2	"I used it in some projects in the classroom" (low experience level)
3	"I used it in my own projects" (average experience degree)
4	"I used it in few projects in the industry" (high experience degree)
5	"I used it in several industrial projects" (very high experience level)

Table 7.4: Experience degree scale

Table 7.5 presents the academics' experience level (degree). Two academics informed to have high to very high experience in desktop and web development. Regarding mobile development, half of them reported having very low experience, one has very high experience, and one high experience. Considering XR development, two informed to have high experience, one has average experience degree, and one has no experience. Table 7.6 presents the academics' experience level (time in months).

This item was normalized on a 0-5 scale, considering five as the highest score regarding the average time normalized from lesser and highest time informed, according to Table 7.4. The academics have experience developing desktop, web, mobile, and XR applications for 17.25, 11.75, 5.13, and 1.92 years on average, respectively.

In addition, Table 7.17 presents the approximate number of projects in which the academics participated in the development of applications for education. When analyzing these data with experience time, it is concluded that the participants have more experience in desktop than in XR. We analyzed the level of experience in SE topics also based on the experience scale from 0 to 5. Figure 7.3 presents the levels of experience by topic in SE, as reported by the participants.

Participant Id	Desktop	Web	Mobile	XR
P1	4	4	1	4
P2	5	5	5	4
P3	5	5	4	3
P4	4	4	1	0

Table 7.5: Academics' experience level (degree) from E1 experiment

Participant Id	Desktop	Web	Mobile	XR	Average	Nomalized
P2	240	216	204	36	174.0	5.0
P4	360	180	6	0	136.5	3.9
P3	108	108	36	6	64.5	1.9
P1	120	60	0	50	57.5	1.7
Average	*207.00*	*141.00*	*61.50*	*23.00*	*108.13*	*3.11*

Table 7.6: Academics' experience level (time) from E1 experiment

Participant Id	Desktop	Web	Mobile	XR	Average	Normalized
P1	20	10	0	5	8.8	5
P2	5	12	6	3	6.5	3.7
P4	10	5	1	0	4.0	2.3
P3	2	1	4	0	1.8	1.0
Average	*9.25*	*7.00*	*2.75*	*2.00*	*5.25*	*3.00*

Table 7.7: Academics' number of projects from E1 experiment

Developers' Profile

According to Figure 7.4, 33% of developers reported that their main skill is web application development; 33% reported that they have skills in other areas, 17% have skills in mobile development and 17% in XR. Considering the response time as mentioned in Section 7.2, only this question for analyzing the profile was elaborated.

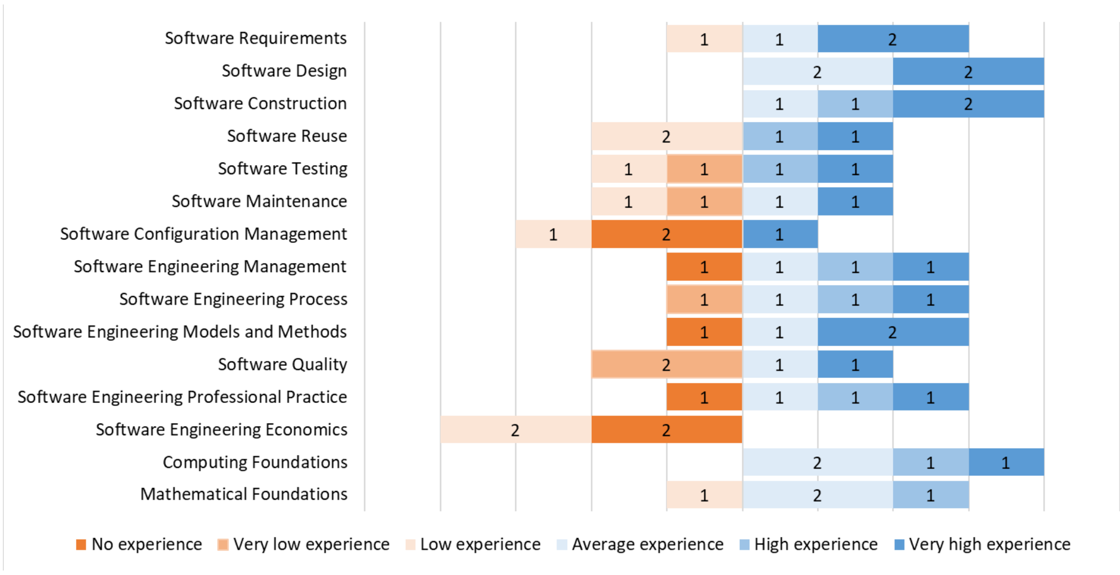


Figure 7.3: Experience of academics in SE topics from E1 experiment

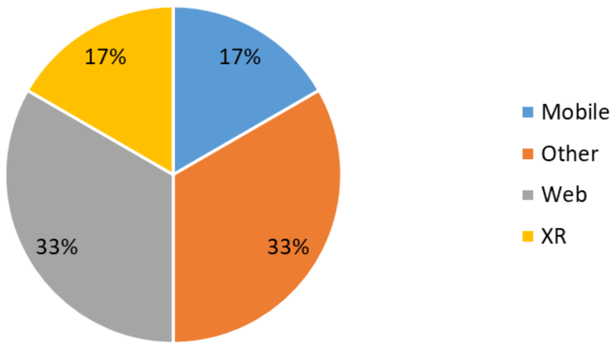


Figure 7.4: Developers' main skill from E1 experiment

Results

The academics, after completing the characterization form and having performed the tasks through the execution form, evaluated the MetaSEE Framework (Appendix C.4). Figure 7.5 presents the result of the answers to the questions, as defined in Table 7.3.

Regarding Q1, half of the participants agree that the framework's guidelines are properly organized and structured. However, the other half disagrees. The purpose of this question was to verify whether the guidelines are well structured in relation to technological and pedagogical affordances. Q2 checked if the guidelines are objective and self-explanatory, that is, if they are clear and easy to understand. According to the opinion of the participants, half agree that the guidelines are self-explanatory. Participant P2 reported that "*with the inclusion of examples in some of them facilitated the understanding*". According to P4, "*questions are sufficiently detailed*". The other half of the participants disagreed and reported that the guidelines are generic. Q3 checked whether the guidelines are relevant and useful in defining key aspects of XR design. Participants P2 and P4 strongly agree that the guidelines are relevant. However, P1 and P3 responded neutrally, as they believe that the guidelines are very generic and that other aspects should be considered, such as business rules. Finally, Q4 investigates whether the framework addresses basic aspects regarding the XR apps project. Three out of four participants agree that the guidelines cover basic aspects of XR apps development. P1 reported his neutrality and justified his answer: "*different apps will deal with different aspects. The framework is combining development decisions (e.g. API to use) with pedagogical decisions. These should be independent. The framework should focus on requirements such as performance, integration, functionality, etc. Implementation details are a different spectrum*".

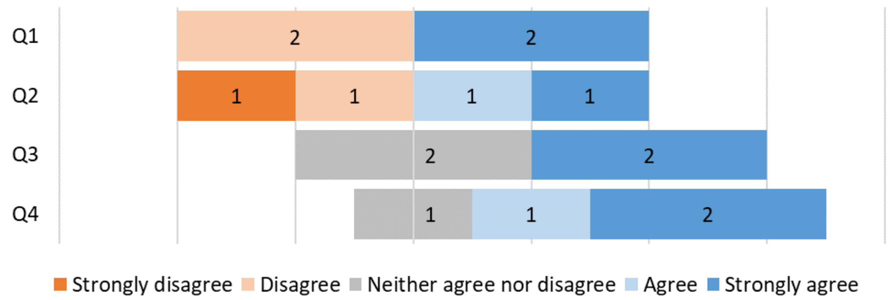


Figure 7.5: Number of academics' responses from E1 experiment

In addition to the above questions, we added six questions in order to extract more details about the participants' opinions. When asking about the experience of defining aspects of XR apps without and with the framework, P3 reported "*without the structure, thinking about everything that is needed for developing an application is a very general question. The framework, on the other hand, makes it a bit easier, but it remains generic. It groups some information, but I believe that things linked to business rules are still missing*". P2 reported that "*it's not easy to create a project with this scope in a few minutes. It is likely that you will not achieve accuracy or consistency in some of the numerous guidelines*". Participant P4 reported that it is difficult since he does not have much experience with XR. Participant P1 did not describe his experience.

Additionally, participants reported whether there are guidelines that should be added to the framework. According to participant P1, the framework should "*start by clarifying functional requirements, integration, and then other non-functional requirements such as data security, budget, performance, etc.*". P3 reported that " *the guidelines are a superficial touch. The group topics together, but it's still quite generic. It would be interesting to think about how to straiten these guidelines so that there is something more concrete at the end of the framework*". According to

P4, "*a more detailed profile of the target audience would certainly be helpful*". P2 did not report contributions.

Regarding whether any framework guidelines should be withdrawn, everyone reported that they should remain. We also asked the participants' opinions regarding the main contribution of the framework. All participants agreed that the framework helps to define essential aspects for the development of XR apps. More precisely, participant P1 declared that "*it may help define pedagogical content and approaches*". P2 informed "*Software Engineering Education is an area of interest that should explore new ways of engaging students and the framework helps in designing applications in XR*". P3 reported that "*group the questions into topics and make the developer remember some points*". Finally, P4 believes that the framework is "*a guided methodology that certainly helps to define the scope and set the major requisites for such project*".

From the point of view of limitations of the MetaSEE Framework, participants reported its generic nature, as well as the mix of aspects with different points of view. For example, participant P2 informed that the framework "*proposals to reach across the horizontal axis of the reality-virtuality continuum theory. There are too many categories of technologies to be achieved at the same time in a generic way*". P3 related that "*the definition of the application remains very generic* " and P1 described that the framework "*mixes completely different sets of concerns*". P4 reported that it is difficult to give an opinion due to limited background.

Finally, the participants reported some improvements in the framework. P1 informed "*separate pedagogical goals, educational context, and development option*". The opinion of participant P2 is "*create separate sub-forms for some technologies because there are several XR technologies*". P3 suggests "*consider ways to make the requirements gathering process a little more concrete at the end of the framework*". Finally, P4 reported that "*more detailed choices of interaction types and XR task goals could benefit the overall design phase*".

After the analysis from the academics' point of view, next we performed the analysis from the developers' point of view.

As explained in Section 7.2, the form applied to developers contains 19 statements, each of which is directly related to framework guidelines (see Section 6.3.1). Therefore, the developers have informed the level of importance for each guideline, considering the context of defining aspects before starting the development of XR apps. According to Figure 7.6, most developers agree that all framework guidelines are important to define relevant aspects of the XR apps project. In addition, some developers reported other aspects that should also be considered, such as budget definition, estimated time for completion, and usability for people experiencing disabilities.

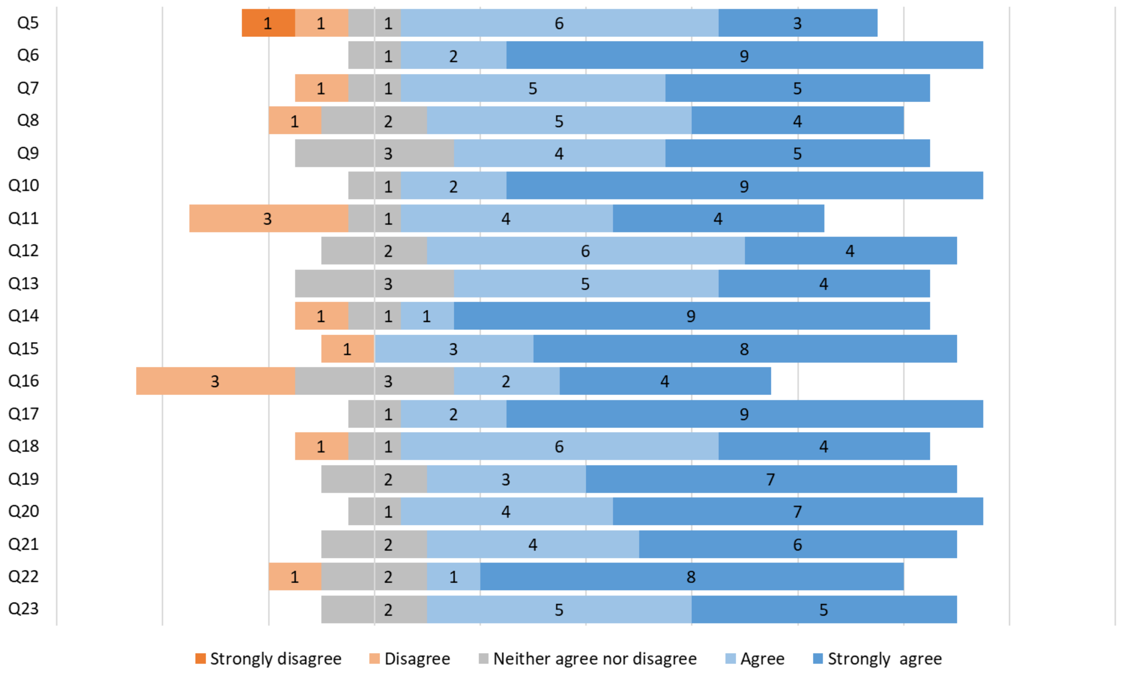


Figure 7.6: Level of importance of the guidelines from the developers' point of view from E1 experiment

7.4 MetaLine Features Model Experiment

7.4.1 Planning

Goals, Questions, and Metrics

In this section, we planned the *MetaLine Features Model Experiment (E2)*. The main purpose of this experiment is to evaluate the compliance of the MetaLine Features Model regarding the Web XR apps features. According to GQM paradigm (BASILI *et al.*, 1999), we designed the evaluation as described in Figure 7.7 and Table 7.8.

Analyze	the MetaLine Features Model
With the purpose of	characterizing
With respect to	compliance of Web XR apps features
The point of view	Web XR apps academics and developers
In the context of	development of Web XR apps

Table 7.8: Goal G2

In order to achieve goal G2, a set of questions was elaborated, as described in Table 7.9. Questions 24 to 27 were elaborated to the academics. We intended to verify in Q24 if the features model is useful to establish the main features for the development of Web XR apps. Q25 verifies if the features model covers all the features needed for the development of Web XR apps. Q26 verifies if the features

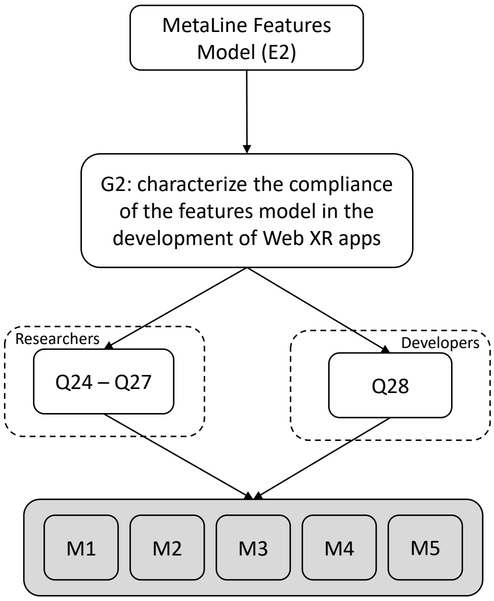


Figure 7.7: GQM model of the MetaLine Features Model experiment

model helps to understand the complexity of the development of Web XR apps. Q27 verifies if it is extensible to add other features. Q28 was elaborated to the developers. As presented in Section 7.2, a set of statements based on the MetaLine Features Model was formulated in order to support the understanding of our proposed model. We made this decision to avoid threats to validity regarding model compression, as there was no guarantee that all participants would have knowledge of the notation for model features. Participants measured each question based on the metrics defined in Table 7.1.

Profile	Question	Description
Researcher	Q24	Is the features model useful for the development of Web XR apps?
	Q25	Does the features model include all the features needed for the development of Web XR apps?
	Q26	Does the features model help the understanding on how the different features relate to each other?
	Q27	Is the feature model flexible enough to allow you to add new features easily?
Developer	Q28	The statements presented reflect the main characteristics of Web XR apps

Table 7.9: Questions elaborated to MetaLine Features Model experiment

Instruments

As presented in Section 7.2, the instruments used by the academics are described in Appendix E, and the instrument used by the developers are described in Appendix D.

Tasks

In this step, the MetaLine Features Model (see Figure 6.4) is presented to the academics, as well as a detailed description of the referred model, according to Section E.3. For developers, the task is to analyze statements about the main characteristics of Web XR apps, according to Appendix D.

Pilot Study

In April 2023 a pilot study was conducted. The participant selected for convenience is an undergraduate student and has high experience in the development of desktop applications. Regarding the development of XR apps, the participant reported having little experience. Subsequent to the evaluation, certain modifications were undertaken, specifically the revision of certain questions to circumvent potential ambiguities.

7.4.2 Execution

Following the modifications implemented as a result of the pilot study, the evaluation of the MetaLine Features Model was carried out in April 2023 with 3 academics and 12 developers. As elucidated in Section 7.2, the evaluation instruments were disseminated through communication channels, based on the profiles of the academics and developers involved.

7.4.3 Analysis

This section encompasses a comprehensive examination of the data collected from the study, including an exploration of the characteristics of the participants and an elaborate discourse on the analysis of the dataset. The profiles of the academics and developers were initially examined separately, followed by a meticulous analysis of the significance of the MetaLine Features Model.

Academics' Profile

Significant facets were discerned through the analysis of the academics' profiles. With regard to academic education, two are doctors, and one undergraduate student. The participants informed experience degree according to Table 7.4.

Table 7.10 describes the academics' experience level (degree). Most respondents have considerable experience in developing desktop, web, and mobile applications. From the point of view of the development of XR apps, two of the three participants reported having an average experience, that is, the knowledge acquired was through their own projects.

Table 7.11 presents the academics' experience level (time in months). This item was normalized on a 0-5 scale, according to the defined in Table 7.4. The academics have experience developing desktop, web, mobile, and XR applications for 10.33, 8.56, 7.17, and 2.67 years on average, respectively.

Furthermore, we analyzed the level of experience in SE topics also based on 0-5 scale experience (see Table 7.4). Figure 7.9 elucidates the levels of expertise in various domains of SE, as indicated by the participants' self-reported experiences.

Participant Id	Desktop	Web	Mobile	XR
P1	4	4	4	3
P2	5	4	3	0
P3	4	4	3	3

Table 7.10: Academics' experience level (degree) from E2 experiment

Participant Id	Desktop	Web	Mobile	XR	Average	Normalized
P1	240	216	216	36	177.00	5.0
P2	120	80	30	0	57.50	1.6
P3	12	12	12	60	24.00	0.2
Average	*124.00*	*102.67*	*86.00*	*32.00*	*86.17*	*2.28*

Table 7.11: Academics' experience level (time) from E2 experiment

Developers' Profile

As described in Section 7.2, the developer profile participants who collaborated in E1 are the same in this experiment. Therefore, the analysis of the profile of the participants is reported in Section 7.3.3.

7.4.4 Results

Upon completion of the characterization form (E.2) and the execution of tasks via the execution form (Section E.3), the academics proceeded to assess the results. Figure 7.8 presents the result of the answers to the questions, as defined in Table 7.9.

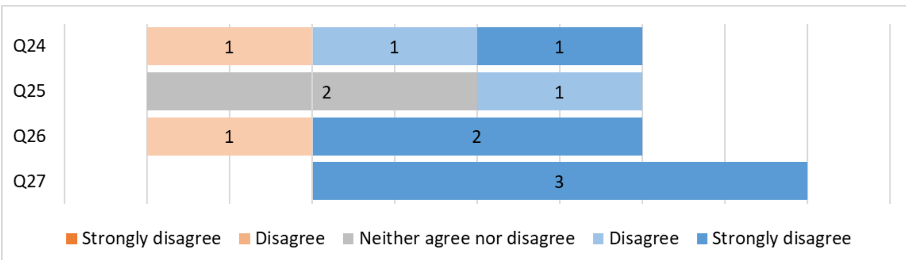


Figure 7.8: Number of academics' responses from E2 experiment

Regarding Q24, most agree that the features model is useful for the development of Web XR apps. P2 disagrees as he informed that "*the model could be used for producing an architectural checklist for a complete XR app architecture*". We check in Q25 if the model includes all the features needed for the development of Web XR apps. Most participants (P1 and P2) report neutrality. P1 reported that "*although it presents a lot of effort, it can be considered the mapping of specific characteristics of the platforms*". The purpose of Q26 is to verify whether the model helps in understanding the different aspects and how they are related. Most participants reported that the features model supports the understanding of features. Finally, we check in Q27 if the model is flexible enough to add other features. All participants agree that the presented model guarantees the evolution of the mapping of Web features XR apps.

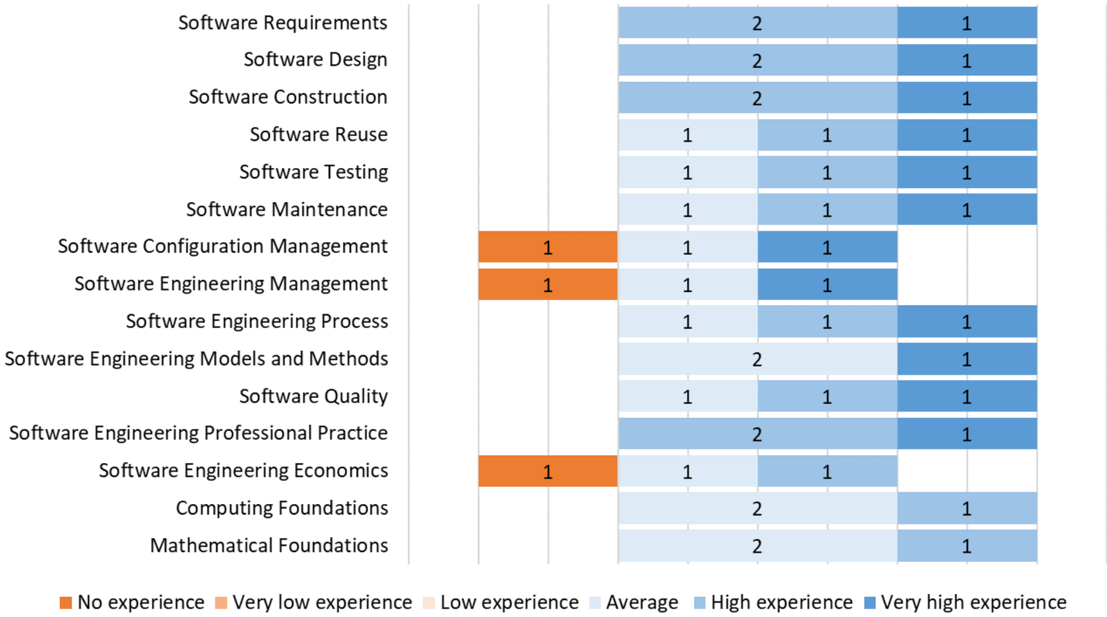


Figure 7.9: Experience of academics in SE topics from E2 experiment

In addition to the aforementioned inquiries, an additional set of four questions were incorporated with the intention of garnering a more comprehensive understanding of the academics' perspectives. From the point of view of the participants' opinion regarding the main contributions of the features model, all reported that the model plays an important role in the development of the Web XR apps, but from different perspectives. For example, P2 reported that "*the features model could be used as one of the inputs for producing XR apps/solutions architecture*". P3 reported that "*it is especially useful to help developers better understand the requirements of the XR apps*". We also asked participants if there were other features that should be added to the model. Only one participant reported that "*it would be a good idea to expand on device features, especially mobile. Since different types of devices have* *certain XR capabilities out of the box e.g. ARCore compatibility*". Regarding the features that should be removed from the model, the participants reported that they do not have enough knowledge and skills to give an opinion. In addition, P3 also reported that "*olfaction and gustation on indirect processing seem out of place for a Web XR app modeling, unless it's for a whole in-place experience that integrates the XR App*". Finally, the participants reported on which aspects of the features model should be improved. P2 informed "*that the use of other perspectives and diagrams can improve the understanding of the mapping*". P3 reported that "*on the topic of multi-platform, it might be useful to model feature characteristics available for each platform. Even using a cross-platform framework, like AR Foundation, some features are only available on certain devices, like object tracking only being available for iOS devices due to ARKit support*".

Following the analysis conducted by the academics, we subsequently conducted an analysis from the developers' points of view.

As shown in Section 7.2, the developers of experiments E1 and E2 are the same and used the same form shared on social networks. Figure 7.10 presents the result of the agreement level with the model. All developers reported agreeing with the modeling.

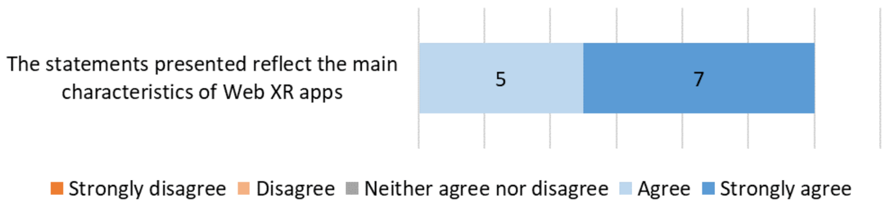


Figure 7.10: Developers' level of agreement regarding the features model

7.5 A-Frame VirtualUML Component Experiment

7.5.1 Planning

Goals, Questions, and Metrics

In this section, we planned the *A-Frame VirtualUML Component Experiment (E3)*. The main purpose of this experiment is to evaluate the ease of use and usefulness of the A-Frame VirtualUML Component for the development of Web XR apps for SEE. According to GQM paradigm (BASILI *et al.*, 1999), we designed the experiment from the point of view of the ease of use and usefulness, as described in Figure 7.11, Table 7.12, and Table 7.13.

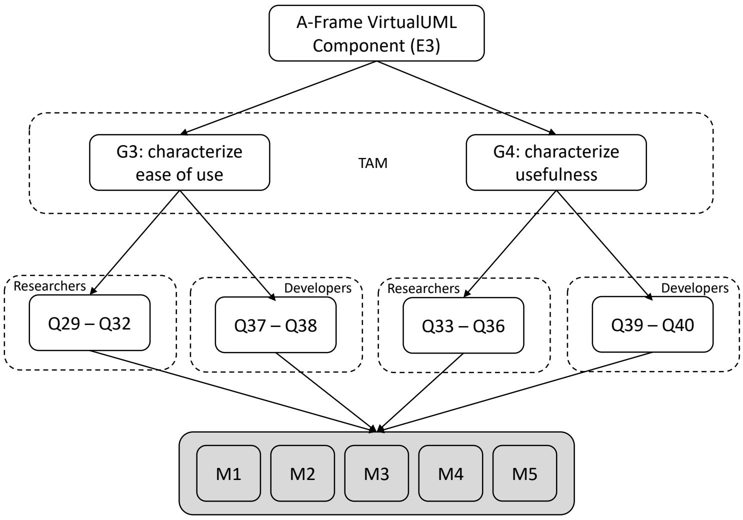


Figure 7.11: GQM model of the A-Frame VirtualUML Component experiment

Analyze	the A-Frame VirtualUML Component
With the purpose of	characterizing
With respect to	ease of use
The point of view	Web XR apps academics and developers
In the context of	development of Web XR apps for SEE

Table 7.12: Goal G3

In order to achieve goal G3, a set of questions was elaborated based on the TAM model. According to POLANČIČ *et al.* (2010), the TAM model strengths are: (i) it focuses on specific information of technologies; (ii) its validity and reliability have been demonstrated in several academics; (iii) it is extensible; and (iv) it can be used during and after the adoption of a particular technology. Table 7.14 describes the questions grouped in ease of use and usefulness dimensions and each question is measured by the participants based on the metrics defined in Table 7.1.

Instruments

As detailed in Section 7.2, the instruments employed by the academics are expounded upon in Appendix F, whereas the instrument utilized by the developers is elucidated in Appendix G.

Tasks

For the academics, a hypothetical scenario was presented so that the participants assumed the role of a SE professor, with the mission of motivating their students in the UML modeling discipline. The purpose of the task is to describe strategies or tools that can be adopted to motivate students. For the developers, the only task was to perform a review of the A-Frame VirtualUML Component documentation.

Analyze	the A-Frame VirtualUML Component
With the purpose of	characterizing
With respect to	usefulness
The point of view	Web XR apps academics and developers
In the context of	development of Web XR apps for SEE

Table 7.13: Goal G4

Profile	Dimension	Question	Description
Researcher	Ease of use	Q29	My interaction with A-Frame VirtualUML Component is clear and understandable
		Q30	It is easy for me to become skillful at using A-Frame VirtualUML Component
		Q31	I find it easy to execute the proposed tasks with the A-Frame VirtualUML Component
		Q32	A-Frame VirtualUML Component's documentation is easy to understand
	Usefulness	Q33	A-Frame VirtualUML Component is useful to create UML class diagrams in 3D
		Q34	A-Frame VirtualUML Component improves my performance to create UML class diagrams in 3D
		Q35	A-Frame VirtualUML Component's documentation is useful to help to create UML class diagrams in 3D
		Q36	A-Frame VirtualUML Component is useful to execute the proposed tasks
Developer	Ease of use	Q37	A-Frame VirtualUML Component's documentation is easy to understand
		Q38	I think I would become skilled when using the A-Frame VirtualUML Component
	Usefulness	Q39	A-Frame VirtualUML Component's documentation is useful to help to create UML class diagrams in 3D
		Q40	A-Frame VirtualUML Component is useful to create UML class diagrams in 3D

Table 7.14: Questions adapted from TAM model to evaluate A-Frame VirtualUML Component

Pilot Study

A pilot study was conducted in April 2023. Two participants were selected by convenience. One is a master's degree student and the other is an undergraduate student. Regarding the experience with XR apps development, one reported having low experience and the other reported having very low experience.

During the study with the two participants, we observed that they were not used to the Glitch[7] tool. Through this tool, participants perform the task of the experiment. Therefore, we decided to add a question about experience with online code editors in the characterization form. Following the assessment, particular adjustments were made, notably the revision of certain inquiries to avoid potential ambiguities.

[7]https://glitch.com/

7.5.2 Execution

After implementing the modifications resulting from the pilot study, the assessment of the A-Frame VirtualUML Component was conducted in April 2023, with the participation of 4 academics and 5 developers. As expounded upon in Section 7.2, the evaluation instruments were distributed through communication channels that were tailored to the profiles of the academics and developers involved in the study.

7.5.3 Analysis

The following section presents a thorough examination of the data gathered from the study, encompassing an exploration of the participants' characteristics as well as a detailed discussion of the dataset analysis. Initially, the profiles of the academics and developers were examined independently, followed by a meticulous evaluation of the significance of the A-Frame VirtualUML Component.

Academics' Profile

The analysis of the academics' profiles revealed notable aspects. With regard to academic background, most are masters' degree and one has a bachelor's degree. The participants informed experience degree according to Table 7.4.

Table 7.15 describes the academics' experience level (degree). It is possible to notice that all of them have considerable experience in the development of desktop and web applications. No participant has experience with XR apps development. Table 7.16 describes the academics' experience level (degree). This item was normalized on a 0-5 scale, according to the defined in Table 7.4. The academics have experience developing desktop, web, and mobile applications for 3.08, 3.71, and 0.54 years on average, respectively. In addition, Table 7.17 presents the average of projects in which the academics participated in the development of applications.

Participant Id	Desktop	Web	Mobile	XR
P1	4	4	2	0
P2	3	4	3	0
P3	5	4	2	0
P4	4	4	2	0

Table 7.15: academics' experience level (degree) from E3 experiment

We also asked academics which online code editor tools they have used. This question was elaborated in order to observe the adaptability with this type of tools, since the task will be executed in the Glitch editor. In most of the tools presented, at least one participant reported using them (see Section F.2). With the exception

Participant Id	Desktop	Web	Mobile	XR	Average	Normalized
P4	36	72	6	0	28.5	5.0
P2	30	60	10	0	25.0	4.4
P3	58	22	4	0	21.0	3.7
P1	24	24	6	0	13.5	2.4
Average	*37.00*	*44.50*	*6.50*	*0.00*	*22.00*	*3.86*

Table 7.16: academics' experience level (time) from E3 experiment

Participant Id	Desktop	Web	Mobile	XR	Average	Normalized
P2	2	10	3	0	3.8	5.0
P1	0	6	0	0	1.5	2.0
P4	0	2	0	0	0.5	0.3
P3	0	0	0	0	0.0	0.0
Average	*0.50*	*4.50*	*0.75*	*0.00*	*1.44*	*1.82*

Table 7.17: academics' number of projects from E3 experiment

of JSFiddle, as two participants reported that they know it. CodeSanbox and Glitch are two tools that are unknown to participants.

Considering VirtualUML as a JS component based on the A-Frame framework, we observed the participants' skill level in relation to the JS frameworks that support the development of 3D and XR applications. A list of frameworks were presented, such as Three.js, A-Frame, Babylon.js, Cesium, and PlayCanvas (see Section F.2). Based on a 5-point Likert scale, with 1 being very poor and very good being 5, notably, all participants reported having a very poor experience. Other frameworks were reported by participants, such as Django, Node.js, Express, and Ruby on Rails. However, these have no relation to JS-based 3D or XR web application development.

Developers' Profile

According to the design of the experiments presented in Section 7.2, 5 developers voluntarily participated in this experiment. Considering the main skill reported by each developer, only one reported that XR application development is the main skill, while the rest reported web application development.

7.5.4 Results

After accepting the research terms via the consent form, having completed the characterization form, as well as performing the tasks, the academics evaluated the A-Frame VirtualUML Component from the point of view of its ease of use and usefulness. Figure 7.12 presents the result of the answers to the questions, as defined in Table 7.9. Overall, most participants agree that the A-Frame VirtualUML Component is easy to use and useful.

In addition to the questions analyzed in Figure 7.12, we asked another set of

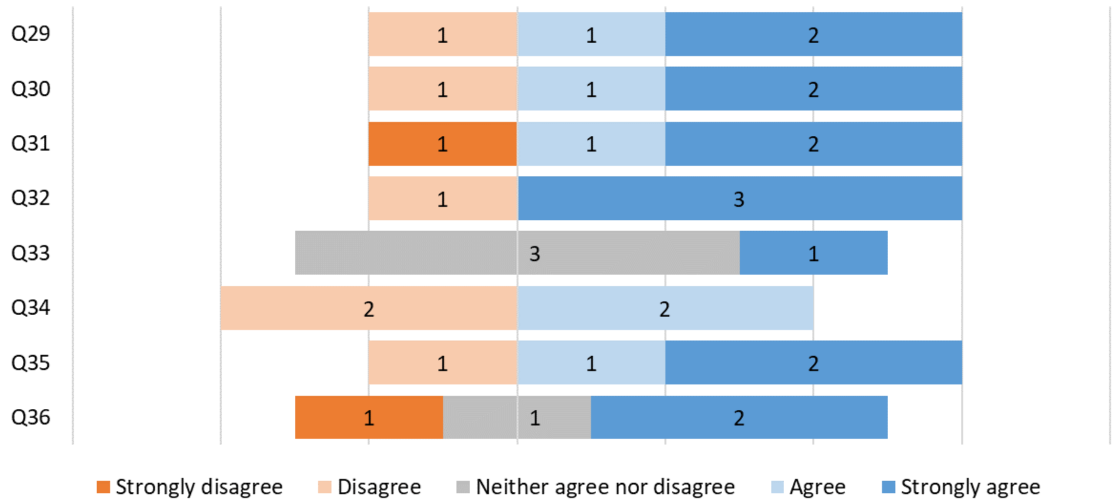


Figure 7.12: Number of academics' responses from E3 experiment

questions in order to obtain more detailed opinions from the participants (see Section F.4). All agree that the component documentation is understandable and only one reported that "*it would be interesting to have documentation with explanations, such as how to control the position of elements through the 3 coordinates*". When asked about the ease of creating a UML class diagram, one participant reported "*I agree that the component is easy to develop, but I don't know how to assess whether it would be possible to implement more complex class modeling scenarios and how this modeling would be created*". As for the limitation of the component, all reported that one of the main restrictions is the inherent complexity of UML class diagrams (number of classes, attributes, methods, types of relationships), as well as the implementation of other UML diagrams. Additionally, participants reported whether they were able to understand the purpose of the component. All participants reported that the component is a framework/tool for creating UML class diagrams. Our intention in having created this question was to verify if the participants could identify that the component is based on the A-Frame framework, which allows the extensibility of its functions for the development of XR apps. Finally, the last question obtained the participants' opinion regarding component improvements. All reported that the component must implement the UML diagrams and their specificities, according to the official document.

From a developers point of view, we also observed that the majority also agree that the A-Frame VirtualUML Component is easy to use and useful. Figure 7.13 presents the results of participants' responses per question.

As in the experiment with the academics, a question was designed in order to obtain the opinion of the developers in detail, regarding component improvements. However, none of the participants reported improvements.

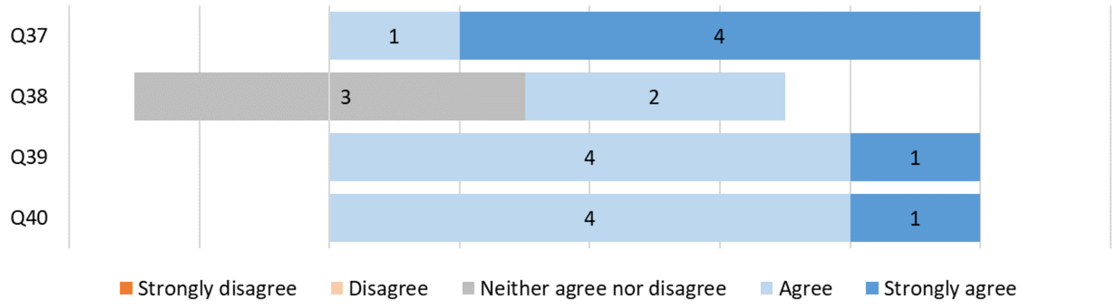


Figure 7.13: Number of developers' responses from E3 experiment

7.6 MetaSEE Platform Experiment

7.6.1 Planning

In this section, we planned the *MetaSEE Platform Experiment (E4)*. The main purpose of this experiment is to evaluate the usability of the MetaSEE Platform. According to GQM paradigm (BASILI *et al.*, 1999), we designed the evaluation as described in Figure 7.14 and Table 7.18.

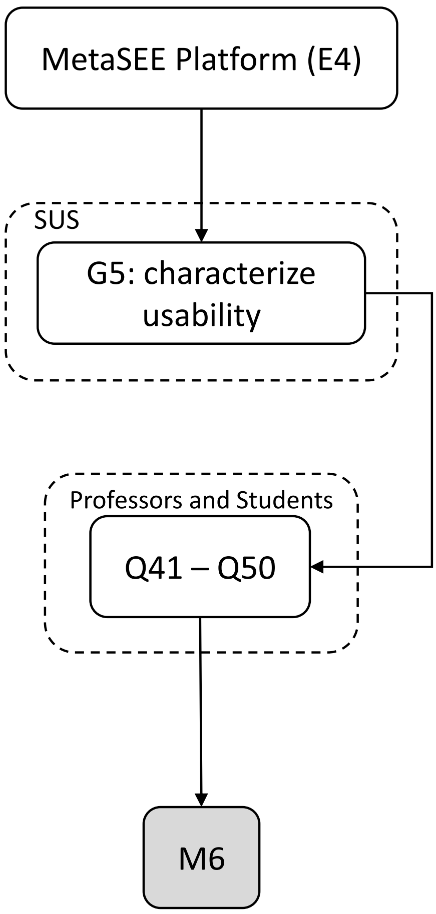


Figure 7.14: GQM model of the MetaSEE Platform experiment

Analyze	the MetaSEE Platform
With the purpose of	characterizing
With respect to	usability
The point of view	SE students and professors
In the context of	SEE

Table 7.18: Goal G5

In order to achieve goal G5, a set of questions was elaborated based on SUS Questionnaire (BROOKE, 1996a). SUS is a widely used and validated questionnaire designed to assess the usability of a wide range of products and systems, including websites, software applications, and hardware devices. It is a valuable tool for assessing the usability of products and systems, offering a reliable and efficient method for measuring user experience and providing actionable insights for improving usability. Table 7.19 presents these questions and each one is measured by the participants based on the metrics defined in Table 7.1.

Question	Description
Q41	I think that I would like to use this system frequently
Q42	I found the system unnecessarily complex
Q43	I thought the system was easy to use
Q44	I think that I would need the support of a technical person to be able to use this system
Q45	I found the various functions in this system were well integrated
Q46	I thought there was too many inconsistencies in this system
Q47	I would imagine that most people would learn to use this system very quickly
Q48	I found the system very cumbersome to use
Q49	I felt very confident using the system
Q50	I needed to learn a lot of things before I could get going with this system

Table 7.19: Questions adapted from SUS questionnaire to evaluate the MetaSEE Platform

Participants

In this experiment, students and professors at IF Sudeste MG participated in the study. A participation questionnaire was shared with computer science students in order to choose the appropriate date and time to carry out the evaluation. Professors were selected by convenience.

Tasks

We elaborated a set of tasks for students and professors in order to explore if participants are able to access VWs and interact with the functionalities provided by the MetaSEE Platform. Groups of students were formed with the intention of enabling them to engage in real-time collaborative tasks completion by synchronizing their study schedules. The specific tasks executed by *students* in our study were:

1. Access the link **https://evaluation.d32btx1ycdzig0.amplifyapp.com/** in another browser window of your choice;

2. You have up to 10 minutes to freely explore the platform;

3. Access the same virtual world;

4. Together, construct an analysis class diagram that reflects the following scenario: *One teacher teaches several subjects and each subject belongs to only one teacher. Each discipline is part of some courses. In addition, each class is made up of students.*

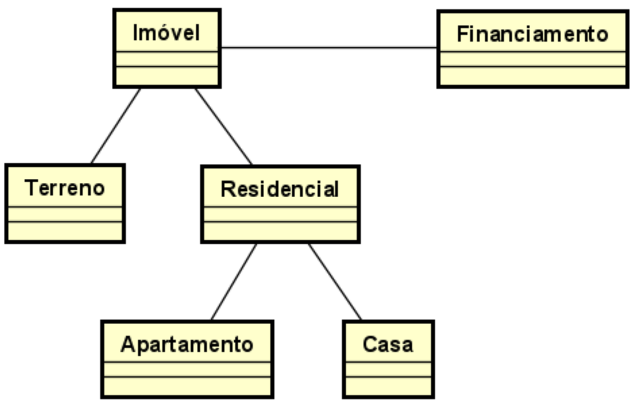
In the case of *professors*, they individually performed the following tasks:

1. Access the link **https://evaluation.d32btx1ycdzig0.amplifyapp.com/** in another browser window of your choice;

2. You have up to 10 minutes to freely explore the platform;

3. Access a virtual world;

4. Construct an analysis class diagram that reflects the following model:



Instruments and Preparation

Following the *E1 experiment instruments* (Section 7.3.1), we elaborated four instruments presented in Appendix H (applied in Portuguese):

- *Informed Consent Form (Section H.1)*: this document serves to articulate the study objective as well as the rights and responsibilities of participants. Additionally, it underscores the principle that the collected data should not be leveraged for evaluating the performance of participants, while expounding on the terms of confidentiality. The distribution of this form to participants prior to study execution is imperative, and each participant is required to return the signed document;
- *Characterization Form (Section H.2)*: through this form academic and professional data will be obtained, as well as the perspective of professors and students of SEE;
- *Execution Form for Students and for Professors*: presents the four proposed tasks for students (Section H.3) and professors (Section H.4);
- *Evaluation Form (Section H.5)*: comprises of a set of questions that each participant is required to respond to, aimed at eliciting an evaluation of their experience subsequent to the tasks execution.

Pilot Study

The pilot study was conducted in April 2023 through remote individual sessions on Google Meet with two participants selected by convenience. The first participant has an incomplete master's degree and filled out the forms as a professor because the participant has experience in programming teaching. The second participant is a master's degree and UX expert, who filled out the forms as a student. Both participants are from the area of SE.

After signing the informed consent form, each participant filled out the characterization form according to the professor or student profile. It was oriented to the participants to express their thoughts verbally in order to identify opportunities for improvement of the study. Both executed the four proposed tasks and filled out the evaluation form. It was identified some opportunities for improvement during the execution tasks and also registered in the evaluation form fields.

The first participant when interacting with the VW for the first time, discovered intuitively, how to move the avatar with the keyboard and rotate the camera with the mouse. Subsequently, when the researcher asked if the commands to interact and move the avatar were intuitive, the participant agreed and informed that she had experience with games, then it was easy to identify them. In the case of the second participant, this scenario was not similar. This participant does not have experiences with games and presented difficulties interacting and moving in the VW. Therefore, we decided to add a question to the characterization form about the experience with games in order to create an indicator to possibly explain the ease of interaction.

In addition, both participants filled out some suggestions based on the proposed tasks carried out in the VW, such as to create a class closer to the avatar, to change the "Edit 3D Model" menu to something that describes an appearance formatting functionality, indicate which class is editing, to reduce the number of clicks to access the functionality of creating associations between classes. These suggestions were implemented.

7.6.2 Execution

After some adjustments, the study was conducted in April 2023 with 14 participants, 6 professors and 8 students. Each session with professors was performed remotely and individually on Google Meet. Regarding students, sessions were performed remotely and in pairs on a private server on Discord[8]. We adopted that application due to its functionality to share many screens in real-time. For this reason, observing and recording all student interactions during the session was possible. The students were organized into four groups according to schedule availability. Student pairs participated in the study simultaneously. A video of a group of students who evaluated the platform is available[9].

7.6.3 Analysis

In this section, we present an analysis of the data obtained from the study, including an examination of the participants' profiles and a discussion of the dataset analysis. First, we analyze the professor's and students' profiles separately, then analyze the usability of the MetaSEE Platform.

Professors' Profile

Through the professors' profile, it was possible to identify some relevant aspects. With regard to academic education, one professor reported having a PhD degree, one is a PhD student and four are master's degree students. The professors informed experience degree according to Table 7.4.

Table 7.20 presents the professors' experience level (degree). Most of them informed to have high experience in SE. This can be interesting when investigating the professors' methodology by demonstrating practical examples instead of toy-examples or focusing only on theory. Table 7.21 presents the professors' experience level (time in months). This item was normalized on a 0-5 scale, considering five

[8]https://discord.com/
[9]https://youtu.be/PesEUIVQvAI

as the highest score regarding the average time normalized from lesser and highest time informed. Most professors have been acting in SEE for 1.81 years on average. Specifically, Figure 7.15 shows the SE topics that professors have been teaching.

Professor Id	Academic education	Main area of activity	SE experience
P1	PhD degree	Operations Research	4
P2	Master's degree	Artificial Intelligence	4
P3	Master's degree	Software Engineering	4
P4	Master's degree	Software Engineering	3
P5	PhD student	Database	4
P6	Master's degree	Software Engineering	4

Table 7.20: Professors' experience level (degree)

Professor Id	SEE experience	SEE experience (NORMALIZED)
P3	36	5.0
P5	12	1.7
P1	12	1.7
P6	6	0.8
P2	6	0.8
P4	6	0.8
AVERAGE	*13.00*	*1.81*

Table 7.21: Professors' SEE experience level (time)

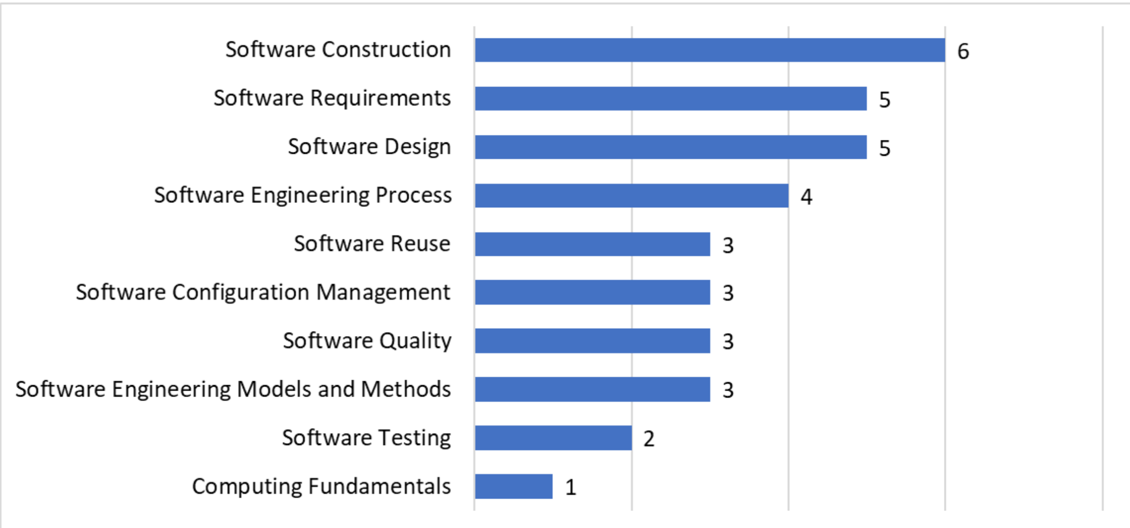


Figure 7.15: SE topics experience

In addition, as discussed previously in Section 7.6.1, we analyzed the professors' game experience. Figure 7.16 presents the use frequency by type of game. It is possible to notice that most of them have little experience with games. This overview can help to understand their feedback regarding adaptation to the platform, from a usability point of view.

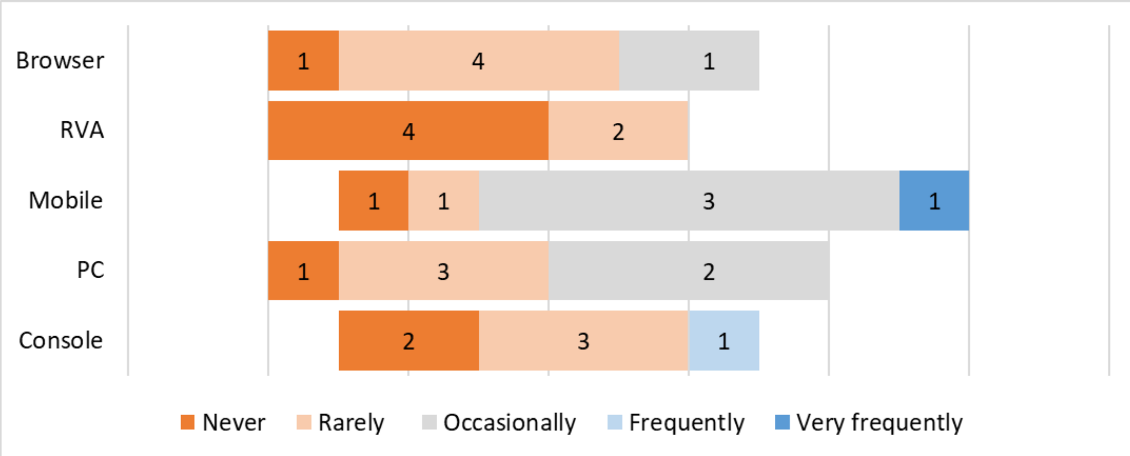


Figure 7.16: Professors' game experience

Students Engagement and Methodologies

In addition to characterizing the professors' profile, we obtain their opinions regarding student engagement, as well as the methodologies used to support SEE. Table 7.22 presents the student engagement from the professors' point of view. Considering that 50% of professors answered that students are unmotivated in SEE and 50% answered that students are neither engaged nor unmotivated, in general, this scenario may indicate that students are not receptive to the SE discipline for some reasons. When professors answered reasons for student unmotivation, most of them indicated that SE is a theoretical discipline and this can be a learning barrier. For example, P1 informed that the main students' demotivation in SE is "*excessively theoretical approaches*", P3 reported "*many theories around what needs to be presented*", and P4 informed "*it can be a very theoretical content depending on the teaching approach*".

Regarding used professors' methodologies, most of them reported adopting theoretical and practical classes, Computer-Aided Software Engineering (CASE) tools, and toy-examples in order to support SEE. In addition, Project-based Learning (PrBL), problem resolution, and articles with case studies were also mentioned. Finally, professors indicated some difficulties in SEE. For example, most of the professors reported that the main barriers are the adoption of mechanisms in order to allow students to apply theory with practical examples that approach real SE scenarios.

Students engagement	Professors
Unmotivated	P1, P3, P4
Neither engaged nor unmotivated	P2, P5, P6

Table 7.22: Student engagement from professors' point of view

Students' Profile

Regarding the students' profile, it was also possible to identify some relevant aspects. With regard to academic education, four students reported that they have complete specialization, three have incomplete graduation, and one has incomplete technical course. Moreover, students also indicated the level of their SE experience based on the scale presented in Table 7.4.

Table 7.23 presents the students' experience level (degree). Most of them informed to have a low experience level (37.5%). However, two students reported having a very high experience level. Table 7.24 presents the students' experience level (time in months). Based on professors' analysis, this item was also normalized on a 0-5 scale, given the range of times provided, with the lowest and highest times, the average time has been normalized to a maximum score of five. Students have studied SE for an average of 2.8 years.

Student Id	Academic education	SE experience
S1	Incomplete Technical Course	5
S2	Incomplete Undergraduate	5
S3	Complete Specialization	3
S4	Complete Specialization	3
S5	Incomplete Undergraduate	2
S6	Incomplete Undergraduate	2
S7	Complete Specialization	4
S8	Incomplete Specialization	2

Table 7.23: Students' experience level (degree)

Student Id	SE learning	SE learning (NORMALIZED)
S8	120	5.0
S6	36	1.5
S7	36	1.5
S5	30	1.3
S3	18	0.8
S4	15	0.6
S1	12	0.5
S2	2	0.1
AVERAGE	*33.63*	*1.40*

Table 7.24: Students' SE experience level (time)

Furthermore, we also analyzed the students' game experience. Figure 7.17 presents the use frequency by type of game. It is possible to notice that few of them have little experience with games. This scenario can aid in comprehending student's feedback concerning the platform's adaptability, from a usability perspective.

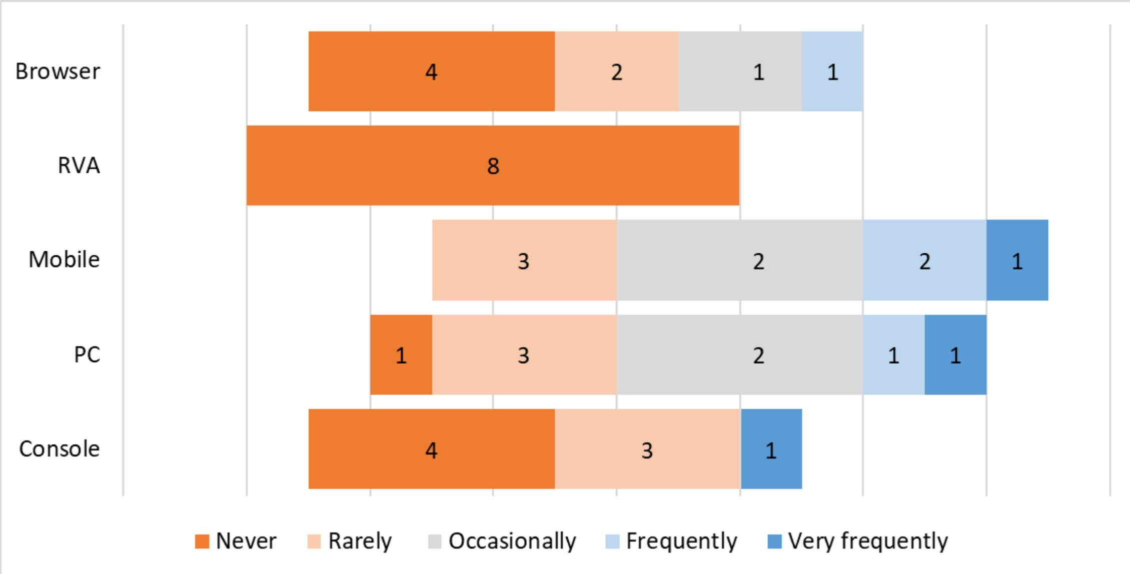


Figure 7.17: Students' game experience

Professors Engagement and Methodologies

Just as professors reported student engagement, students also evaluated professors regarding engagement in SEE. Table 7.25 shows the professors' engagement in the context of SEE. In general, the professors were well evaluated, showing positive points of engagement, that is, 62.5% students reported that professors are very engaged in SEE. Although professors are engaged and use methodologies that allow more SE practice, such as toy-examples and the use of CASE tools, students indicate that it is still necessary to adopt approaches that facilitate the application of theory in real SE scenarios.

Professors engagement	Students
Engaged	S3, S4, S7
Very engaged	S1, S2, S5, S6, S8

Table 7.25: Professor engagement from students' point of view

Results

After the professors and students had answered the characterization form, both performed the tasks according to Appendix H.4 and Appendix H.3 and then evaluated the platform from the point of view of usability based on the SUS (Appendix H.5), according to the defined objective of Table 7.18.

By applying the evaluation form, it was possible to obtain an average acceptability score of 81.25 from professors and 79.38 from students. Figure 7.18 and Figure 7.19 show the total responses for each of the five levels of the ten questions for the professors and students, respectively. Based on the score, it can be concluded that the system is considered acceptable in terms of usability, since it exceeds the acceptable baseline average of 68 points, as mentioned in (BROOKE, 1996a).

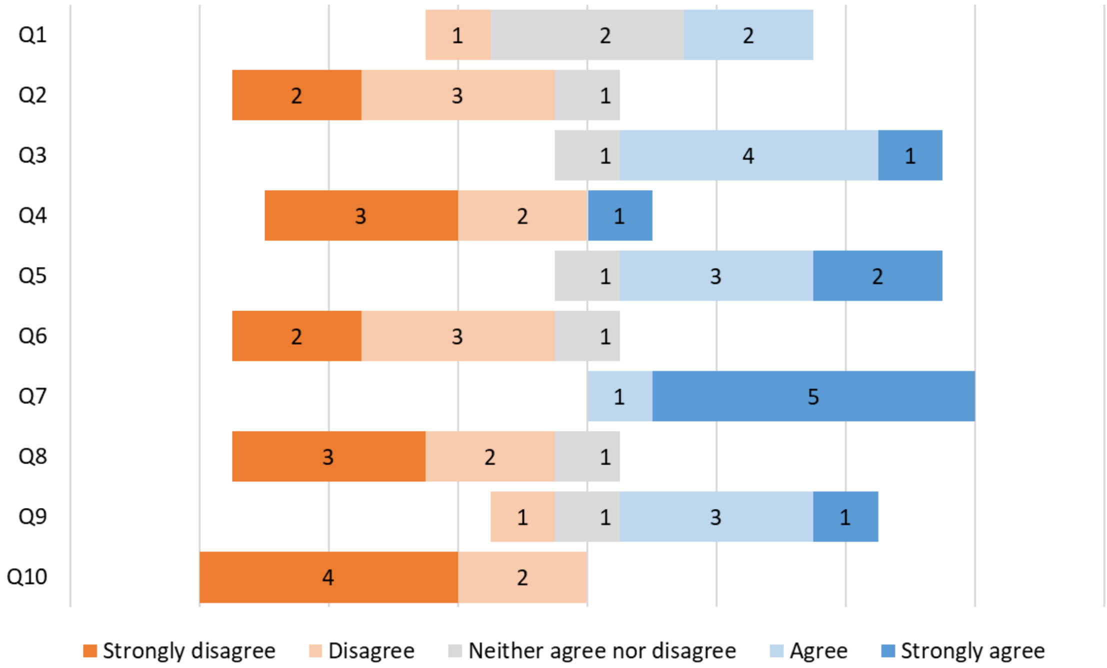


Figure 7.18: Number of professors' responses to SUS questionnaire

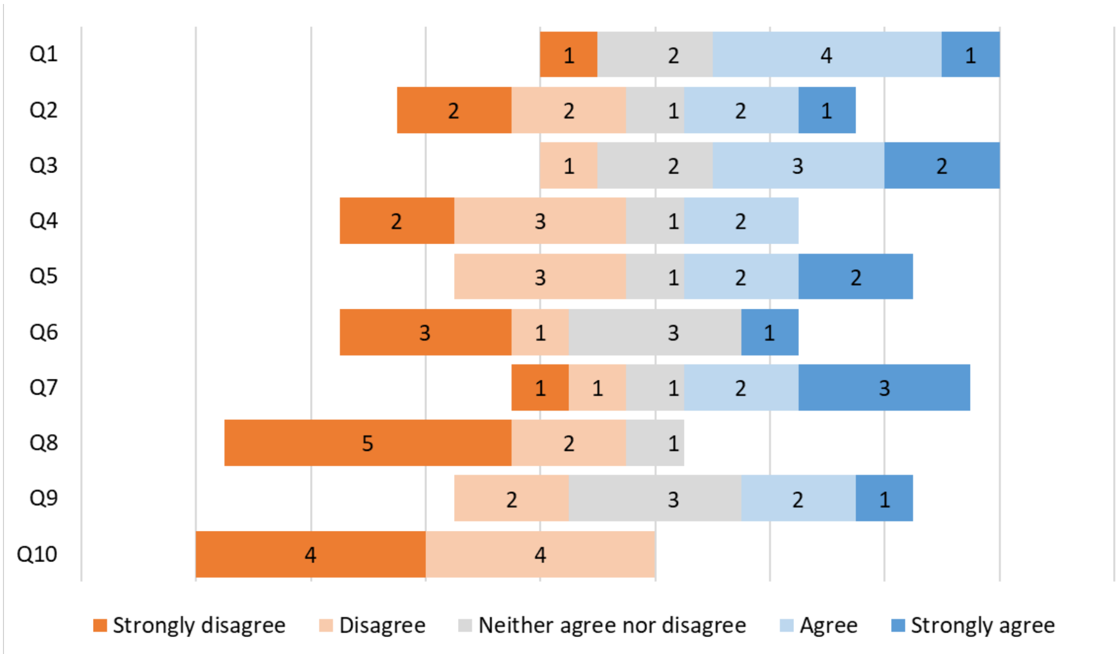


Figure 7.19: Number of students' responses to SUS questionnaire

In addition to SUS questions, we added some open questions for participants to better express their opinions. Table 7.26 presents professors and students with experience feedback when carrying out the tasks in the VW.

Category	Experience feedback	#Professors rating number	#Students rating number	Total
Positive	Attractive for students	1		1
	Ease of use	1	5	6
	Good experience	1	1	2
	Intuitive		5	5
	Quick to learning		1	1
Negative	Chaotic		1	1
	Difficulty interacting		1	1
	Difficulty of use	4	1	5
	Difficulty of viewing	1		1
	More time to adapt		1	1

Table 7.26: Experience creating UML diagrams in the VW

According to the participants, in addition to having faced some difficulties, most of the reports are positive. When asked about improvements in the platform, the participants answered: tutorial to help in the interaction and manipulation of the elements; other types of camera views (e.g., top view); hierarchical view of classes; and positioning of classes by moving them with the mouse instead of the slider.

From the advantage point of view, most participants reported that VWs for SE has the main purpose of engaging and motivating classes that have a high theoretical load. For example, P2 reported that the advantages are "*greater student interest in the subjects, greater integration between students and teachers, the possibility of creating diverse, creating virtual worlds that may be related to the subjects being studied*". P6 reported that the advantage is "*creating scenarios that facilitate the students' understanding of software design, creating a favorable environment for understanding the architecture of more complex software, and using the third dimension in modeling*". S6 declared that "*believes that the system is easy to use and because it is an immersive virtual world, it has the potential to draw the student's attention and the teacher could have one more way to hold the student's attention, making the task more fun, since theoretical subjects are not so attractive*". However, there are some disadvantages reported, such as complexity in the elaboration of classes; UX with limitations; professor can spend a lot of time producing the diagrams; it can distract students; and equipment limitations.

7.7 General Discussions

In this section we discuss the findings of the four performed experiments presented in Sections 7.3, 7.4, 7.5, and 7.6. Each experiment evaluated a perspective of the MetaSEE approach. The E1 experiment evaluated the importance of the MetaSEE Framework guidelines as support for the XR apps project. The E2 experiment evaluated the adherence of the MetaLine Features Model to the main features of Web XR apps. The E3 experiment evaluated the ease of use and usefulness of the A-Frame VirtualUML Component. Finally, the E4 experiment evaluated the usability of the MetaSEE Platform.

In experiments E1, E2, and E3, groups of participants were divided into academics and developers. This grouping was carried out through the means of communication used to publicize the research and capture a relevant sample. In experiment E4, professors and students participated in the study.

The relevant number of population samples in scientific research may vary depending on the type of research, the size of the target population, the desired level of precision and the statistical method used (LOHR, 2021). In addition, NIELSEN (1992) states that 3 to 5 specialists is a satisfactory number for carrying out assessments. Table 7.27 presents the overview of the sample involved in the experiments. In total, 54 participants evaluated the MetaSEE approach from the four perspectives.

	E1	E2	E3	E4	Total
Academic	4	3	4	0	11
Developer	12	12	5	0	29
Professor	0	0	0	6	6
Student	0	0	0	8	8
Total	16	15	9	14	54

Table 7.27: Number of participants

As for the perspective of supporting the development of XR apps, the MetaSEE Framework has shown signs that it has achieved its objective. As demonstrated in Figure 7.6, most developers reported that framework guidelines are important in order to support defining key aspects for XR apps. In addition, we obtain academics' opinion regarding opportunities for improvement, such as adding other aspects, such as budget and deadline, as well as more specific rather than generic guidelines. Below we perform an analysis of the previous suggestions.

MetaSEE Framework was conceived from a methodological and scientific process that involved two literature reviews (RR and SLR) and a PoC. Starting from the SLR described in the Chapter 2, we carried out a comparative analysis between the main technological, pedagogical and psychological aspects of the iL frameworks, on which the MetaSEE Framework was based. Therefore, considering the addition of other aspects involves carrying out other studies to evolve it, such as its use in real scenarios with specialists with relevant state of practice.

Commonly in SE, a theoretical framework is a conceptual framework that provides a way to think about a set of problems and solutions in a specific software domain. A theoretical framework provides a common language and a systematic approach to understanding a problem and proposing solutions. Classic examples of theoretical frameworks in SE include maturity models for software process improvement, such as Capability Maturity Model Integration (CMMI) and ??. In this way, mentioning specific aspects is beyond the scope of our framework. MetaSEE Framework includes some issues closer to development such as SDK, API and engines, as these decisions, if changed during development, can generate technical debts, which can impact software quality, as well as financial debt. Probably, technical debts can be more complex due to the involvement of multimodal interfaces and the need for compatibility between software and immersive devices. Therefore, defining basic aspects of the development environment impacts the quality and maintenance of XR apps.

According to Figure 7.8 and 7.10, academics and developers agree that aspects modeled in the MetaLine Feautures Model are adherent to the XR apps Web family. However, due to the profiles and number of participants, it is not possible to generalize the result. Future studies should be carried out with a relevant sample to also validate the model.

Regarding A-Frame VirtualUML Component, most academics and developers also agree on its ease of use and usefulness (Figure 7.12 and Figure 7.13). As presented in Section 7.5, all academics suggested adding the other functions of UML class diagrams that were not implemented, such as the other types of relationships, stereotypes, adding attributes and methods. In addition, they also suggested the implementation of the other UML diagrams, according to the official documentation. In our point of view, these comments reinforce the assertive decision to modularize the implementation of functionalities to the MetaSEE Platform. In this way, a community of developers can build other MetaSEE extensions (see Section 6.3.3) with SE-specific features.

Finally, MetaSEE Platform was evaluated from a usability point of view. Usability assessment is an important technique for understanding how users interact with the platform and identifying areas that need improvement. In this context, the SUS questionnaire is a commonly used tool to assess the usability of a platform.

The results showed that the platform obtained an average of 81.25 from the professors' point of view and 79.38 from the students' point of view, indicating that the platform's usability was considered good by the users.

The difference between professors' and students' evaluations can be explained by their different expectations regarding the platform. While professors may have focused more on platform functionality in relation to educational goals, students may have been more concerned with ease of use and user experience. These results suggest that improvements in platform usability should take into account the expectations and needs of both user groups.

In general, the evaluation of platform usability using the SUS provided an objective measure of users' perception of the ease of use of the platform. The results indicated that the usability of the platform was considered good by users, although there is a difference between the evaluations of professors and students. These results can guide improvements in platform usability to meet the needs and expectations of both user groups.

7.8 Threats to Validity

Although NIELSEN (1992) states that 3 to 5 specialists is a satisfactory number for carrying out assessments, in experiments E1, E2 , E3 it was not possible to guarantee the expertise of each participant, which may indicate a threat to the validity of this study. We classified participants into academics by considering the audience of the media used to disseminate the research, being Brazilian Computer Society (SBC - acronym in portuguese)'s interest group email lists, as well as specific servers on Discord. With this strategy, we intended to capture people both with extensive experience in scientific research, as well as in the field of subjects according to their participation in the media.

In addition, another indication of threat to the validity of this study is the lack of guarantee of the veracity of the information provided by both the academics and especially the developers. Analogous to the classification of academics, we classified participants into developers considering the audience of the media used to disseminate the research, with Discord and Slack servers selected for convenience (see Appendix B).

Another possible threat to validity is the different instruments of experiments E1, E2, and E3 used by two profiles with the purpose of evaluating the same object of study. However, we believe that the comments made and deeper analysis have contributed to the investigations.

In general, considering the evaluation carried out in this thesis, as a qualitative research there are some threats to the validity inherent to this approach (MOEN & MIDDELTHON, 2015), such as researcher bias that may affect data analysis and interpretation of results; participants may provide information that is not accurate or complete; the sample may not be representative of the population; data analysis may be unreliable due to lack of methodological rigor or misinterpretation of results; the results may not be generalizable to other populations or contexts, which may limit the relevance of the results.

7.9 Final Remarks

This chapter presented the experiments carried out to validate the MetaSEE approach. Considering the contributions of the approach, an experiment was performed for each perspective. MetaSEE Framework, MetaLine Features Model and A-Frame VirtualUML Component were evaluated by academics and developers. MetaSEE Platform was evaluated by professores and students. Despite the limitations and possible threats to validity, we can conclude that the MetaSEE approach provides adequate mechanisms to support immersive experiences, mainly in the context of SEE.

Chapter 8

Conclusions

8.1 Summary

iL, characterized by the use of immersive technologies, has emerged as a promising educational approach in SE. The immersive nature of these technologies provides an experiential learning environment that enables learners to gain practical skills and knowledge by simulating real-world scenarios. As SE involves complex processes and procedures, immersive learning can help students to develop a deeper understanding of the subject matter.

One of the primary benefits of iL in SEE is that it can provide students with a safe environment in which they can make mistakes and learn from them without the fear of causing any real-world consequences. This approach enables students to experiment and explore software systems and their functionalities in a risk-free environment, promoting creative thinking, problem-solving skills, and critical analysis.

Another key advantage of iL is that it can enhance engagement and motivation among learners. By enabling students to interact with software systems in a more intuitive and engaging manner, iL can increase students' interest and motivation in the subject matter.

In this thesis, we explore mechanisms to support iL in SE through the Metaverse. The Metaverse is a network of XR apps connected to each other, over the Internet infrastructure, allowing network users, systems, and devices to access them (FERNANDES & WERNER, 2022). The Metaverse has been identified as a beneficial training environment that can provide individuals with experiential learning opportunities that closely mimic real-world scenarios (PATLE *et al.*, 2019). One of the key advantages of the Metaverse is its ability to enable virtual attendance in classes and provide elements that simulate those found in traditional classrooms. Through the use of avatars, students can interact with instructors and communicate with their peers, which can foster an iL environment that enhances their motivation to learn (TLILI *et al.*, 2022).

However, Metaverse goes beyond providing immersive experiences. In the teaching context, engaging students is paramount to improve learning outcomes. Nevertheless, enabling Metaverse-based SEE requires a structure that allows interoperability between XR apps, ensuring the monitoring of the evolution of learning outcomes in SE, in addition to establishing methods that support the development of XR apps. In this way, the MetaSEE approach was proposed with the objective of enabling the Metaverse to focus on SEE. Four experiments were conducted to validate aspects of this thesis, namely: a framework to support the design and development of XR apps; a features model that maps the variables of a Web XR apps family; an A-Frame component to facilitate the rendering of UML diagrams; and a platform that allows professors and students to access XR apps from the Metaverse for SEE.

8.2 Contribution

This PhD thesis contributes with: (a) the development of a framework to support the design and development of XR apps through guidelines grouped into technological and pedagogical affordances; (b) the Metaverse structure that defines the main concepts and technologies to support SEE, which are grouped into five layers; (c) an SPL-based approach with the purpose of providing mechanisms for the instantiation of a Web XR apps family; (d) the Metaverse architecture for SEE that allows the interoperability of XR apps and the monitoring of learning evolution; and (e) the conduction of four experiments with the purpose of validating contributions of this thesis through the framework, features model, A-Frame component, and platform.

This PhD research and work provided the SE community with the following detailed contributions in the context of the Metaverse-based SEE:

- *iL frameworks literature review (Chapter 2)*: the primary objective of this SLR was to identify the current state of the art of iL frameworks. A total of 15 articles were selected for analysis, which allowed for an overview of the field's contributions and the identification of research gaps and opportunities. The significance of this study stems from its ability to facilitate a discussion and definition of the immersion concept, enhance comprehension of immersive learning, identify gaps, and propose a research roadmap that would enable frameworks to address the development of immersive environments in greater detail, as well as the use of immersive experiences by educators and instructors;
- *Metaverse for SEE literature review (Chapter 3)*: in this work the state-of-the-art of the Metaverse for SEE was characterized. The analysis revealed

several works limitations, including a lack of coverage of SEE topics by the applications, a lack of analysis of learning data to enhance the immersive experience, an absence of learning performance indicators to support decision-making, no proposed mechanisms to support the development of Metaverse for SEE digital assets, lack of interoperability between the applications, and centralized and non-scalable architecture;

- *PoC (Chapter 4)*: preliminary results in order to validate the ideas of this thesis were obtained. In case 1, the framework was tested by a team formed by a professor specialized in SE and SEE, a specialist in AVR, and a doctoral student specialized in serious games. In case 2, three evaluations investigated a specific perspective of a virtual classroom prototype: usability, UX, and learning outcomes. The results of cases 1 and 2 contributed to evolving the framework, as well as the approach as a whole;

- *MetaSEE conceptualization (Chapter 6)*: the studies performed in the research activities allowed us to conclude that acquirers need an approach to enable the Metaverse-based SEE. We defined the approach with mechanisms to support the design and development of XR app, as well as engage students through a platform that enables access to VWs for SEE;

- *MetaSEE tools*: an infrastructure to support the approach was developed, specifically a platform to ensure access to VWs for SEE and an A-Frame component which is treated in the platform as an extension. Extensions are plugins that can be added to the platform in order to implement new functionalities and ensure coverage of a range of SE topics;

- *Feasibility study through four experiments (Chapter 7)*: participants evaluated the MetaSEE approach from four perspectives: a framework to support XR apps design and development, a mapping of the main Web XR apps variabilities, a component based on the A-Frame framework, and a platform to enable immersive experiences in the context of SEE. Considering the analysis carried out, despite limitations and threats to validity, we conclude that there are indications that the MetaSEE approach provides adequate mechanisms to support immersive experiences in SEE.

8.2.1 Publications

Research activities performed in this PhD produced the following publications:

- FERNANDES, F., WERNER, C., 2019, "Towards Immersive Learning in Object-Oriented Paradigm: A Preliminary Study". In: *2019 21st Symposium* *on Virtual and Augmented Reality (SVR)*, pp. 59-68;

- FERNANDES, F., CASTRO, D., WERNER, C., 2021, "A Systematic Mapping Literature of Immersive Learning from SVR Publications". In: *Symposium on Virtual and Augmented Reality, SVR'21*, pp. 1–13;

- FERNANDES, F., WERNER, C., 2021, "Work-in-Progress–Supporting Software Engineering Education through Immersive Learning". In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 1–3;

- FERNANDES, F., CASTRO, D., WERNER, C., 2022, "Evaluating User Experience of a Software Engineering Education Virtual Environment". In: *Proceedings of the 24th Symposium on Virtual and Augmented Reality, SVR'24*, pp. 1–5;

- FERNANDES, F., WERNER, C., 2022, "Accessibility in the Metaverse: Are We Prepared?". In: *Proceedings of the 13th Workshop on Aspects of Human-Computer Interaction for the Social Web*, pp. 9-15. Porto Alegre: SBC;

- FERNANDES, F., CASTRO, D., RODRIGUES, C., WERNER, C., 2022, "Development of the Software Engineering Education Virtual Classroom Prototype: An Experience Report". In: *Proceedings of the 30th Workshop on Computing Education*, pp. 85– 96, Porto Alegre, RS, Brazil, SBC;

- FERNANDES, F., CASTRO, D., WERNER, C., 2022, "Immersive Learning Research from SVR Publications: A Re-conduction of the Systematic Mapping Study", *Journal on Interactive Systems*, 13(1), 205–220;

- FERNANDES, F., WERNER, C., 2022, "Software Product Line for Metaverse: Preliminary Results". In: *Proceedings of the 2022 IEEE International Conference on Metaverse*, pp. 1–9;

- FERNANDES, F. A., RODRIGUES, C. S. C., TEIXEIRA, E. N., et al., 2023, "Immersive Learning Frameworks: A Systematic Literature Review", *IEEE Transactions on Learning Technologies*, pp. 1–12. ISSN: 1939-1382;

- FERNANDES, F. A., WERNER, C. M. L., 2023, "A Scoping Review of the Metaverse for Software Engineering Education: Overview, Challenges and Opportunities", *PRESENCE: Virtual and Augmented Reality*, (03), pp. 1–56. ISSN: 1054-7460;

- FERNANDES, F., WERNER, C., 2023 (in press), "Towards a Blockchain-based Software Engineering Education". In: Colloquium on Blockchain and Decentralized Web (CSBC).

8.3 Limitation

Through a critical evaluation of the approach presented in this thesis, some limitations were identified. In this section, those that refer to the decisions adopted during the process of designing the MetaSEE approach will be listed.

The approach is quite ambitious and only four perspectives were implemented: a framework to support the design and development of XR apps, a features model that maps the main variables of a family of Web XR apps, a component based on the A-Frame framework in which it implements the design of platform extensions, and finally, a platform that allows immersive experiences in support of the SEE. The implemented perspectives present limitations arising from the fact that it was conceived by a single individual, and not by a multidisciplinary team, as is usually required for the development of immersive environments intended to support teaching and learning in this area.

Another limitation of the approach is that the Learning Analytics module of the MetaSEE Layer has not been implemented. We believe that promising results could be provided through its implementation.

There are, additionally, restrictions with regard to the assessment conducted. It is possible to mention that the sample size is considered insufficient from a statistical point of view, despite being acceptable in studies in the area of SE. In addition, threats to validity of the study were identified.

8.4 Future Work

Some opportunities were identified from this PhD thesis:

- Investigation of user experience through immersive devices, such as XR headsets and gesture and motion sensors, in the context of SEE;

- Implementation of the Learning Analytics component, as well as its analysis from the point of view of helping to monitor the evolution of learning results in SEE;

- Importing files from CASE tools, for example, UML diagrams, source-code, etc.;

- Architecture and API evolution in order to guarantee interoperability between independent XR app;

- Integration of AI in order to improve immersive experiences and the development of XR apps;

- Implementation of Blockchain-based mechanisms to enrich the experience on the platform. For example, a paper was submitted that defines the Software Engineering Skill (SES) token for the purpose of engaging and motivating students in order to improve experiences, as mentioned in Section 8.2.1. SES token can provide tangible incentives for students, which can be used as rewards for achieving learning goals or performing other activities within the platform;

- Investigation regarding the use of biometric data to enrich the analyzes of immersive experiences.

8.5 Author's Reflection

Can science fiction and reality dialogue? Does reality influence fiction or does fiction influence reality? Is there an intersection between them?

On September 8, 1966, the first episode of the original Star Trek series aired. In the Star Trek universe, the Holodeck is used for training purposes, recreation, and even as a scientific research tool. Holodeck users can experience sensations and situations that would be impossible in real life, such as flying in a zero-gravity environment or interacting with fictional characters and creatures. The Holodeck is a room equipped with advanced virtual reality technology that allows the characters from the series to enter a fully immersive and interactive simulated world. Based on the technologies available at the time, people may have judged such technology as just a work of fiction. However, in the same decade, Ivan Sutherland started the development of the first VR device called "The Sword of Damocles". This equipment consisted of a helmet that allowed the user to view computer-generated images in a three-dimensional environment.

A few decades later, in 1992, in the science fiction novel "Snow Crash" written by Neal Stephenson, the term "metaverse" was used for the first time. In the book, the metaverse is described as a shared virtual space, similar to a video game in which users can interact with each other in a virtual, three-dimensional world. The metaverse in "Snow Crash" is described as a vast and complex environment with its own economy, society and culture.

In 2011, "Ready Player One", a science fiction book by American author Ernest Cline was published. The story takes place in a dystopian future in the year 2044, where the world has become a dark and decaying place due to economic, environmental and social problems. In the novel, the only way to escape from reality is through the OASIS, created by computer genius James Halliday. The OASIS environment is a vast, complex and advanced XR environment, with numerous virtual worlds, each with its own setting and play style. In general, OASIS is an environment that allows people to do practically everything they would do in the real world, such as receiving sensory stimuli, intrinsically natural interactions, self-economy, among others.

Currently as a professor at the IF Sudeste MG, I have witnessed the students' lack of interest in the SE discipline several times. Some complain about the high theoretical load, as well as the abstraction complexity involved. We are in contact with a generation that grew up completely in the digital age, which strongly influenced their perspectives, values and behavior. Thus, non-traditional teaching methods should be used to engage this type of student.

The main motivation of this thesis was to design an engaging environment in which students can feel motivated and have experiences that can enrich learning. However, through the methodological and scientific process, it was identified that, first, it would be necessary to prepare an initial structure in which the Metaverse for SEE could be enabled, that is, to define the main aspects and technologies to implement it.

What was managed to add to the scientific community with this work was the definition of a framework to support the design and development of XR apps, an approach for the instantiation of a family of Web XR apps and a reusable A-Frame component for the rendering of UML class diagrams. These mechanisms were conceived, as it is also necessary to support the developer community in order to foster the Metaverse. Another contribution was the development of the platform prototype so that students and teachers could access MetaSEE.

Considering scientific research conducted by one person, it would obviously be impossible to implement an OASIS for SEE in this thesis. However, the researcher of this thesis has the goal of conducting future research so that it is possible, in fact, to enable Metaverse-based Software Engineering Education.

Regarding the initial questions:

> "*imagination is more important than knowledge. For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution.*" - Albert Einstein.

References

A-FRAME, 2022. "A-Frame". Available at: <https://aframe.io>.

ABBATE, S., CENTOBELLI, P., CERCHIONE, R., et al., 2022, "A first bibliometric literature review on Metaverse". In: *2022 IEEE Technology and Engineering Management Conference (TEMSCON EUROPE)*, pp. 254–260. doi: 10.1109/TEMSCONEUROPE54743.2022.9802015.

ABDELAZIZ, H. A., 2014, "Immersive learning design (ILD): A new model to assure the quality of learning through flipped classrooms". In: *2014 IIAI 3rd International Conference on Advanced Applied Informatics*, pp. 291–296. IEEE.

ABURBEIAN, A. M., OWDA, A. Y., OWDA, M., 2022, "A Technology Acceptance Model Survey of the Metaverse Prospects", *AI*, v. 3, n. 2, pp. 285–302. ISSN: 2673-2688. doi: 10.3390/ai3020018. Available at: <https://www.mdpi.com/2673-2688/3/2/18>.

ADCOCK, R., ALEF, E., AMATO, B., et al., 2009, *Curriculum Guidelines for Graduate Degree Programs in Software Engineering*. ACM.

AGUAYO, C., EAMES, C., COCHRANE, T., 2020, "A Framework for Mixed Reality Free-Choice, Self-Determined Learning", *Research in Learning Technology*, v. 28 (Mar.). doi: 10.25304/rlt.v28.2347. Available at: <https://journal.alt.ac.uk/index.php/rlt/article/view/2347>.

AKBULUT, A., CATAL, C., YILDIZ, B., 2018a, "On the effectiveness of virtual reality in the education of software engineering", *Computer Applications in Engineering Education*, v. 26, n. 4, pp. 918–927. doi: https://doi.org/10.1002/cae.21935. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.21935>.

AKBULUT, A., CATAL, C., YILDIZ, B., 2018b, "On the effectiveness of virtual reality in the education of software engineering", *Computer Applications in Engineering Education*, v. 26, n. 4, pp. 918–927. doi: https://doi.org/10.1002/cae.21935. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.21935>.

AKS, S. M. Y., KARMILA, M., GIVAN, B., et al., 2022, "A Review of Blockchain for Security Data Privacy with Metaverse". In: *2022 International Conference on ICT for Smart Society (ICISS)*, pp. 1–5. doi: 10.1109/ICISS55894.2022.9915055.

AL-GHAILI, A. M., KASIM, H., AL-HADA, N. M., et al., 2022, "A Review of Metaverse's Definitions, Architecture, Applications, Challenges, Issues, Solutions, and Future Trends", *IEEE Access*, v. 10, pp. 125835–125866. doi: 10.1109/ACCESS.2022.3225638.

ALBERT, B. E., 2014, *SECOGov: A Software Ecosystem Governance Model to Support IT Architecture Activities.* Master Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.

ALHAMMAD, M. M., MORENO, A. M., 2018, "Gamification in software engineering education: A systematic mapping", *Journal of Systems and Software*, v. 141, pp. 131–150. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2018.03.065.

ALMOQBEL, M. Y., NADERI, A., WOHN, D. Y., et al., 2022, "The Metaverse: A Systematic Literature Review to Map Scholarly Definitions". In: *Companion Publication of the 2022 Conference on Computer Supported Cooperative Work and Social Computing*, CSCW'22 Companion, p. 80–84, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450391900. doi: 10.1145/3500868.3559448. Available at: <https://doi.org/10.1145/3500868.3559448>.

ALSPAUGH, T. A., ANTÓN, A. I., 2008, "Scenario support for effective requirements", *Information and Software Technology*, v. 50, n. 3, pp. 198–220. ISSN: 0950-5849. doi: https://doi.org/10.1016/j.infsof.2006.12.003.

ARDIS, M. A., BUDGEN, D., HISLOP, G. W., et al., 2015, "SE 2014: Curriculum Guidelines for Undergraduate Degree Programs in Software Engineering." *Computer*, v. 48, n. 11, pp. 106–109.

AUGSTEIN, M., NEUMAYR, T., 2019, "A Human-Centered Taxonomy of Interaction Modalities and Devices", *Interacting with Computers*, v. 31, n. 1 (jan.), pp. 27–58. ISSN: 0953-5438. doi: 10.1093/iwc/iwz003. Available at: <https://doi.org/10.1093/iwc/iwz003>.

BAKER, A., OH NAVARRO, E., VAN DER HOEK, A., 2005, "An experimental card game for teaching software engineering processes", *Journal of Systems and Software*, v. 75, n. 1, pp. 3–16. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2004.02.033. Software Engineering Education and Training.

BALL, M., 2022, *The Metaverse: And How It Will Revolutionize Everything*. Liveright.

BANSAL, G., RAJGOPAL, K., CHAMOLA, V., et al., 2022, "Healthcare in Metaverse: A Survey on Current Metaverse Applications in Healthcare", *IEEE Access*, v. 10, pp. 119914–119946. doi: 10.1109/ACCESS.2022.3219845.

BARRETO, A. O. S., 2011, *Definition and Management of Strategically Aligned Software Improvement Goals*. PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 240. In Portuguese.

BASILI, V., SHULL, F., LANUBILE, F., 1999, "Building knowledge through families of experiments", *IEEE Transactions on Software Engineering*, v. 25, n. 4, pp. 456–473. doi: 10.1109/32.799939.

BESSA, B., SANTOS, S., 2017a, "A Virtual Environment for Problem-Based Learning in Software Engineering Education." In: *2017 29th International Conference on Software Engineering and Knowledge Engineering*, pp. 535–540, a.

BESSA, B., SANTOS, S., 2017b, "A Virtual Environment for Problem-Based Learning in Software Engineering Education." In: *2017 29th International Conference on Software Engineering and Knowledge Engineering*, pp. 535–540, b.

BIOCCA, F., LEVY, M. R., 2013, *Communication in the age of virtual reality*. Routledge.

BLOIS, A. P. T. B., DE OLIVEIRA, R. F., MAIA, N., et al., 2006, "Variability Modeling in a Component-Based Domain Engineering Process". In: Morisio, M. (Ed.), *Reuse of Off-the-Shelf Components*, Lecture Notes in Computer Science, pp. 395–398, Berlin, Heidelberg. Springer. ISBN: 978-3-540-34607-4. doi: 10.1007/11763864$_3$1.

BOEHM, 1976, "Software Engineering", *IEEE Transactions on Computers*, v. C-25, n. 12, pp. 1226–1241. doi: 10.1109/TC.1976.1674590.

BOURQUE, P., FAIRLEY, R. E., 2014, *SWEBOK: Guide to the Software Engineering Body of Knowledge.* Version 3.0 ed. Los Alamitos, CA, IEEE Computer Society. ISBN: 978-0-7695-5166-1. Available at: <http://www.swebok.org/>.

BOWMAN, D. A., MCMAHAN, R. P., 2007, "Virtual reality: how much immersion is enough?" *Computer*, v. 40, n. 7, pp. 36–43.

BRAGA, R., WERNER, C., MATTOSO, M., 1999, "Odyssey: a reuse environment based on domain models". In: *Proceedings 1999 IEEE Symposium on Application-Specific Systems and Software Engineering and Technology. ASSET'99 (Cat. No.PR00122)*, pp. 50–57, mar. doi: 10.1109/ASSET.1999.756751.

BROOKE, J., 1996a, "SUS: A 'Quick and Dirty' Usability Scale". In: Jordan, P. W., Thomas, B. A., Weerdmeester, B. A. (Eds.), *Usability Evaluation in Industry*, CRC Press, pp. 189–194, a.

BROOKE, J., 1996b, "System usability scale (SUS)", *Usability Evaluation in Industry. Taylor and Francis, London.*

BURDEA, G., COIFFET, P., 2003, *Virtual reality technology.* MIT Press.

CANBAY, Y., UTKU, A., CANBAY, P., 2022, "Privacy Concerns and Measures in Metaverse: A Review". In: *2022 15th International Conference on Information Security and Cryptography (ISCTURKEY)*, pp. 80–85. doi: 10.1109/ISCTURKEY56345.2022.9931866.

CARDONA-REYES, H., GUZMAN-MENDOZA, J. E., ORTIZ-AGUIÑAGA, G., et al., 2019, "An Architectural Model for the Production of Virtual Reality Learning". In: *International Congress on Education and Technology in Sciences*, pp. 73–87. Springer, Cham.

CHAN, J. K., WONG, R. Y., CHEUNG, C. M., 2019, "How Affordances of Immersive Visualization Systems Affect Learning Outcomes through Aesthetic Experience", *Proceedings of the Pacific Asia Conference on Information Systems (PACIS).*

CHANG, L., ZHANG, Z., LI, P., et al., 2022. "6G-enabled Edge AI for Metaverse: Challenges, Methods, and Future Research Directions". Available at: <https://arxiv.org/abs/2204.06192>.

CHATTI, M. A., DYCKHOFF, A. L., SCHROEDER, U., et al., 2013, "A reference model for learning analytics", *International Journal of Technology Enhanced Learning*, v. 4, n. 5-6, pp. 318–331.

CHEN, C., CHONG, P. P., 2011, "Software engineering education: A study on conducting collaborative senior project development", *Journal of Systems and Software*, v. 84, n. 3, pp. 479–491. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2010.10.042. Available at: <https://www.sciencedirect.com/science/article/pii/S0164121210002931>.

CHEN, L., LIU, Q., SUN, X., 2010a, "Augmenting teamwork skills through Web3D technologies in software engineering course". In: *The 2010 14th International Conference on Computer Supported Cooperative Work in Design*, pp. 682–688, a. doi: 10.1109/CSCWD.2010.5471887.

CHEN, L., LIU, Q., SUN, X., 2010b, "Augmenting teamwork skills through Web3D technologies in software engineering course". In: *The 2010 14th International Conference on Computer Supported Cooperative Work in Design*, pp. 682–688, b. doi: 10.1109/CSCWD.2010.5471887.

CHEN, T., ZHOU, H., YANG, H., et al., 2022a, "A Review of Research on Metaverse Defining Taxonomy and Adaptive Architecture". In: *2022 5th International Conference on Pattern Recognition and Artificial Intelligence (PRAI)*, pp. 960–965, a. doi: 10.1109/PRAI55851.2022.9904076.

CHEN, Z., WU, J., GAN, W., et al., 2022b. "Metaverse Security and Privacy: An Overview". b. Available at: <https://doi.org/10.48550/arXiv.2211.14948>.

CHENGODEN, R., VICTOR, N., HUYNH-THE, T., et al., 2022. "Metaverse for Healthcare: A Survey on Potential Applications, Challenges and Future Directions". Available at: <https://doi.org/10.48550/arXiv.2209.04160>.

COCCOLI, M., STANGANELLI, L., MARESCA, P., 2011, "Computer Supported Collaborative Learning in software engineering". In: *2011 IEEE Global Engineering Education Conference (EDUCON)*, pp. 990–995. doi: 10.1109/EDUCON.2011.5773267.

COVACI, A., ZOU, L., TAL, I., et al., 2018, "Is multimedia multisensorial?-a review of mulsemedia systems", *ACM Computing Surveys (CSUR)*, v. 51, n. 5, pp. 1–35.

DALGARNO, B., LEE, M. J., 2010, "What are the learning affordances of 3-D virtual environments?" *British Journal of Educational Technology*, v. 41, n. 1, pp. 10–32.

DALGARNO, B., HEDBERG, J., HARPER, B., 2002, "The contribution of 3D environments to conceptual understanding". In: *Proceedings of the 19th Annual Conference of the Australasian Society for Computers in Learning in Tertiary Education*, pp. 149–158, Auckland, New Zealand. UNITEC, Institute of Technology.

DALPRA, G. C. B. C., 2018, *Supporting Software Processes Analysis and Decision-Making Using Provenance Data*. PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 214.

DAVEY, B., TATNALL, A., 2008, "Where Will Professional Software Engineering Education Go Next?" In: Kendall, M., Samways, B. (Eds.), *Learning to Live in the Knowledge Society*, pp. 185–192, Boston, MA. Springer US. ISBN: 978-0-387-09729-9.

DAVIS, F. D., 1985, *A technology acceptance model for empirically testing new end-user information systems: Theory and results. A technology acceptance model for empirically testing new end-user information systems: Theory and results*, Massachusetts Institute of Technology.

DAVIS, F. D., 1989, "Perceived usefulness, perceived ease of use, and user acceptance of information technology", *MIS quarterly*, pp. 319–340.

DAWSON, R., 2000, "Twenty Dirty Tricks to Train Software Engineers". In: *Proceedings of the 22nd International Conference on Software Engineering*, ICSE '00, p. 209–218, New York, NY, USA. Association for Computing Machinery. ISBN: 1581132069. doi: 10.1145/337180.337204. Available at: <https://doi-org.ez29.periodicos.capes.gov.br/10.1145/337180.337204>.

DE FRANÇA COSTA, M., 2019, *Director: a Cloud Microservice Selection Framework*. PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 199.

DE FREITAS, S., REBOLLEDO-MENDEZ, G., LIAROKAPIS, F., et al., 2010, "Learning as immersive experiences: Using the four-dimensional framework for designing and evaluating immersive learning experiences in a virtual world", *British Journal of Educational Technology*, v. 41, n. 1, pp. 69–85.

DENGEL, A., MÄGDEFRAU, J., 2020, "Immersive Learning Predicted: Presence, Prior Knowledge, and School Performance Influence Learning Outcomes in Immersive Educational Virtual Environments". In: *2020 6th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 163–170. IEEE.

DENGEL, A., MÄGDEFRAU, J., 2018, "Immersive Learning Explored: Subjective and Objective Factors Influencing Learning Outcomes in Immersive Educational Virtual Environments". In: *2018 IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE)*, pp. 608–615. doi: 10.1109/TALE.2018.8615281.

DIEHL, S., 2005, "Software Visualization". In: *Proceedings of the 27th International Conference on Software Engineering*, ICSE '05, p. 718–719, New York, NY, USA. Association for Computing Machinery. ISBN: 1581139632. doi: 10.1145/1062455.1062634. Available at: <https://doi.org/10.1145/1062455.1062634>.

DINCELLI, E., YAYLA, A., 2022, "Immersive virtual reality in the age of the Metaverse: A hybrid-narrative review based on the technology affordance perspective", *The Journal of Strategic Information Systems*, v. 31, n. 2, pp. 101717. ISSN: 0963-8687. doi: https://doi.org/10.1016/j.jsis.2022.101717. Available at: <https://www.sciencedirect.com/science/article/pii/S0963868722000130>. 2021 Review Issue.

DIONISIO, J. D. N., III, W. G. B., GILBERT, R., 2013, "3D Virtual Worlds and the Metaverse: Current Status and Future Possibilities", *ACM Comput. Surv.*, v. 45, n. 3 (jul). ISSN: 0360-0300. doi: 10.1145/2480741.2480751. Available at: <https://doi.org/10.1145/2480741.2480751>.

DOS SANTOS, R. P., 2016, *Managing and Monitoring Software Ecosystem to Support Demand and Solution Analysis*. PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 246.

DUAN, H., LI, J., FAN, S., et al., 2021, "Metaverse for Social Good: A University Campus Prototype". In: *Proceedings of the 29th ACM International Conference on Multimedia*, MM '21, p. 153–161, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450386517. doi: 10.1145/3474085.3479238. Available at: <https://doi-org.ez29.periodicos.capes.gov.br/10.1145/3474085.3479238>.

DYBA, T., DINGSOYR, T., HANSSEN, G. K., 2007, "Applying Systematic Reviews to Diverse Study Types: An Experience Report". In: *First International Symposium on Empirical Software Engineering and Measurement (ESEM 2007)*, pp. 225–234. doi: 10.1109/ESEM.2007.59.

ECHEVERRÍA, V., DOMÍNGUEZ, F., CHILUIZA, K., 2016, "Towards a Distributed Framework to Analyze Multimodal Data". In: Maldonado, R. M., Leo, D. H. (Eds.), *Proceedings of the First International Workshop on Learning Analytics Across Physical and Digital Spaces (CrossLAK 2016) co-located with 6th International Conference on Learning Analytics & Knowledge (LAK 2016), Edinburgh, Scotland, UK, April 25-29, 2016*, v. 1601, *CEUR Workshop Proceedings*, pp. 52–57. CEUR-WS.org. Available at: <https://ceur-ws.org/Vol-1601/CrossLAK16Paper10.pdf>.

ELY, D., 1983, "Development and use of the ARCS Model of Motivational Design", *Classic Writings on Instructional.*

FERNANDES, F., WERNER, C., 2021a, "Work-in-Progress–Supporting Software Engineering Education through Immersive Learning". In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 1–3, a. doi: 10.23919/iLRN52045.2021.9459361.

FERNANDES, F., WERNER, C., 2021b, "Work-in-Progress–Supporting Software Engineering Education through Immersive Learning". In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 1–3, b. doi: 10.23919/iLRN52045.2021.9459361.

FERNANDES, F., WERNER, C., 2021c, "Work-in-Progress–Supporting Software Engineering Education through Immersive Learning". In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 1–3, c. doi: 10.23919/iLRN52045.2021.9459361.

FERNANDES, F., WERNER, C., 2022, "Software Product Line for Metaverse: Preliminary Results". In: *Proceeding of the 2022 IEEE International Conference on Metaverse*, 12.

FERNANDES, F., RODRIGUES, C. S., WERNER, C., 2017, "Dynamic Analysis of Software Systems through Virtual Reality". In: *2017 19th Symposium on Virtual and Augmented Reality (SVR)*, pp. 331–340. doi: 10.1109/SVR.2017.52.

FERNANDES, F., CASTRO, D., WERNER, C., 2021, "A Systematic Mapping Literature of Immersive Learning from SVR Publications". In: *Symposium on Virtual and Augmented Reality*, SVR'21, p. 1–13, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450395526. doi: 10.1145/3488162.3488163. Available at: <https://doi.org/10.1145/3488162.3488163>.

FERNANDES, F., CASTRO, D., RODRIGUES, C., et al., 2022a, "Development of the Software Engineering Education Virtual Classroom Prototype: An Experience Report". In: *Proceedings of the 30th Workshop on Computing Education*, pp. 85–96, Porto Alegre, RS, Brasil, a. SBC. doi: 10.5753/wei.2022.222590. Available at: <https://sol.sbc.org.br/index.php/wei/article/view/20821>.

FERNANDES, F., CASTRO, D., WERNER, C., 2022b, "Evaluating User Experience of a Software Engineering Education Virtual Environment". In: *Proceedings of the 24th Symposium on Virtual and Augmented Reality*, SVR'24, pp. 1–5, b.

FERNANDES, F. A., WERNER, C. M. L., 2023, "A Scoping Review of the Metaverse for Software Engineering Education: Overview, Challenges and Opportunities", *PRESENCE: Virtual and Augmented Reality*, (03), pp. 1–56. ISSN: 1054-7460. doi: 10.1162/pres$_{a0}$0371.*Availableat* :< https://doi.org/10.1162/pres_a_00371 > .

FERNANDES, F. A., RODRIGUES, C. S. C., TEIXEIRA, E. N., et al., 2023, "Immersive Learning Frameworks: A Systematic Literature Review", *IEEE Transactions on Learning Technologies*, pp. 1–12. doi: 10.1109/TLT.2023.3242553.

FIALHO, F. A. P., CATAPAN, A. H., 1999, "Knowledge Building by Full Integration With Virtual Reality Environments and Its Effects on Personal and Social Life", *Bulletin of Science, Technology & Society*, v. 19, n. 3, pp. 237–243.

FORTE, M., LERCARI, N., GALEAZZI, F., et al., 2010, "Metaverse communities and archaeology: the case of Teramo", *Proceedings of EuroMed*, pp. 79–84.

FOWLER, C., 2015, "Virtual reality and learning: Where is the pedagogy?" *British journal of educational technology*, v. 46, n. 2, pp. 412–422.

FU, Y., LI, C., YU, F. R., et al., 2022, "A Survey of Blockchain and Intelligent Networking for the Metaverse", *IEEE Internet of Things Journal*, pp. 1–1. doi: 10.1109/JIOT.2022.3222521.

GADEKALLU, T. R., HUYNH-THE, T., WANG, W., et al., 2022. "Blockchain for the Metaverse: A Review". Available at: <https://arxiv.org/abs/2203.09738>.

GALLAGHER, K., HATCH, A., MUNRO, M., 2005, "A Framework for Software Architecture Visualisation Assessment". In: *3rd IEEE International Workshop on Visualizing Software for Understanding and Analysis*, pp. 1–6. doi: 10.1109/VISSOF.2005.1684309.

GAMMA, E., HELM, R., JOHNSON, R., et al., 1995, *Design Patterns: Elements of Reusable Object-Oriented Software*. Pearson Deutschland GmbH. ISBN: 978-3-8273-3043-7. Google-Books-ID: tmNNfSkfTlcC.

GARAVAND, A., ASLANI, N., 2022, "Metaverse phenomenon and its impact on health: A scoping review", *Informatics in Medicine Unlocked*, v. 32, pp. 101029. ISSN: 2352-9148. doi: https://doi.org/10.1016/j.imu.2022.101029. Available at: <https://www.sciencedirect.com/science/article/pii/S235291482200171X>.

GAROUSI, V., GIRAY, G., TUZUN, E., 2019, "Understanding the Knowledge Gaps of Software Engineers: An Empirical Analysis Based on SWEBOK", *ACM Trans. Comput. Educ.*, v. 20, n. 1 (nov). doi: 10.1145/3360497. Available at: <https://doi-org.ez29.periodicos.capes.gov.br/10.1145/3360497>.

GHINEA, G., TIMMERER, C., LIN, W., et al., 2014, "Mulsemedia: State of the art, perspectives, and challenges", *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, v. 11, n. 1s, pp. 1–23.

GIANAROS, P. J., MUTH, E. R., MORDKOFF, J. T., et al., 2001, "A questionnaire for the assessment of the multiple dimensions of motion sickness", *Aviation, space, and environmental medicine*, v. 72, n. 2, pp. 115.

GIANG BARRERA, K., SHAH, D., 2023, "Marketing in the Metaverse: Conceptual understanding, framework, and research agenda", *Journal of Business Research*, v. 155, pp. 113420. ISSN: 0148-2963. doi: https://doi.org/10.1016/j.jbusres.2022.113420. Available at: <https://www.sciencedirect.com/science/article/pii/S0148296322008852>.

GULEC, U., YILMAZ, M., ISLER, V., et al., 2021a, "Applying virtual reality to teach the software development process to novice software engineers", *IET Software*, v. 15, n. 6, pp. 464–483. doi: https://doi.org/10.1049/sfw2.12047. Available at: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/sfw2.12047>.

GULEC, U., YILMAZ, M., ISLER, V., et al., 2021b, "Applying virtual reality to teach the software development process to novice software engineers", *IET Software*, v. 15, n. 6, pp. 464–483. doi: https://doi.org/10.1049/sfw2.12047. Available at: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/sfw2.12047>.

GUPTA, A., CECIL, J., TAPIA, O., et al., 2019, "Design of Cyber-Human Frameworks for Immersive Learning". In: *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, pp. 1563–1568. IEEE.

HANDELSMAN, M. M., BRIGGS, W. L., SULLIVAN, N., et al., 2005, "A Measure of College Student Course Engagement", *The Journal of Educational Research*, v. 98, n. 3, pp. 184–192. doi: 10.3200/JOER.98.3.184-192. Available at: <https://doi.org/10.3200/JOER.98.3.184-192>.

HARMELEN, M. V., WORKMAN, D., 2012, "Analytics for learning and teaching", *CETIS Analytics Series*, v. 1, n. 3, pp. 1–40.

HEVNER, A. R., MARCH, S. T., PARK, J., et al., 2004, "Design Science in Information Systems Research", *MIS Quarterly*, v. 28, n. 1, pp. 75–105. ISSN: 02767783. Available at: <http://www.jstor.org/stable/25148625>.

HIDAYATI, A., BUDIARDJO, E. K., PURWANDARI, B., 2020, "Hard and Soft Skills for Scrum Global Software Development Teams". In: *Proceedings of the 3rd International Conference on Software Engineering and Information Management*, ICSIM '20, p. 110–114, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450376907. doi: 10.1145/3378936.3378966. Available at: <https://doi.org/10.1145/3378936.3378966>.

HSIAO, I. Y. T., LAN, Y.-J., KAO, C.-L., et al., 2017, "Visualization Analytics for Second Language Vocabulary Learning in Virtual Worlds", *Journal of Educational Technology Society*, v. 20, n. 2, pp. 161–175. ISSN: 11763647, 14364522. Available at: <http://www.jstor.org/stable/90002172>.

HUANG, H., ZENG, X., ZHAO, L., et al., 2022a, "Fusion of Building Information Modeling and Blockchain for Metaverse: A Survey", *IEEE Open Journal of the Computer Society*, v. 3, pp. 195–207. doi: 10.1109/OJCS.2022.3206494.

HUANG, X., ZOU, D., CHENG, G., et al., 2021, "A Systematic Review of AR and VR Enhanced Language Learning", *Sustainability*, v. 13, n. 9, pp. 4639.

HUANG, Y., LI, Y., CAI, Z., 2022b, "Security and Privacy in Metaverse: A Comprehensive Survey", *Big Data Mining and Analytics*, (11). doi: 10.26599/BDMA.2022.9020047.

HUGGETT, J., 2020, "Virtually real or really virtual: Towards a heritage metaverse", *Studies in Digital Heritage*, v. 4, n. 1, pp. 1–15.

HUYNH-THE, T., PHAM, Q.-V., PHAM, X.-Q., et al., 2022. "Artificial Intelligence for the Metaverse: A Survey". Available at: <https://arxiv.org/abs/2202.10336>.

ILRN, 2022. "Immersive Learning Research Network". Available at: <https://immersivelrn.org/>.

INAYAT, I., INAYAT, Z., AMIN, R. U., 2016a, "Teaching and Learning Object-Oriented Analysis and Design with 3D Game". In: *2016 International Conference on Frontiers of Information Technology (FIT)*, pp. 46–51, a. doi: 10.1109/FIT.2016.017.

INAYAT, I., INAYAT, Z., AMIN, R. U., 2016b, "Teaching and Learning Object-Oriented Analysis and Design with 3D Game". In: *2016 International Conference on Frontiers of Information Technology (FIT)*, pp. 46–51, b. doi: 10.1109/FIT.2016.017.

IP, H. H. S., LI, C., LEONI, S., et al., 2018, "Design and evaluate immersive learning experience for massive open online courses (MOOCs)", *IEEE Transactions on Learning Technologies*, v. 12, n. 4, pp. 503–515.

IWANAGA, J., MUO, E. C., TABIRA, Y., et al., 2022, "Who really needs a Metaverse in anatomy education? A review with preliminary survey results", *Clinical Anatomy*, v. n/a, n. n/a. doi: https://doi.org/10.1002/ca.23949. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/ca.23949>.

JALALI, S., WOHLIN, C., 2012, "Systematic literature studies: Database searches vs. backward snowballing". In: *Proceedings of the 2012 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement*, pp. 29–38. doi: 10.1145/2372251.2372257.

JENNETT, C., COX, A. L., CAIRNS, P., et al., 2008, "Measuring and defining the experience of immersion in games", *International journal of human-computer studies*, v. 66, n. 9, pp. 641–661.

KAPEC, P., BRNDIAROVÁ, G., GLOGER, M., et al., 2015, "Visual analysis of software systems in virtual and augmented reality". In: *2015 IEEE 19th International Conference on Intelligent Engineering Systems (INES)*, pp. 307–312. doi: 10.1109/INES.2015.7329727.

KAWARASE IV, M. A., ANJANKAR, A., 2022, "Dynamics of Metaverse and Medicine: A Review Article", *Cureus*, v. 14, n. 11. ISSN: 2168-8184. doi: 10.7759/cureus.31232. Available at: <`https://www.doi.org/10.7759/cureus.31232`>.

KICKMEIER-RUST, M. D., ALBERT, D., 2013, "Learning Analytics to Support the Use of Virtual Worlds in the Classroom". In: Holzinger, A., Pasi, G. (Eds.), *Human-Computer Interaction and Knowledge Discovery in Complex, Unstructured, Big Data*, pp. 358–365, Berlin, Heidelberg. Springer Berlin Heidelberg. ISBN: 978-3-642-39146-0.

KIM, C., LEE, S.-G., KANG, M., 2012, "I became an attractive person in the virtual world: Users' identification with virtual communities and avatars", *Computers in Human Behavior*, v. 28, n. 5, pp. 1663–1669. ISSN: 0747-5632. doi: https://doi.org/10.1016/j.chb.2012.04.004. Available at: <`https://www.sciencedirect.com/science/article/pii/S0747563212000969`>.

KIM, Y. Y., KIM, H. J., KIM, E. N., et al., 2005, "Characteristic changes in the physiological components of cybersickness", *Psychophysiology*, v. 42, n. 5, pp. 616–625.

KITCHENHAM, B., CHARTERS, S., 2007, *Guidelines for performing systematic literature reviews in software engineering - Version 2.3.* Technical Report EBSE-2007-01, Keele University and University of Durham.

KITCHENHAM, B., BRERETON, O. P., BUDGEN, D., et al., 2009, "Systematic literature reviews in software engineering–a systematic literature review", *Information and software technology*, v. 51, n. 1, pp. 7–15.

KLIPPEL, A., ZHAO, J., SAJJADI, P., et al., 2020, "Immersive place-based learning–an extended research framework". In: *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 449–454. IEEE.

KOUTROMANOS, G., MIKROPOULOS, T. A., 2021, "Mobile Augmented Reality Applications in Teaching: A Proposed Technology Acceptance Model". In: *2021 7th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 1–8. IEEE.

KUSUMA, A. T., SUPANGKAT, S. H., 2022, "Metaverse Fundamental Technologies for Smart City: A Literature Review". In: *2022 International Conference on ICT for Smart Society (ICISS)*, pp. 1–7. doi: 10.1109/ICISS55894.2022.9915079.

KYE, B., HAN, N., KIM, E., et al., 2021, "Educational applications of metaverse: possibilities and limitations", *jeehp*, v. 18, n. 0, pp. 32–0. doi: 10.3352/jeehp.2021.18.32. Available at: <http://www.e-sciencecentral.org/articles/?scid=1149230>.

LAVALLE, S. M., 2020, *Virtual Reality*. Cambridge University Press. Available at: <http://vr.cs.uiuc.edu/>.

LAWHEAD, P. B., DUNCAN, M. E., BLAND, C. G., et al., 2002, "A Road Map for Teaching Introductory Programming Using LEGO© Mindstorms Robots". In: *Working Group Reports from ITiCSE on Innovation and Technology in Computer Science Education*, ITiCSE-WGR '02, p. 191–201, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450374491. doi: 10.1145/960568.783002. Available at: <https://doi-org.ez367.periodicos.capes.gov.br/10.1145/960568.783002>.

LEARY, M. R., KOWALSKI, R. M., 1993, "The Interaction Anxiousness Scale: Construct and Criterion-Related Validity", *Journal of Personality Assessment*, v. 61, n. 1, pp. 136–146. doi: 10.1207/s15327752jpa6101_10. Available at: <https://doi.org/10.1207/s15327752jpa6101$_1$0 $> .PMID$: 8377098.

LEE, E. A.-L., WONG, K. W., 2014, "Learning with desktop virtual reality: Low spatial ability learners are more positively affected", *Computers & Education*, v. 79, pp. 49–58.

LEE, E. A.-L., WONG, K. W., FUNG, C. C., 2010, "How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach", *Computers & Education*, v. 55, n. 4, pp. 1424–1442.

LEE, L.-H., BRAUD, T., ZHOU, P., et al., 2021a, "All One Needs to Know about Metaverse: A Complete Survey on Technological Singularity, Virtual Ecosystem, and Research Agenda". arXiv, a.

LEE, L.-H., LIN, Z., HU, R., et al., 2021b, "When Creators Meet the Metaverse: A Survey on Computational Arts". arXiv, b. doi: 10.48550/ARXIV.2111.13486. Available at: <https://arxiv.org/abs/2111.13486>.

LEE, M., GEORGIEVA, M., ALEXANDER, B., et al., 2021c, "State of XR & Immersive Learning Outlook Report 2021", *Walnut, CA: Immersive Learning Research Network*.

LETHBRIDGE, T. C., DIAZ-HERRERA, J., LEBLANC, R. J. J., et al., 2007, “Improving software practice through education: Challenges and future trends”. In: *Future of Software Engineering (FOSE ’07)*, pp. 12–28. doi: 10.1109/FOSE.2007.13.

LI, J., VINAYAGAMOORTHY, V., WILLIAMSON, J., et al., 2021, “Social VR: A New Medium for Remote Communication and Collaboration”. In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI EA ’21, New York, NY, USA. Association for Computing Machinery. ISBN: 9781450380959. doi: 10.1145/3411763.3441346. Available at: <https://doi-org.ez29.periodicos.capes.gov.br/10.1145/3411763.3441346>.

LIEBOWITZ, M. R., PHARMACOPSYCHIATRY, M. P., 1987, “Social phobia”, *New York, NY: Guilford Publications.*

LIN, H., WAN, S., GAN, W., et al., 2022. “Metaverse in Education: Vision, Opportunities, and Challenges”. Available at: <https://arxiv.org/abs/2211.14951>.

LIU, T.-Y., CHU, Y.-L., 2010, “Using ubiquitous games in an English listening and speaking course: Impact on learning outcomes and motivation”, *Computers Education*, v. 55, n. 2, pp. 630–643. ISSN: 0360-1315. doi: https://doi.org/10.1016/j.compedu.2010.02.023. Available at: <https://www.sciencedirect.com/science/article/pii/S0360131510000667>.

LOES, C. N., PASCARELLA, E. T., 2017, “Collaborative Learning and Critical Thinking: Testing the Link”, *The Journal of Higher Education*, v. 88, n. 5, pp. 726–753. doi: 10.1080/00221546.2017.1291257. Available at: <https://doi.org/10.1080/00221546.2017.1291257>.

LOHR, S. L., 2021, *Sampling: design and analysis*. CRC Press. ISBN: 0367279509.

LOMBARD, M., DITTON, T., 1997, “At the heart of it all: The concept of presence”, *Journal of computer-mediated communication*, v. 3, n. 2, pp. JCMC321.

MAGDALENO, A. M., 2013, *COMPOOTIM: Towards Planning, Monitoring and Optimization of Collaboration in Software Process Definition*. PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 253.

MALONEY, J., RESNICK, M., RUSK, N., et al., 2010, “The Scratch Programming Language and Environment”, v. 10, n. 4 (nov). doi: 10.1145/1868358.1868363. Available at: <https://doi-org.ez367.periodicos.capes.gov.br/10.1145/1868358.1868363>.

MARINHO, F. G., LIMA, F., FERREIRA FILHO, J. B., et al., 2010, “A Software Product Line for the Mobile and Context-Aware Applications Domain”. In: Bosch, J., Lee,

J. (Eds.), *Software Product Lines: Going Beyond*, pp. 346–360, Berlin, Heidelberg. Springer Berlin Heidelberg. ISBN: 978-3-642-15579-6.

MARTINEZ, M., ARBELAEZ GARCES, G., DUPONT, L., et al., 2020, "Physiological assessment of User eXprience supported by Immersive Environments: First input from a literature review". In: Virtual, L. (Ed.), *ConVRgence (VRIC) Virtual Reality International Conference*, Proceedings of Virtual Reality International Conference (VRIC), pp. 89–108, Laval, France, abr. Laval Virtual, Laval Virtual. Available at: <https://hal.archives-ouvertes.fr/hal-02551341>.

MATTURRO, G., RASCHETTI, F., FONTÁN, C., 2019, "A Systematic Mapping Study on Soft Skills in Software Engineering", *JUCS - Journal of Universal Computer Science*, v. 25, n. 1, pp. 16–41. ISSN: 0948-695X. doi: 10.3217/jucs-025-01-0016. Available at: <https://doi.org/10.3217/jucs-025-01-0016>.

MAYOR, J., LÓPEZ-FERNÁNDEZ, D., 2021a, "Scrum VR: Virtual Reality Serious Video Game to Learn Scrum", *Applied Sciences*, v. 11, n. 19. ISSN: 2076-3417. doi: 10.3390/app11199015. Available at: <https://www.mdpi.com/2076-3417/11/19/9015>.

MAYOR, J., LÓPEZ-FERNÁNDEZ, D., 2021b, "Scrum VR: Virtual Reality Serious Video Game to Learn Scrum", *Applied Sciences*, v. 11, n. 19. ISSN: 2076-3417. doi: 10.3390/app11199015. Available at: <https://www.mdpi.com/2076-3417/11/19/9015>.

MERINO, L., BERGEL, A., NIERSTRASZ, O., 2018, "Overcoming Issues of 3D Software Visualization through Immersive Augmented Reality". In: *2018 IEEE Working Conference on Software Visualization (VISSOFT)*, pp. 54–64. doi: 10.1109/VISSOFT.2018.00014.

META, 2022. "Meta Quest 2". Accessed 3 September 2022, <https://store.facebook.com/quest/products/quest-2>.

MILGRAM, P., TAKEMURA, H., UTSUMI, A., et al., 1995, "Augmented reality: a class of displays on the reality-virtuality continuum". In: Das, H. (Ed.), *Telemanipulator and Telepresence Technologies*, v. 2351, pp. 282 – 292. International Society for Optics and Photonics, SPIE. doi: 10.1117/12.197321. Available at: <https://doi.org/10.1117/12.197321>.

MISBHAUDDIN, M., 2018, "VREdu: a framework for interactive immersive lectures using virtual reality". In: *2018 21st Saudi Computer Society National Computer Conference (NCC)*, pp. 1–6. IEEE.

MOEN, K., MIDDELTHON, A.-L., 2015, "Chapter 10 - Qualitative Research Methods". In: Laake, P., Benestad, H. B., Olsen, B. R. (Eds.), *Research in Medical and Biological Sciences (Second Edition)*, second edition ed., Academic Press, pp. 321–378, Amsterdam. ISBN: 978-0-12-799943-2. doi: https://doi.org/10.1016/B978-0-12-799943-2.00010-0. Available at: <https://www.sciencedirect.com/science/article/pii/B9780127999432000100>.

MOHER, D., LIBERATI, A., TETZLAFF, J., et al., 2009, "Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement", *PLoS medicine*, v. 6, n. 7, pp. e1000097.

MORGADO, L., BECK, D., 2020, "Unifying protocols for conducting systematic scoping reviews with application to immersive learning research". In: *2020 6th International Conference of the Immersive Learning Research Network (iLRN)*, pp. 155–162. IEEE.

MUNN, Z., PETERS, M. D. J., STERN, C., et al., 2018, "Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach", *BMC Medical Research Methodology*, v. 18, n. 1 (11), pp. 201–213.

MURRAY, J. H., 1997, *Hamlet on the holodeck: The future of narrativity in cyberspace*. Cambridge: MIT Press.

MYSTAKIDIS, S., 2022, "Metaverse", *Encyclopedia*, v. 2, n. 1, pp. 486–497. ISSN: 2673-8392. doi: 10.3390/encyclopedia2010031. Available at: <https://www.mdpi.com/2673-8392/2/1/31>.

NARIN, N. G., 2021, "A Content Analysis of the Metaverse Articles", *Journal of Metaverse*, v. 1, n. 1, pp. 17–24.

NAZLIGUL, M. D., YILMAZ, M., GULEC, U., et al., 2017, "Overcoming Public Speaking Anxiety of Software Engineers Using Virtual Reality Exposure Therapy". In: Stolfa, J., Stolfa, S., O'Connor, R. V., et al. (Eds.), *Systems, Software and Services Process Improvement*, pp. 191–202, Cham. Springer International Publishing. ISBN: 978-3-319-64218-5.

NG, V., TANG, Z., 2012a, "Acquiring software project specifications in a virtual world", *Electronic Journal of e-Learning*, v. 10, n. 1, pp. 120–131.

NG, V., TANG, Z., 2012b, "Acquiring software project specifications in a virtual world", *Electronic Journal of e-Learning*, v. 10, n. 1, pp. 120–131.

NIELSEN, J., 1992, "The usability engineering life cycle", *Computer*, v. 25, n. 3, pp. 12–22. doi: 10.1109/2.121503.

NING, H., WANG, H., LIN, Y., et al., 2021. "A Survey on Metaverse: the State-of-the-art, Technologies, Applications, and Challenges". Available at: <https://arxiv.org/abs/2111.09673>.

NJOKU, J. N., NWAKANMA, C. I., AMAIZU, G. C., et al., 2022, "Prospects and challenges of Metaverse application in data-driven intelligent transportation systems", *IET Intelligent Transport Systems*, v. n/a, n. n/a. doi: https://doi.org/10.1049/itr2.12252. Available at: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/itr2.12252>.

NORTHROP, L., CLEMENTS, P., BACHMANN, F., et al., 2007, *A framework for software product line practice, version 5.0.* Technical Report 5, Software Engineering Institute (SEI), Carnegie Mellon Universit, December.

NORTHROP, L., 2002, "SEI's software product line tenets", *IEEE Software*, v. 19, n. 4 (jul.), pp. 32–40. ISSN: 1937-4194. doi: 10.1109/MS.2002.1020285. Conference Name: IEEE Software.

NTABA, A., JANTJIES, M., 2021, "Open Distance Learning and Immersive Technologies: A Literature Analysis", *Balancing the Tension between Digital Technologies and Learning Sciences*, pp. 183–198.

NUNES, V. T., 2014, *Dynamic Process Adaptation: Planning in a Context-Aware Approach.* PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 133.

OCHOA, O., BABBIT, A., 2019a, "Incorporating a Virtual Reality Environment in the Teaching of Analysis of Software Requirements". In: *2019 IEEE Frontiers in Education Conference (FIE)*, pp. 1–5, a. doi: 10.1109/FIE43999.2019.9028676.

OCHOA, O., BABBIT, A., 2019b, "Incorporating a Virtual Reality Environment in the Teaching of Analysis of Software Requirements". In: *2019 IEEE Frontiers in Education Conference (FIE)*, pp. 1–5, b. doi: 10.1109/FIE43999.2019.9028676.

OCHOA, X., WORSLEY, M., 2016, "Editorial: Augmenting Learning Analytics with Multimodal Sensory Data", *Journal of Learning Analytics*, v. 3, n. 2 (Sep.), pp. 213–219. doi: 10.18608/jla.2016.32.10. Available at: <https://learning-analytics.info/index.php/JLA/article/view/5081>.

OCHODEK, M., KOPCZYŃSKA, S., 2018, "Perceived importance of agile requirements engineering practices – A survey", *Journal of Systems and Software*, v. 143, pp. 29–43. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2018.05.012. Available at: <https://www.sciencedirect.com/science/article/pii/S0164121218300955>.

OUHAICHI, H., SPIKOL, D., VOGEL, B., 2023, "Research trends in multimodal learning analytics: A systematic mapping study", *Computers and Education: Artificial Intelligence*, p. 100136. ISSN: 2666-920X. doi: https://doi.org/10.1016/j.caeai.2023.100136. Available at: <https://www.sciencedirect.com/science/article/pii/S2666920X23000152>.

OUHBI, S., POMBO, N., 2020, "Software Engineering Education: Challenges and Perspectives". In: *2020 IEEE Global Engineering Education Conference (EDUCON)*, pp. 202–209. doi: 10.1109/EDUCON45650.2020.9125353.

OZKAYA, I., 2020, "What Should a Software Engineer Know?" *IEEE Software*, v. 37, n. 1, pp. 3–6. doi: 10.1109/MS.2019.2946668.

PACHECO, C., GARCIA, I., 2012, "A systematic literature review of stakeholder identification methods in requirements elicitation", *Journal of Systems and Software*, v. 85, n. 9, pp. 2171–2181. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2012.04.075. Available at: <https://www.sciencedirect.com/science/article/pii/S0164121212001288>. Selected papers from the 2011 Joint Working IEEE/IFIP Conference on Software Architecture (WICSA 2011).

PAGE, M. J., MCKENZIE, J. E., BOSSUYT, P. M., et al., 2021, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews", *Systematic Reviews*, v. 10, n. 1, pp. 1–11.

PARK, S.-M., KIM, Y.-G., 2022, "A Metaverse: Taxonomy, Components, Applications, and Open Challenges", *IEEE Access*, v. 10, pp. 4209–4251. doi: 10.1109/ACCESS.2021.3140175.

PATLE, D. S., MANCA, D., NAZIR, S., et al., 2019, "Operator training simulators in virtual reality environment for process operators: a review", *Virtual Reality*, v. 23, n. 3, pp. 293–311. ISSN: 1434-9957.

PEDREIRA, O., GARCÍA, F., BRISABOA, N., et al., 2015, "Gamification in software engineering – A systematic mapping", *Information and Software Technology*, v. 57, pp. 157–168. ISSN: 0950-5849. doi: https://doi.org/10.1016/j.infsof.2014.08.007. Available at: <https://www.sciencedirect.com/science/article/pii/S0950584914001980>.

PELLAS, N., KAZANIDIS, I., PALAIGEORGIOU, G., 2020, "A systematic literature review of mixed reality environments in K-12 education", *Education and Information Technologies*, v. 25, n. 4, pp. 2481–2520.

PETRIGNA, L., MUSUMECI, G., 2022, “The Metaverse: A New Challenge for the Healthcare System: A Scoping Review”, *Journal of Functional Morphology and Kinesiology*, v. 7, n. 3. ISSN: 2411-5142. doi: 10.3390/jfmk7030063. Available at: <https://www.mdpi.com/2411-5142/7/3/63>.

PEÑA-AYALA, A., 2018, “Learning analytics: A glance of evolution, status, and trends according to a proposed taxonomy”, *WIREs Data Mining and Knowledge Discovery*, v. 8, n. 3, pp. e1243. doi: https://doi.org/10.1002/widm.1243. Available at: <https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/widm.1243>.

POLANČIČ, G., HERIČKO, M., ROZMAN, I., 2010, “An empirical examination of application frameworks success based on technology acceptance model”, *Journal of Systems and Software*, v. 83, n. 4, pp. 574–584. ISSN: 0164-1212. doi: https://doi.org/10.1016/j.jss.2009.10.036. Available at: <https://www.sciencedirect.com/science/article/pii/S0164121209002799>.

PRIETO-DIAZ, R., 1990, “Domain analysis: An introduction”, *ACM SIGSOFT Software Engineering Notes*, v. 15, n. 2, pp. 47–54.

QIAO, J., XU, J., LI, L., et al., 2021, “The integration of immersive virtual reality simulation in interprofessional education: A scoping review”, *Nurse Education Today*, p. 104773.

QUAYE, S. J., HARPER, S. R., PENDAKUR, S. L., 2019, *Student Engagement in Higher Education: Theoretical Perspectives and Practical Approaches for Diverse Populations*. Routledge. ISBN: 9780429683459.

RADIANTI, J., MAJCHRZAK, T. A., FROMM, J., et al., 2020, “A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda”, *Computers & Education*, v. 147, pp. 103778.

RAMESHWAR, J. R., KING, G. S., 2022, “Caribbean Metaverse Development: A Literature Review Perspective”, *Journal of Metaverse*, v. 2, n. 2, pp. 83 – 99.

REBELO, F., NORIEGA, P., DUARTE, E., et al., 2012, “Using Virtual Reality to Assess User Experience”, *Human Factors*, v. 54, n. 6, pp. 964–982. doi: 10.1177/0018720812465006. Available at: <https://doi.org/10.1177/0018720812465006>. PMID: 23397807.

REGAN, E. C., PRICE, K. R., 1994, “The frequency of occurrence and severity of side-effects of immersion virtual reality.” *Aviation, Space, and Environmental Medicine, 65(6)*, pp. 527–530.

REGONIEL, P. A., 2015. "Conceptual framework: A step by step guide on how to make one". Available at: <https://simplyeducate.me/2015/01/05/conceptual-framework-guide/>.

REIS, R., MARQUES, B. P., 2021, "Learning Analytics in the Monitoring of Learning Processes: 3D Educational Collaborative Virtual Environments". In: *Advancing the Power of Learning Analytics and Big Data in Education*, IGI Global, pp. 142–169.

REY-BECERRA, E., BARRERO, L. H., ELLEGAST, R., et al., 2021, "The effectiveness of virtual safety training in work at heights: A literature review", *Applied Ergonomics*, v. 94, pp. 103419.

RILLING, J., MUDUR, S. P., 2002, "On the use of metaballs to visually map source code structures and analysis results onto 3D space". In: *Ninth Working Conference on Reverse Engineering, 2002. Proceedings.*, pp. 299–308. doi: 10.1109/WCRE.2002.1173087.

RODRIGUES, C. S. C., WERNER, C. M. L., LANDAU, L., 2016a, "VisAr3D: An Innovative 3D Visualization of UML Models". In: *2016 IEEE/ACM 38th International Conference on Software Engineering Companion (ICSE-C)*, pp. 451–460, a.

RODRIGUES, C. S. C., WERNER, C. M. L., LANDAU, L., 2016b, "VisAr3D: An Innovative 3D Visualization of UML Models". In: *2016 IEEE/ACM 38th International Conference on Software Engineering Companion (ICSE-C)*, pp. 451–460, b.

RODRIGUEZ, G., SORIA, , CAMPO, M., 2015, "Virtual Scrum: A teaching aid to introduce undergraduate software engineering students to scrum", *Computer Applications in Engineering Education*, v. 23, n. 1, pp. 147–156. doi: https://doi.org/10.1002/cae.21588. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.21588>.

ROSCA, D., 2018, "Acquiring Professional Software Engineering Skills through Studio-based Learning". In: *2018 17th International Conference on Information Technology Based Higher Education and Training (ITHET)*, pp. 1–6. doi: 10.1109/ITHET.2018.8424773.

SARITAŞ, M. T., TOPRAKLIKOĞLU, K., 2022, "Systematic literature review on the use of metaverse in education", *International Journal of Technology in Education*, v. 5, n. 4, pp. 586–607.

SCHMITT, M., 2022. "Metaverse: Bibliometric Review, Building Blocks, and Implications for Business, Government, and Society". Available at: <https://dx.doi.org/10.2139/ssrn.4168458>.

SCHOTT, C., MARSHALL, S., 2018, "Virtual reality and situated experiential education: A conceptualization and exploratory trial", *Journal of computer assisted learning*, v. 34, n. 6, pp. 843–852.

SCHUBERT, T., FRIEDMANN, F., REGENBRECHT, H., 2001, "The experience of presence: Factor analytic insights", *Presence: Teleoperators & Virtual Environments*, v. 10, n. 3, pp. 266–281.

SETIAWAN, K. D., ANTHONY, A., MEYLIANA, et al., 2022, "The Essential Factor of Metaverse for Business Based on 7 Layers of Metaverse – Systematic Literature Review". In: *2022 International Conference on Information Management and Technology (ICIMTech)*, pp. 687–692. doi: 10.1109/ICIMTech55957.2022.9915136.

SHANKAR, S. K., PRIETO, L. P., RODRÍGUEZ-TRIANA, M. J., et al., 2018, "A Review of Multimodal Learning Analytics Architectures". In: *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*, pp. 212–214. doi: 10.1109/ICALT.2018.00057.

SHARMA, V., TALUKDAR, J., BHAGAR, K., 2019, "CodAR: An Augmented Reality Based Game to Teach Programming". In: *Proceedings of the 27th International Conference on Computers in Education, Kenting, Taiwan*, pp. 2–6.

SHEN, B., TAN, W., GUO, J., et al., 2021, "How to Promote User Purchase in Metaverse? A Systematic Literature Review on Consumer Behavior Research and Virtual Commerce Application Design", *Applied Sciences*, v. 11, n. 23. ISSN: 2076-3417. doi: 10.3390/app112311087. Available at: <https://www.mdpi.com/2076-3417/11/23/11087>.

SHULL, F., CARVER, J., TRAVASSOS, G. H., 2001, "An Empirical Methodology for Introducing Software Processes". In: *Proceedings of the 8th European Software Engineering Conference Held Jointly with 9th ACM SIGSOFT International Symposium on Foundations of Software Engineering*, ESEC/FSE-9, p. 288–296, New York, NY, USA. Association for Computing Machinery. ISBN: 1581133901. doi: 10.1145/503209.503248. Available at: <https://doi.org/10.1145/503209.503248>.

SITTIYUNO, S., CHAIPAH, K., 2019, "ARCode: Augmented Reality Application for Learning Elementary Computer Programming". In: *2019 16th International Joint Conference on Computer Science and Software Engineering (JCSSE)*, pp. 32–37. doi: 10.1109/JCSSE.2019.8864173.

SLATER, M., 1999, "Measuring presence: A response to the Witmer and Singer presence questionnaire", *Presence*, v. 8, n. 5, pp. 560–565.

SLATER, M., 2003, “A note on presence terminology”, *Presence connect*, v. 3, n. 3, pp. 1–5.

SLATER, M., 2004, “How colorful was your day? Why questionnaires cannot assess presence in virtual environments”, *Presence*, v. 13, n. 4, pp. 484–493.

SLATER, M., WILBUR, S., 1997, “A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments”, *Presence: Teleoperators & Virtual Environments*, v. 6, n. 6, pp. 603–616.

SNELSON, C., HSU, Y.-C., 2020, “Educational 360-degree videos in virtual reality: A scoping review of the emerging research”, *TechTrends*, v. 64, n. 3, pp. 404–412.

SOCIETY, I. C., 2014, *Software Engineering Competency Model (SWECOM)*. ISBN: 978-0-7695-5373-3.

SOLOMON, C., HARVEY, B., KAHN, K., et al., 2020, “History of Logo”, *Proc. ACM Program. Lang.*, v. 4, n. HOPL (jun). doi: 10.1145/3386329. Available at: <https://doi-org.ez367.periodicos.capes.gov.br/10.1145/3386329>.

SOMMERVILLE, I., 2010, *Software Engineering*. 9 ed. , Pearson. ISBN: 978-0137035151.

SOUZA, R., SILVA, B., MENDES, T., et al., 2012, “SkyscrapAR: An augmented reality visualization for software evolution”. In: Souza, R., Silva, B., Mendes, T., et al. (Eds.), *Proceedings of 2nd Brazilian Workshop on Software Visualization (WBVS 2012)*.

SU, A. Y., YANG, S. J., HWANG, W.-Y., et al., 2010, “A Web 2.0-based collaborative annotation system for enhancing knowledge sharing in collaborative learning environments”, *Computers Education*, v. 55, n. 2, pp. 752–766. ISSN: 0360-1315. doi: https://doi.org/10.1016/j.compedu.2010.03.008. Available at: <https://www.sciencedirect.com/science/article/pii/S0360131510000886>.

SU, C.-H., CHENG, C.-H., 2013, “3D Game-Based Learning System for Improving Learning Achievement in Software Engineering Curriculum.” *Turkish Online Journal of Educational Technology-TOJET*, v. 12, n. 2, pp. 1–12.

SUN, J., GAN, W., CHAO, H.-C., et al., 2022a. “Metaverse: Survey, Applications, Security, and Opportunities”. a. Available at: <https://arxiv.org/abs/2210.07990>.

SUN, J., GAN, W., CHEN, Z., et al., 2022b. “Big Data Meets Metaverse: A Survey”. b. Available at: <https://doi.org/10.48550/arXiv.2210.16282>.

SUN, P., ZHAO, S., YANG, Y., et al., 2022c, “How do Plastic Surgeons use the Metaverse: A Systematic Review”, *Journal of Craniofacial Surgery*. ISSN: 1049-2275. doi: 10.1097/SCS.0000000000009100.

SUTCLIFFE, A., GAULT, B., 2004, "Heuristic evaluation of virtual reality applications", *Interacting with Computers*, v. 16, n. 4 (06), pp. 831–849. ISSN: 0953-5438. doi: 10.1016/j.intcom.2004.05.001. Available at: <https://doi.org/10.1016/j.intcom.2004.05.001>.

TELEA, A. C., VOINEA, L., 2004, "A framework for interactive visualization of component-based software". In: *Proceedings. 30th Euromicro Conference, 2004.*, pp. 567–574. doi: 10.1109/EURMIC.2004.1333424.

TEYSEYRE, A. R., CAMPO, M. R., 2009, "An Overview of 3D Software Visualization", *IEEE Transactions on Visualization and Computer Graphics*, v. 15, n. 1, pp. 87–105. doi: 10.1109/TVCG.2008.86.

TLILI, A., HUANG, R., SHEHATA, B., et al., 2022, "Is Metaverse in education a blessing or a curse: a combined content and bibliometric analysis", *Smart Learning Environments*, v. 9, n. 24. ISSN: 2196-7091. doi: s40561-022-00205-x. Available at: <https://doi.org/10.1186/s40561-022-00205-x>.

TRAVASSOS, G., DMYTRO, G., AMARAL, E., 2002, *Introduction to Experimental Software Engineering.* Technical Report PESC/COPPE – ES-590/02, COPPE – Federal University of Rio de Janeiro.

USMANI, S. S., SHARATH, M., MEHENDALE, M., 2022, "Future of mental health in the metaverse", *General Psychiatry*, v. 35, n. 4, pp. e100825.

VASCONCELOS, A., 2007, *An Approach to Support the Creation of Domain Reference Architectures Based on Legacy Systems Analysis.* PhD Thesis in Computer Science and System Engineering, COPPE – Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, p. 267.

VLADIMIROV, I., NENOVA, M., NIKOLOVA, D., et al., 2022, "Security and Privacy Protection Obstacles with 3D Reconstructed Models of People in Applications and the Metaverse: A Survey". In: *2022 57th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, pp. 1–4. doi: 10.1109/ICEST55168.2022.9828791.

WANG, Q., LI, R., WANG, Q., et al., 2021. "Non-Fungible Token (NFT): Overview, Evaluation, Opportunities and Challenges". Available at: <https://arxiv.org/abs/2105.07447>.

WANG, T., ZHU, Q., 2009a, "A Software Engineering Education Game in a 3-D Online Virtual Environment". In: *2009 First International Workshop on Education Technology and Computer Science*, v. 2, pp. 708–710, a. doi: 10.1109/ETCS.2009.418.

WANG, T., ZHU, Q., 2009b, "A Software Engineering Education Game in a 3-D Online Virtual Environment". In: *2009 First International Workshop on Education Technology and Computer Science*, v. 2, pp. 708–710, b. doi: 10.1109/ETCS.2009.418.

WANG, X., MO, X., FAN, M., et al., 2022a. "Reducing Stress and Anxiety in the Metaverse: A Systematic Review of Meditation, Mindfulness and Virtual Reality". a. Available at: <https://arxiv.org/abs/2209.14645>.

WANG, Y., ZHAO, J., 2022. "A Survey of Mobile Edge Computing for the Metaverse: Architectures, Applications, and Challenges". Available at: <https://doi.org/10.48550/arXiv.2212.00481>.

WANG, Y., SU, Z., ZHANG, N., et al., 2022b. "A Survey on Metaverse: Fundamentals, Security, and Privacy". b. Available at: <https://arxiv.org/abs/2203.02662>.

WARPEFELT, H., 2016, *The Non-Player Character : Exploring the believability of NPC presentation and behavior. The Non-Player Character : Exploring the believability of NPC presentation and behavior*, Stockholm University, Department of Computer and Systems Sciences, p. 118.

WERNER, C. M. L., TRAVASSOS, G. H., DA ROCHA, A., et al., 1997, "Memphis: a reuse based OO software development environment". In: *Proceedings. Technology of Object-Oriented Languages. TOOLS 24 (Cat. No. 97TB100240)*, pp. 182–191. IEEE.

WETTEL, R., LANZA, M., 2007, "Program Comprehension through Software Habitability". In: *15th IEEE International Conference on Program Comprehension (ICPC '07)*, pp. 231–240. doi: 10.1109/ICPC.2007.30.

WISE, J. A., THOMAS, J. J., PENNOCK, K., et al., 1995, "Visualizing the non-visual: spatial analysis and interaction with information from text documents". In: *Proceedings of Visualization 1995 Conference*, pp. 51–58. doi: 10.1109/INFVIS.1995.528686.

WITMER, B. G., SINGER, M. J., 1998a, "Measuring Presence in Virtual Environments: A Presence Questionnaire", *Presence: Teleoperators and Virtual Environments*, v. 7, n. 3 (06), pp. 225–240. doi: 10.1162/105474698565686. Available at: <https://doi.org/10.1162/105474698565686>.

WITMER, B. G., SINGER, M. J., 1998b, "Measuring presence in virtual environments: A presence questionnaire", *Presence*, v. 7, n. 3, pp. 225–240.

WOHLIN, C., 2014, "Guidelines for snowballing in systematic literature studies and a replication in software engineering". In: *Proceedings of the 18th international conference on evaluation and assessment in software engineering*, pp. 1–10.

WOLPE, J., 1968. "Psychotherapy by reciprocal inhibition". ISSN: 1936-3567. Available at: <https://doi.org/10.1007/BF03000093>.

WU, B., YU, X., GU, X., 2020, "Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis", *British Journal of Educational Technology*, v. 51, n. 6, pp. 1991–2005.

WU, T.-C., HO, C.-T. B., 2022, "A scoping review of metaverse in emergency medicine", *Australasian Emergency Care*. ISSN: 2588-994X. doi: https://doi.org/10.1016/j.auec.2022.08.002. Available at: <https://www.sciencedirect.com/science/article/pii/S2588994X22000525>.

XU, M., NG, W. C., LIM, W. Y. B., et al., 2022. "A Full Dive into Realizing the Edge-enabled Metaverse: Visions, Enabling Technologies,and Challenges". Available at: <https://arxiv.org/abs/2203.05471>.

YACOUB, S., AMMAR, H., ROBINSON, T., 2000, "A methodology for architectural-level risk assessment using dynamic metrics". In: *Proceedings 11th International Symposium on Software Reliability Engineering. ISSRE 2000*, pp. 210–221. doi: 10.1109/ISSRE.2000.885873.

YANG, B., YANG, S., LV, Z., et al., 2022a, "Application of Digital Twins and Metaverse in the Field of Fluid Machinery Pumps and Fans: A Review", *Sensors*, v. 22, n. 23. ISSN: 1424-8220. doi: 10.3390/s22239294. Available at: <https://www.mdpi.com/1424-8220/22/23/9294>.

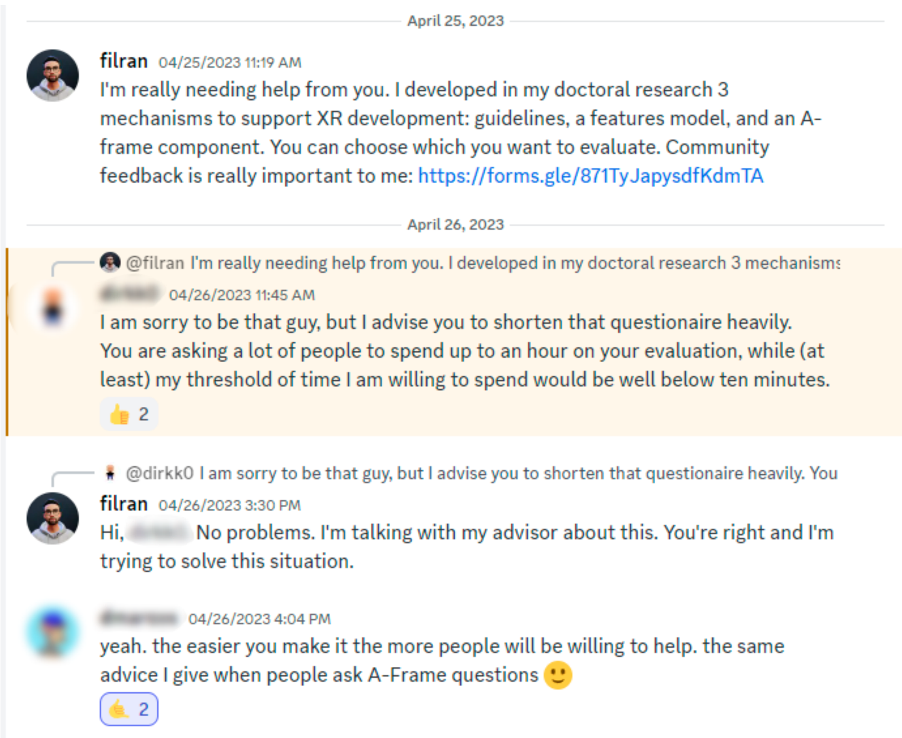
YANG, Q., ZHAO, Y., HUANG, H., et al., 2022b, "Fusing Blockchain and AI With Metaverse: A Survey", *IEEE Open Journal of the Computer Society*, v. 3, pp. 122–136. doi: 10.1109/OJCS.2022.3188249.

YE, E., LIU, C., POLACK-WAHL, J. A., 2007, "Enhancing software engineering education using teaching aids in 3-D online virtual worlds". In: *2007 37th Annual Frontiers In Education Conference - Global Engineering: Knowledge Without Borders, Opportunities Without Passports*, pp. T1E–8–T1E–13. doi: 10.1109/FIE.2007.4417884.

ÉCOLE P. BOURQUE, FAIRLY, R. E., 2014. "Guide to the Software Engineering Body of Knowledge, Version 3.0". IEEE Computer Society.

Appendix A

Discord Users Message



April 25, 2023

filran 04/25/2023 11:19 AM
I'm really needing help from you. I developed in my doctoral research 3 mechanisms to support XR development: guidelines, a features model, and an A-frame component. You can choose which you want to evaluate. Community feedback is really important to me: https://forms.gle/871TyJapysdfKdmTA

April 26, 2023

@filran I'm really needing help from you. I developed in my doctoral research 3 mechanisms
04/26/2023 11:45 AM
I am sorry to be that guy, but I advise you to shorten that questionaire heavily. You are asking a lot of people to spend up to an hour on your evaluation, while (at least) my threshold of time I am willing to spend would be well below ten minutes.
👍 2

@dirkk0 I am sorry to be that guy, but I advise you to shorten that questionaire heavily. You
filran 04/26/2023 3:30 PM
Hi, No problems. I'm talking with my advisor about this. You're right and I'm trying to solve this situation.

04/26/2023 4:04 PM
yeah. the easier you make it the more people will be willing to help. the same advice I give when people ask A-Frame questions 🙂
👍 2

Appendix B

Servers List

B.1 Slack

- **A-Frame**: https://join.slack.com/t/aframevr/shared_invite/zt-1ui277f7a-z62LbvMXm1SqPrayQ2eT1A;
- **XRBR**: https://join.slack.com/t/xrbr/shared_invite/zt-1ujqtwx6t-z9xXoZJD_7Hy lFjGWQamA;
- **Udacity VR Developer**: https://join.slack.com/t/udacityvrdeveloper/shared_-invite/zt-1uef1xh3b-FAO7a5NgwnAN45zjnEhDiw.

B.2 Discord

- **ABMETA**: https://discord.gg/3vUubKCA;
- **XRMust**: https://discord.gg/uUuy2qZK;
- **WEB3DEV**: https://discord.gg/web3dev;
- **IEEE SB VIT Pune**: https://discord.gg/DeGRfDAr;
- **Spatial.io**: https://discord.gg/spatial;
- **WebXR**: https://discord.gg/webxr;
- **GlobalXR.Community**: https://discord.gg/q4uxCTbY;
- **MongoDB**: https://discord.gg/mongodb-714857985389625415;
- **FRAME**: https://discord.gg/mrKDsYm7;
- **XR Creators**: https://discord.gg/xr-creators-706144559884927046;

- **Three.js**: https://discord.gg/2gF9Vw2A;
- **Hubs**: https://discord.gg/hubs-498741086295031808;
- **Supermedium**: https://supermedium.com/discord/;
- **Virtual Reality**: https://discord.gg/virtualreality.

Appendix C

MetaSEE Framework Experiment Instruments for Academics

This appendix presents the instruments we used to evaluate the importance of MetaSEE Framework guidelines to define the main affordances to design XR apps for SEE, as explained in Section 7.3.

C.1 Informed Consent Form

STUDY GOAL

This study aims to carry out an investigation on the design of XR apps for Software Engineering Education (SEE).

AGREEMENT

I declare that I am over 18 (eighteen) years of age and agree to participate in a study conducted by Filipe Arantes Fernandes from COPPE/UFRJ, under the guidance of Professor Cláudia Maria Lima Werner.

PROCEDURE

After reading and agreeing to participate in this experiment, you should fill out your professional and academic profile. Then, a hypothetical scenario is presented and you must carry out one task. After, you should fill out the feedback according to your task experience. Next, a framework to support the design of XR apps is presented. Finally, an evaluation form is presented in order to capture your feedback according to our framework for the designing of XR apps for SEE.

CONFIDENTIALITY

I am aware that my name will not be disclosed under any circumstance. I am also aware that the data obtained through this study will be kept confidential, and the results will later be presented in aggregated form, so that a participant is not associated with specific data.

Likewise, I commit not to communicate my results until the study is completed, as well as to maintain confidentiality of the techniques and documents presented and that are part of the experiment.

BENEFITS AND FREEDOM TO CANCEL

I understand that, once the experiment is over, the works I developed will be studied in order to understand the efficiency of the procedures and techniques that I was taught.

The benefits I will receive from this study are limited to learning the material that is distributed and taught. I also understand that I am free to ask questions at any time, request that any information related to me will not be included in the study or communicate my withdrawal from participation, without any penalty. Finally, I declare that I participate of my own free will with the sole purpose of contributing to the advancement and development of techniques and processes for Software Engineering.

RESEARCHER IN CHARGE

Filipe Arantes Fernandes (ffernandes@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

ADVISOR

Professor Cláudia Maria Lima Werner (werner@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

Do you agree to participate in the experiment?

( ) Yes, I agree.

( ) No, I disagree.

C.2 Characterization Form

ACADEMIC BACKGROUND

( ) Completed postdoctoral

( ) Postdoctoral in progress

( ) Completed doctoral degree

( ) Doctoral degree in progress

( ) Completed master's degree

( ) Master's degree in progress

( ) Completed specialization

( ) Specialization in progress

( ) Completed bachelor's degree

( ) Bachelor's degree in progress

PROFESSIONAL BACKGROUND

Experience Level

Please indicate your experience level in the following development skills, based on the scale below:

Development skills	Experience level					
	0	1	2	3	4	5
Desktop development						
Web development						
Mobile development						
XR development (virtual reality, augmented reality or mixed reality)						

0 = none (never participated in activities of this type)

1 = studied in class or in a book (has theoretical knowledge only)

2 = practiced in projects in the classroom (has theoretical knowledge applied only in the academic context)

3 = I used it in personal projects (has theoretical knowledge added to individual practical experiences)

4 = I used it in a few projects in the industry (has theoretical knowledge added to a few real practical experiences)

5 = I used it in many projects in the industry (has theoretical knowledge added to many real practical experiences)

Experience Time

Please detail your answer. Include the number of months of experience for each of the development skills.

Development skills	Experience level (in months)
Desktop development	
Web development	
Mobile development	
XR development (virtual reality, augmented reality or mixed reality)	

Applications for Education

Please, if you have already developed an application for education, indicate the number of projects you were involved in according to the type of application.

Type of application	Number of projects
Desktop application	
Web application	
Mobile application	
XR application (virtual reality, augmented reality or mixed reality)	

Software Engineering Skills

Please indicate your experience level in the following software engineering skills, based on the scale below:

Software engineering skills	Experience level					
	0	1	2	3	4	5
Software Requirements						
Software Design						
Software Construction						
Software Reuse						
Software Testing						
Software Maintenance						
Software Configuration Management						
Software Engineering Management						
Software Engineering Process						
Software Engineering Models and Methods						
Software Quality						
Software Engineering Professional Practice						
Software Engineering Economics						
Computing Foundations						
Mathematical Foundations						

0 = none (never participated in activities of this type)

1 = studied in class or in a book (has theoretical knowledge only)

2 = practiced in projects in the classroom (has theoretical knowledge applied only in the academic context)

3 = I used it in personal projects (has theoretical knowledge added to individual practical experiences)

4 = I used it in a few projects in the industry (has theoretical knowledge added to a few real practical experiences)

5 = I used it in many projects in the industry (has theoretical knowledge added to many real practical experiences)

C.3 Execution Form

SCENARIO

In a hypothetical scenario, you are a developer for a company that develops XR apps. Your team was invited to participate in a project to develop an XR app to support Software Engineering Education (SEE).

You, as a leader, must define what are the fundamental requirements needed to develop the XR app that comply with both the technical characteristics and the teaching and learning characteristics in Software Engineering (SE).

Thus, in general terms, you should communicate to your team members what are the general aspects that every XR app has, as well as the general aspects of the domain, in the SEE case. The purpose is to define the design of the XR app (type of oracle) in order to guide all technological and teaching decisions during the project development.

Considering the scenario presented previously, your task is establishing the fundamental and general requirements/aspects of XR app for SEE development (you can choose any software engineering topic, such as logic, coding, modeling, project management etc.).

Please describe the design (that is, fundamental project decisions) of XR app for SEE in the format of short and objective sentences.

Comments:

FEEDBACK

Thank you very much for your contribution. Now, we would like to know how was your experience to elaborate on the designing of the XR app for SEE.

Were you able to effectively carry out the proposed task?

( ) Yes

( ) I don't know / I am not sure

( ) No

Please justify your previous answer:

Were you satisfied with the task result?

( ) Yes

( ) I don't know / I am not sure

( ) No

Please justify your previous answer:

What is the degree of difficulty in carrying out the task?

( ) Very difficult

( ) Difficult

( ) Neither difficult nor easy

( ) Easy

( ) Very easy

Please justify your previous answer:

What was the biggest difficulty encountered in carrying out the task?

Comments:

SUPPORTING THE DESIGN

Now, we would like to propose to you redesign your XR app for SEE, but with guidelines to facilitate and support your design.

Our **framework** provides guidelines grouped in **technologial and pedagogical affordances** to support the design of XR apps for SEE.

Please, continue to redesign your XR app.

TECHNOLOGIAL AFFORDANCES

Technological affordances are concepts that can be **quantified** (e.g., immersive devices, the immersive virtual world itself and methods of interaction).

Therefore, the following sections are according to these affordances.

IMMERSION

This affordance is directly related to the quality and characteristics of immersive devices used to interact with the virtual world. The greater the use of the human senses through immersive devices, the greater the degree of immersion. Thus, the following questions must be answered:

IM1: Which sensory stimuli will be used during the immersive experience? *Please check all the options that apply.*

( ) Vision

( ) Hearing

( ) Smell

( ) Taste

( ) Touch

IM2: Which kind of reality will be used during the immersive experiences? *Please check all the options that apply.*

( ) Virtual Reality

( ) Mixed Reality (Augmented Reality or Virtuality Aumented)

( ) Extended Reality

IM3: Which immersive devices will be used during the immersive experiences and that are adherent to IM2? *Example: Oculus family, HTC VIVE family, PICO family, HoloLens, Windows MR family etc.*

Answer:

USER EXPERIENCE

Optimizing the user experience through intuitive interface design, responsive performance, engaging content, and social interaction is essential for the success of XR apps. For these reasons, the following questions must be answered:

UX1: What human-computer interface techniques will be used to support user interaction with the XR app? *Example: vector-based pointing techniques (ray-casting, fishing reel, image-plane pointing. . .), volume-based pointing techniques (flashlight, aperture selection, sphere-casting) etc.*

Answer:

UX2: What mechanisms will be adopted to provide the user's perception of the VW of the XR app? *Example: field of view, frames per second, 360º audio, occlusion etc.*

Answer:

UX3: What mechanisms will be adopted to mitigate the problem of motion sickness? *Example: movement through teleportation, rendering rate, etc.*

SOFTWARE VISUALIZATION

Choosing appropriate information visualization can also improve user experience, reduce cognitive load, and increase engagement and retention in the virtual world. This affordance intend to represent graphically, in an appropriate way, the elements related to Software Engineering according to the learning objective of the immersive educational applications. Therefore, the following question must be answered:

SV1: What metaphors will adequately represent aspects of software during the immersive experiences? *Example: visual metaphors (graphs, trees, abstract geometrical shapes, cities, solar system), technical notations, such as UML, BPMN, flowchart, etc.*

Answer:

DEVELOPING TOOLS

Choosing the right development tools and SDK for each platform can also facilitate cross-platform compatibility, enabling users to access the virtual world from different devices and platforms seamlessly. Therefore, selecting the appropriate development tools and SDK for each platform is crucial for optimizing performance, ensuring compatibility, and enhancing the overall user experience in XR apps. Therefore, the following questions must be answered:

DT1: What SDK and/or API will be used to implement communication between the application and the immersive devices? *Example: Oculus Integration SDK, Steam VR SDK, OpenXR, OpenVR, etc.*

Answer:

DT2: What development environments will be used to build the immersive applications? *Example: Unity, Unreal, Android, iOS, Web, etc.*

Answer:

APPLICATION FEATURES

Application features such as the number of users the XR apps can support, the required space around the user, the supported languages, and the system requirements are essential for XR apps as they directly impact the user experience and the overall success of the platform. Therefore, taking into account these application features, the following questions must be answered:

AF1: How many users will the XR app support?

( ) Single user

( ) Multi users

AF2: Which space around the user is needed for the immersive experience? *Please check all the options that apply.*

( ) Seated

( ) Standing

( ) Room-scale

( ) Other: ______________

AF3: What languages will the XR app be developed? *Example: Portuguese, English, among others.*

Answer:

AF4: What system requirements must be met in order to guarantee a good performance of the immersive experience? *Example: processor, memory, system operation, disk space, etc.*

Answer:

LEARNING INDICATORS

Analyzing and interpreting these learning indicators can provide valuable insights into the effectiveness of virtual world-based learning, identify areas for improvement, and inform future instructional design and development. Therefore, the following question must be answered:

LI1: What indicators will be used to track student performance during the immersive experience? *Example: tokens, scores, ranking, rewards, time of use, etc.*

Answer:

PEDAGOCIAL AFFORDANCES

Pedagogical Affordances are related to pedagogical aspects and **qualitative** issues (e.g., feeling of being present in the XR app, engagement, the pedagogical theory and learning outcomes).

Therefore, the following sections are according to these affordances.

LEARNING OUTCOMES

The purpose of this affordance is to establish the topics of Software Engineering, as well as the competences and skills, which must be acquired. The questions that make up this affordance are:

LO1: What Software Engineering topics will be covered? *Based on SWE-BOK skill areas. Please check all the options that apply.*

( ) Software Requirements

( ) Software Design

( ) Software Construction

( ) Software Reuse

( ) Software Testing

( ) Software Maintenance

( ) Software Configuration Management

( ) Software Engineering Management

( ) Software Engineering Process

( ) Software Engineering Models and Methods

( ) Software Quality

( ) Software Engineering Professional Practice

( ) Software Engineering Economics

( ) Computing Foundations

( ) Mathematical Foundations

( ) Other: _______________

LO2: What skills and competencies must be achieved? *Based on SWECOM knowledge, skills, and abilities. Please check all the options that apply.*

( ) Technical Skills: these are the foundational technical competencies required for software engineering roles, including programming languages, algorithms, data structures, databases, operating systems, and software development methodologies.

( ) Methodologies and Process: these skill areas focus on software development methodologies and process-related competencies, such as software lifecycle management, Agile/Scrum, DevOps, and software configuration management.

( ) Systems Thinking: these skill areas encompass the ability to understand and analyze complex software systems, including system architecture, system integration, system modeling, and system optimization.

( ) Problem Solving: these skill areas involve critical thinking, analytical skills, and problem-solving techniques, including debugging, troubleshooting, root cause analysis, and software testing.

( ) Interpersonal Skills: these skill areas focus on effective communication, teamwork, leadership, and collaboration, including requirements gathering, user interface design, team dynamics, and stakeholder management.

( ) Professionalism: these skill areas encompass the professional competencies required for software engineering roles, including ethics, project management, quality assurance, and continuous learning.

( ) Other: ______________

PEDAGOGICAL APPROACHES

The appropriate selection of theories and learning approaches positively impacts the expected learning results. This affordance aims to select the theory and pedagogical approaches that are adequate to the expected learning results and is guided by the following question:

PA1: Which theories and pedagogical approaches are adherent to the expected learning outcomes? *Example: game-based learning, problem-based learning, project-based learning, experiential learning, etc.*

Answer:

STUDENT PROFILE

SP1: What is the profile of the student who will use the XR app? *Example: degree of knowledge in an area (beginner, median or advanced), age range, familiarity with XR/games, etc.*

Answer:

CONTEXT

In addition to establishing the affordance presented previously, it is also important to define in which context the XR app will be used. Therefore, this affordance aims to establish the place where the XR app will be used through the following question:

CO1: What is the context in which the XR app will be used? *Example: classroom, training in a professional environment, anywhere the experience is not interrupted, anywhere that meets physical space requirements, etc.*

Answer:

C.4 Evaluation Form

Dear participant,

This is the last step. The purpose of this form is to obtain your feedback according to our framework for the design of XR apps for SEE.

Q1 - The questions are properly organized and structured.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q2 - The questions are objective and self-explanatory, that is, they are clear and easy to understand.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q3 - The questions are relevant and useful in defining key aspects of XR app design.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q4 - The framework addresses the basic aspects of XR app design.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Please, describe your experience when you designed without guidelines and with guidelines (our framework).

Answer:

Are there technological or pedagogical affordances that should be ADDED to the framework?

Answer:

Are there technological or pedagogical affordances that should be REMOVED from the framework?

Answer:

In your opinion, what are the main contributions of the framework to support the design of XR apps for SEE?

Answer:

In your opinion, what are the main limitations of the framework?

Answer:

Please, suggest any aspect of the framework to be improved.

Answer:

Again, we would like to thank you for your availability and participation in this study.

Filipe Arantes Fernandes / Cláudia Maria Lima Werner

Appendix D

MetaSEE Framework and MetaLine Features Model Experiment Instruments for Developers

This appendix presents the form we used to evaluate the MetaSEE Framework guidelines and MetaLine Features Model from point of view of developers, as explained in Section 7.2.

D.1 Rate the importance of each aspect before starting to develop any XR app

It is important to specify the sensory stimulus (vision, hearing, smell, taste, touch, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify the kind of reality (VR, MR or XR).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify the devices (XR headset, controllers, mouse, keyboard, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify interface-human computer techniques, such as gaze point, voice commands, detection of surfaces, etc.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify mechanisms to provide the user's perception of the virtual world (visual overlays, space-aware sound, vibration, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify mechanisms to mitigate the problem of motion sickness.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify the adequate graphical representation according to audience (metaphors, color scale, dimensions, etc..

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify tools in order to integrate XR app and devices (Oculus Integration SDK, Steam VR SDK, OpenXR, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify development and design tools (SDK, API, engine, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify how many users will use the XR app (single or multi users).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify space around the user (seated, standing, room-scale, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify the XR app language.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify the system requirements must be met in order to guarantee a good performance.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is important to specify some indicators that will be used to track user performance (sequences of actions and time, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Considering any XR app for education, it is important to specify the topics that will be covered (gravity, electromagnetic field, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Considering any XR app for education, it is important to specify skills and competencies that must be achieved (understand how the force of gravity affects the motions of bodies, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Considering any XR app for education, it is important to specify the theories and pedagogical approaches (project-based learning, game-based learning, experiential learning, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Considering any XR app for education, it is important to specify the student profile (beginner, K-12, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Considering any XR app for education, it is important to specify the context (online college, classroom in-person, distance learning, etc.).

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Are there other important aspects to define before developing XR apps? If there are, what are they?

Answer:

Now, considering any WEB XR APP developed, the main characteristics are:

- to allow users access them and have their respective avatars;
- a virtual world with 3D objects to interact them;
- to ensure devices compatible with wearable, desktop, and mobile
- platforms;
- to ensure interaction events compatible with wearable, desktop,
- and mobile platforms;
- to allow sensory input and output (vision, audition, touch,
- etc.) according to device compatibility;
- to ensure compatible browsers; and
- to ensure experiences in VR/AR/MR.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Please, feel free to justify your answer above.

Answer:

If you have contribution, suggestions, and issues, please let us know.

Answer:

What is your main skill?

( ) Desktop development

( ) Web development

( ) Mobile development

( ) XR development (virtual reality, augmented reality or mixed reality)

( ) Other

Appendix E

MetaLine Features Model Experiment Instruments

This annex presents the instruments we used to evaluate the compliance of the MetaLine Features Model regarding the Web XR apps features, as explained in Section 7.4.

E.1 Informed Consent Form

STUDY GOAL

This study aims to carry out an investigation on the MetaLine Features Model for Web XR apps development.

AGREEMENT

I declare that I am over 18 (eighteen) years of age and agree to participate in a study conducted by Filipe Arantes Fernandes from COPPE/UFRJ, under the guidance of Professor Cláudia Maria Lima Werner.

PROCEDURE

After reading and agreeing to participate in this experiment, you should fill out your professional and academic profile. Then, a features model is presented. Finally, an evaluation form is presented in order to capture your feedback.

BENEFITS AND FREEDOM TO CANCEL

I understand that, once the experiment is over, the works I developed will be studied in order to understand the efficiency of the procedures and techniques that I was taught.

The benefits I will receive from this study are limited to learning the material that is distributed and taught. I also understand that I am free to ask questions at any time, request that any information related to me will not be included in the study or communicate my withdrawal from participation, without any penalty. Finally, I declare that I participate of my own free will with the sole purpose of contributing to the advancement and development of techniques and processes for Software Engineering.

RESEARCHER IN CHARGE

Filipe Arantes Fernandes (ffernandes@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

ADVISOR

Professor Cláudia Maria Lima Werner (werner@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

Do you agree to participate in the experiment?

( ) Yes, I agree.

( ) No, I disagree.

E.2 Characterization Form

ACADEMIC BACKGROUND

( ) Completed postdoctoral

( ) Postdoctoral in progress

( ) Completed doctoral degree

( ) Doctoral degree in progress

( ) Completed master's degree

( ) Master's degree in progress

( ) Completed specialization

( ) Specialization in progress

( ) Completed bachelor's degree

( ) Bachelor's degree in progress

PROFESSIONAL BACKGROUND

Experience Level

Please indicate your experience level in the following development skills, based on the scale below:

Development skills	Experience level					
	0	1	2	3	4	5
Desktop development						
Web development						
Mobile development						
XR development (virtual reality, augmented reality or mixed reality)						

0 = none (never participated in activities of this type)

1 = studied in class or in a book (has theoretical knowledge only)

2 = practiced in projects in the classroom (has theoretical knowledge applied only in the academic context)

3 = I used it in personal projects (has theoretical knowledge added to individual practical experiences)

4 = I used it in a few projects in the industry (has theoretical knowledge added to a few real practical experiences)

5 = I used it in many projects in the industry (has theoretical knowledge added to many real practical experiences)

Experience Time

Please detail your answer. Include the number of months of experience for each of the development skills.

Development skills	Experience level (in months)
Desktop development	
Web development	
Mobile development	
XR development (virtual reality, augmented reality or mixed reality)	

Software Engineering Skills

Please indicate your experience level in the following software engineering skills, based on the scale below:

Software engineering skills	Experience level					
	0	1	2	3	4	5
Software Requirements						
Software Design						
Software Construction						
Software Reuse						
Software Testing						
Software Maintenance						
Software Configuration Management						
Software Engineering Management						
Software Engineering Process						
Software Engineering Models and Methods						
Software Quality						
Software Engineering Professional Practice						
Software Engineering Economics						
Computing Foundations						
Mathematical Foundations						

0 = none (never participated in activities of this type)

1 = studied in class or in a book (has theoretical knowledge only)

2 = practiced in projects in the classroom (has theoretical knowledge applied only in the academic context)

3 = I used it in personal projects (has theoretical knowledge added to individual practical experiences)

4 = I used it in a few projects in the industry (has theoretical knowledge added to a few real practical experiences)

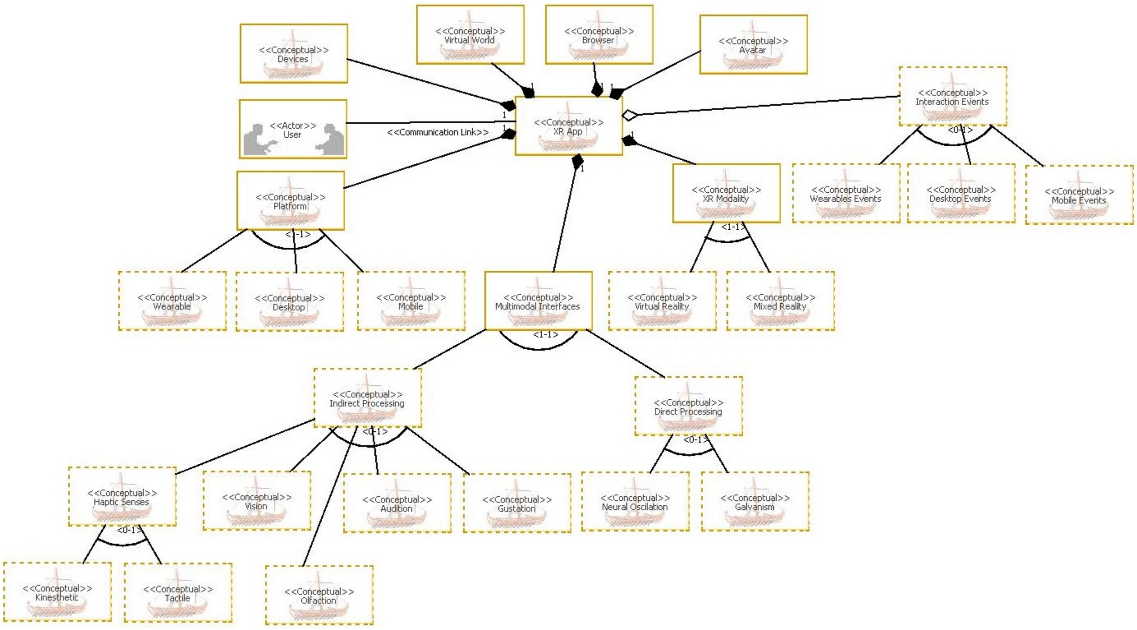
5 = I used it in many projects in the industry (has theoretical knowledge added to many real practical experiences)

E.3 Execution Form

FEATURES MODELING

Features model in software engineering is used to describe the features, characteristics, and capabilities of the software product in a structured manner. The feature model captures the relationships among different features, such as mandatory, optional, and alternative features, and their dependencies.

From our framework, we developed a features model in the Web XR app context, according to the figure below.



From **XR App** characteristics (in the center of the model), some characteristics are mandatory components for every XR apps: **Platform**, **User**, **Devices**, **Virtual World**, **Browser**, **Avatar**, **XR Modality**, and **Multimodal Interfaces**. **Interaction Events** are the only optional characteristic. It is optional because an XR app can only display virtual objects without requiring any kind of interaction and/or feedback.

Some characteristics have configuration alternatives. **Platform** is composed of *Wearable* (e.g., XR headsets, datagloves etc.), *Desktop*, and *Mobile* (e.g., smartphone or tablet). That is, an XR app can be accessed from some of these alternativities. Considering the platform, interaction events between humans and devices must be implemented. Therefore, **Interaction Events** are composed of *Wearable Events*, *Desktop Events*, and *Mobile Events*. **XR Modality** is composed of *Virtual Reality* (VR) and *Mixed Reality* (MR). We classified immersive or non-immersive experiences as VR and experiences that involve the coexistence of objects and real and virtual, like Augmented Reality (AR), we classified as MR.

Finally, **Multimodal Interfaces** are composed of *Indirect Processing* and *Direct Processing*. It is a variation point that establishes which modalities (i.e., human senses) that may be present in the applications in order to enable the engagement of immersive experiences. This modeling is based on the taxonomy of interaction modalities for XR (https://academic.oup.com/iwc/article-abstract/31/1/27/5366300AUGSTEIN & NEUMAYR, 2019). *Direct processing* works directly between a computer and the brain or muscles. *Indirect processing* refers to the multi-stage process where an output stimulus is perceived by a human receptor and then the information is delivered via electrical signals for further processing to the brain. The flow is similar for input stimulus from a human via sensors to the computer.

E.4 Evaluation Form

Dear participant,

This is the last step. The purpose of this form is to obtain your feedback according to our features model for Web XR apps.

Q5 - Is the features model useful for the development of Web XR apps?

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q6 - Does the features model include all the features needed for the development of Web XR apps?

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q7 - Does the features model help the understanding on how the different features relate to each other?

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

Q8 - Is the feature model flexible enough to allow you to add new features easily?

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Comments:

In your opinion, what are the main contributions of the features model to support the development of Web XR apps?

Answer:

In your opinion, what features should be ADDED to the model?

Answer:

In your opinion, what features should be REMOVED to the model?

Answer:

Please, suggest any aspect of the features model to be improved.

Answer:

Again, we would like to thank you for your availability and participation in this study.

Filipe Arantes Fernandes / Cláudia Maria Lima Werner

Appendix F

A-Frame VirtualUML Experiment Instruments for Academics

This annex presents the instruments we used to evaluate the ease of use and usefulness of A-Frame VirtualUML Component to support XR apps development with SE-specific features, as explained in Section 7.5.

F.1 Informed Consent Form

STUDY GOAL

This study aim to carry out an investigation on the A-Frame VirtualUML Component development.

AGREEMENT

I declare that I am over 18 (eighteen) years of age and agree to participate in a study conducted by Filipe Arantes Fernandes from COPPE/UFRJ, under the guidance of Professor Cláudia Maria Lima Werner.

PROCEDURE

After reading and agreeing to participate in this experiment, you should fill out your professional and academic profile. Then, a hypothetical scenario is presented and you must carry out some task. Finally, an evaluation form is presented in order to capture your feedback according to A-Frame VirtualUML Component.

CONFIDENTIALITY

I am aware that my name will not be disclosed under any circumstance. I am also aware that the data obtained through this study will be kept confidential, and the results will later be presented in aggregated form, so that a participant is not associated with specific data.

Likewise, I commit not to communicate my results until the study is completed, as well as to maintain confidentiality of the techniques and documents presented and that are part of the experiment.

BENEFITS AND FREEDOM TO CANCEL

I understand that, once the experiment is over, the works I developed will be studied in order to understand the efficiency of the procedures and techniques that I was taught.

The benefits I will receive from this study are limited to learning the material that is distributed and taught. I also understand that I am free to ask questions at any time, request that any information related to me will not be included in the study or communicate my withdrawal from participation, without any penalty. Finally, I declare that I participate of my own free will with the sole purpose of contributing to the advancement and development of techniques and processes for Software Engineering.

RESEARCHER IN CHARGE

Filipe Arantes Fernandes (ffernandes@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

ADVISOR

Professor Cláudia Maria Lima Werner (werner@cos.ufrj.br)

Systems Engineering and Computer Science - COPPE/UFRJ

Do you agree to participate in the experiment?

( ) Yes, I agree.

( ) No, I disagree.

F.2 Characterization Form

ACADEMIC BACKGROUND

( ) Completed postdoctoral

( ) Postdoctoral in progress

( ) Completed doctoral degree

( ) Doctoral degree in progress

( ) Completed master's degree

( ) Master's degree in progress

( ) Completed specialization

( ) Specialization in progress

( ) Completed bachelor's degree

( ) Bachelor's degree in progress

PROFESSIONAL BACKGROUND

Experience Level

Please indicate your experience level in the following development skills, based on the scale below:

Development skills	Experience level					
	0	1	2	3	4	5
Desktop development						
Web development						
Mobile development						
XR development (virtual reality, augmented reality or mixed reality)						

0 = none (never participated in activities of this type)

1 = studied in class or in a book (has theoretical knowledge only)

2 = practiced in projects in the classroom (has theoretical knowledge applied only in the academic context)

3 = I used it in personal projects (has theoretical knowledge added to individual practical experiences)

4 = I used it in a few projects in the industry (has theoretical knowledge added to a few real practical experiences)

5 = I used it in many projects in the industry (has theoretical knowledge added to many real practical experiences)

Experience Time

Please detail your answer. Include the number of months of experience for each of the development skills.

Development skills	Experience level (in months)
Desktop development	
Web development	
Mobile development	
XR development (virtual reality, augmented reality or mixed reality)	

Applications for Education

Please, if you have already developed an application for education, indicate the number of projects you were involved in according to the type of application.

Type of application	Number of projects
Desktop application	
Web application	
Mobile application	
XR application (virtual reality, augmented reality or mixed reality)	

Development Tools

Choose what online code editors you have used before. *Please check all the options that apply.*

( ) Replit

( ) CodeSandbox

( ) JSFiddle

( ) GitHub Codespaces

( ) AWS Cloud9

( ) Glitch

( ) Other

How do you rate your ability considering the following frameworks?

Three.js: ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

A-Frame: ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

Babylon.js: ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

Cesium: ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

PlayCanvas: ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

Other: ______________ ( ) Very poor ( ) Poor ( ) Fair ( ) Very good ( ) Good

F.3 Execution Form

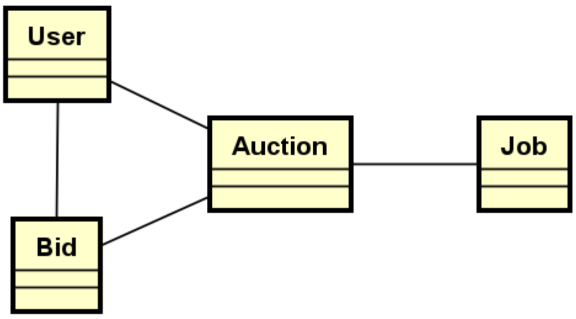
SCENARIO

You are a professor in Software Engineering and your students are dismotivated with the UML Modeling discipline.

Your misson is to create a virtual world with 3D diagram class as a method to engage your students.

TASKS

1. Access the link https://github.com/MetaSEE/aframe-virtualuml-componenthttps://github.com/MetaSEE/aframe-virtualuml-component;
2. Read the documentation;
3. Access the link https://glitch.com/edit/!/aframe-virtualuml-component-evaluationhttps://glitch.com/edit/!/aframe-virtualuml-component-evaluation;
4. Click on "Remix" button;
5. Now, in index.html, coding a 3D diagram class according to the following diagram:



6. Please, inform the link of your Glitch project remixed: ________________

F.4 Evaluation Form

Dear participant,

This is the last step. The purpose of this form is to obtain your feedback **according to the development of UML class diagrams with A-Frame VirtualUML Component**, that is, it is not to consider the Glitch.

My interaction with A-Frame VirtualUML Component is clear and understandable.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

It is easy for me to become skillful at using A-Frame VirtualUML Component.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

I find it easy to execute the proposed tasks with the A-Frame VirtualUML Component.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component's documentation is easy to understand.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component is useful to create UML class diagrams in 3D.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component improves my performance to create UML class diagrams in 3D.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component's documentation is useful to help to create UML class diagrams in 3D.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component is useful to execute the proposed tasks.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

Is the A-Frame VirtualUML Component documentation understandable?

Answer:

Is the A-Frame VirtualUML Component easy to develop?

Answer:

What are the limitations of the A-Frame VirtualUML Component?

Answer:

In your opinion, the development of Web XR frameworks-based components, like A-Frame VirtualUML Component, can aid popularize the use of immersive experiences in software engineering education?

Answer:

Please, comment anything to improve the A-Frame VirtualUML Component.

Answer:

Again, we would like to thank you for your availability and participation in this study.

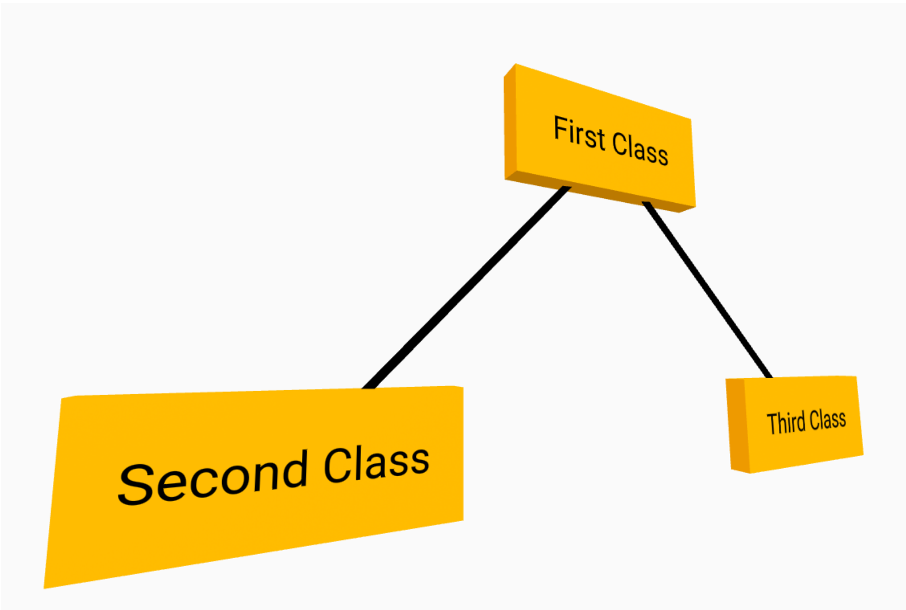
Filipe Arantes Fernandes / Cláudia Maria Lima Werner

Appendix G

A-Frame VirtualUML Experiment Instruments for Developers

This appendix presents the form we used to evaluate the A-Frame VirtualUML Component from point of view of developers, as explained in Section 7.2.

G.1 Give us your opinion about the A-Frame VirtualUML component



aframe-virtualuml-component

Make UML class diagrams to the Metaverse.

Make sure you are using **A-Frame 1.4.0** or later and **lib/THREE.MeshLine.js**.

Then just include virtualuml.min.js in your HTML:

```
<script src="dist/virtualuml.min.js">
```

and add the **a-umlclass** and **a-association** components to create your UML class diagram:

```
<!DOCTYPE html>
<html lang="en">
<head>
  <meta charset="UTF-8">
  <meta http-equiv="X-UA-Compatible" content="IE=edge">
  <meta name="viewport" content="width=device-width, initial-scale=1.0">
  <title>Virtual UML</title>
  <script src="https://aframe.io/releases/1.4.0/aframe.min.js"></script>
  <script src="lib/THREE.MeshLine.js"></script>
  <script src="dist/virtualuml.min.js"></script>
</head>
<body>
  <a-scene background="color: #FAFAFA">
    <a-camera position="0 .5 5"></a-camera>

    <!-- First, we created 3 UML classes:
    #firstclass, #secondclass, and #thirdclass  -->
    <a-umlclass
      id="firstclass"
      classname="First Class"
      position="0 2 0"
    ></a-umlclass>

    <a-umlclass
      id="secondclass"
      classname="Second Class"
      position="-2 0 0"
    ></a-umlclass>

    <a-umlclass
      id="thirdclass"
```

```
      classname="Third Class"
      position="2 0 0"
    ></a-umlclass>

    <!-- Now, we created the associations between UML classes -->
    <!-- This association connect #firstclass and #secondclass -->
    <a-association
      start="#firstclass"
      end="#secondclass"
    ></a-association>

    <!-- This association connect #firstclass and #thirdclass -->
    <a-association
      start="#firstclass"
      end="#thirdclass"
    ></a-association>
  </a-scene>
</body>
</html>
```

Links:

- GitHub: https://github.com/MetaSEE/aframe-virtualuml-component
- Glitch: https://aframe-virtualuml-component-evaluation.glitch.me

A-Frame VirtualUML Component's documentation is easy to understand.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

I think I would become skilled when using the A-Frame VirtualUML Component.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component's documentation is useful to help to create UML class diagrams in 3D.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

A-Frame VirtualUML Component is useful to create UML class diagrams in 3D.

( ) Strongly disagree

( ) Disagree

( ) Neither agree nor disagree

( ) Agree

( ) Strongly agree

If you have contribuition, suggestions, and issues, please let us know.

Answer:

What is your main skill?

( ) Desktop development

( ) Web development

( ) Mobile development

( ) XR development (virtual reality, augmented reality or mixed reality)

( ) Other

Appendix H

MetaSEE Platform Experiment Instruments

This annex presents the instruments (in portuguese) we used to evaluate the usability of MetaSEE Platform, as explained in Section 7.6.

H.1 Formulário de Consentimento

OBJETIVO DO ESTUDO

Este estudo tem como objetivo realizar uma investigação sobre a usabilidade da plataforma de Metaverso para Educação de Engenharia de Software (EES).

IDADE

Declaro que sou maior de 18 (dezoito) anos e concordo em participar do estudo conduzido por Filipe Arantes Fernandes da COPPE/UFRJ, sob a orientação da Professora Cláudia Maria Lima Werner.

PROCEDIMENTO

Após ler e concordar em participar do experimento, você irá preencher dados do seu perfil acadêmico e profissional. Após, você realizará no máximo 6 tarefas em nossa plataforma. Finalmente, você preencherá um formulário a fim de saber como foi a sua experiência na plataforma.

CONFIDENCIALIDADE

Estou ciente de que meu nome não será divulgado em hipótese alguma. Também estou ciente de que os dados obtidos através deste estudo serão mantidos em sigilo, e os resultados serão posteriormente apresentados de forma agregada, para que um participante não seja associado a dados específicos.

Da mesma forma, me comprometo a não comunicar meus resultados até que o estudo seja concluído, bem como a manter a confidencialidade das técnicas e documentos apresentados e que fazem parte do experimento.

BENEFÍCIOS, LIBERDADE DE DESISTÊNCIA

Entendo que, uma vez finalizada a experiência, serão estudados os trabalhos que desenvolvi a fim de compreender a eficácia dos procedimentos e técnicas que me foram ensinados.

Os benefícios que receberei deste estudo se limitam ao aprendizado do material que é distribuído e ensinado. Também entendo que sou livre para fazer perguntas a qualquer momento, solicitar que qualquer informação a meu respeito não seja incluída no estudo ou comunicar minha desistência da participação, sem qualquer penalidade. Por fim, declaro que participo de livre e espontânea vontade com o único propósito de contribuir para o avanço e desenvolvimento de técnicas e processos de Engenharia de Software.

PESQUISADOR RESPONSÁVEL

Filipe Arantes Fernandes (ffernandes@cos.ufrj.br)

Engenharia de Sistemas e Computação - COPPE/UFRJ

PROFESSOR RESPONSÁVEL

Professor Cláudia Maria Lima Werner (werner@cos.ufrj.br)

Engenharia de Sistemas e Computação - COPPE/UFRJ

Você concorda em participar do experimento?

( ) Sim, eu concordo.

( ) Não, eu disconcordo.

H.2 Formulário de Caracterização

FORMAÇÃO ACADÊMICA

( ) Pósdoc completo

( ) Pósdoc incompleto

( ) Doutorado completo

( ) Doutorado incompleto

( ) Mestrado completo

( ) Mestrado incompleto

( ) Especialização completa

( ) Especialização incompleta

( ) Graduação completa

( ) Graduação incompleta

( ) Curso técnico completo

( ) Curso técnico incompleto

EXPERIÊNCIA COM JOGOS

Com que frequência você tem contato com jogos durante o mês?

Jogos para consoles de videogame (PlayStation, Xbox, Nintendo Switch, entre outros.):

( ) Nunca ( ) Raramente ( ) Ocasionalmente ( ) Frequentemente ( ) Muita frequência

Jogos para PC:

( ) Nunca ( ) Raramente ( ) Ocasionalmente ( ) Frequentemente ( ) Muita frequência

Jogos para dispositivos móveis:

( ) Nunca ( ) Raramente ( ) Ocasionalmente ( ) Frequentemente ( ) Muita frequência

Jogos de Realidade Virtual e Aumentada:

( ) Nunca ( ) Raramente ( ) Ocasionalmente ( ) Frequentemente ( ) Muita frequência

Jogos via navegador (browser):

( ) Nunca ( ) Raramente ( ) Ocasionalmente ( ) Frequentemente ( ) Muita frequência

PERFIL

Em qual tipo de perfil você se enquadra?

( ) Eu sou ESTUDANTE de Engenharia de Software ou em outro tópico da Ciência da Computação

( ) Eu sou PROFESSOR de Engenharia de Software ou em outro tópico da Ciência da Computação

( ) Outro

Esta seção será apresentada apenas para o participante que tenha selecionado a opção "Outro" da pergunta anterior e o questionário será encerrado.

Muito obrigado!

Este estudo é direcionado para estudantes e professores de Ciência da Computação. Mesmo assim, agradecemos o seu interesse.

Por favor, sinta-se à vontade para compartilhar este estudo.

EXPERIÊNCIA - PARA PROFESSORES

Área de Atuação

Informe qual a sua área de atuação em Ciência da Computação.

Resposta:

Experiência

Em quais atividades você adquiriu experiência em Engenharia de Software? *Por favor, marque todas as opções que se enquadram.*

( ) nenhum (nunca participou de atividades deste tipo)

( ) estudei em aula ou em livro (possui conhecimento teórico apenas)

( ) pratiquei em projetos em sala de aula (possui conhecimento teórico aplicado apenas no contexto acadêmico)

( ) usei em projetos pessoais (possui conhecimento teórico somado de experiências práticas individuais)

( ) usei em poucos projetos na indústria (possui conhecimento teórico somado de poucas experiências práticas reais)

( ) usei em muitos projetos na indústria (possui conhecimento teórico somado de muitas experiências práticas reais)

Tempo de Experiência

Em relação ao ensino sobre algum tópico de Engenharia de Software, informe o período de experiência em meses:

Resposta:

Educação de Engenharia de Software

Em quais tópicos de Engenharia de Software você possui experência de ensino? *Por favor, marque todas as opções que se enquadram.*

( ) Requisitos de software

( ) Design de software

( ) Construção de software

( ) Reutilização de software

( ) Teste de software

( ) Manutenção de software

( ) Gerenciamento de configuração de software

( ) Gerenciamento de Engenharia de Software

( ) Processo de Engenharia de Software

( ) Modelos e Métodos de Engenharia de Software

( ) Qualidade de Software

( ) Prática Profissional de Engenharia de Software

( ) Economia da Engenharia de Software

( ) Fundamentos de Computação

( ) Fundamentos Matemáticos

( ) Outro: ______________

Engajamento dos Estudantes

Considerando sua experiência em sala de aula, informe o grau de engagamento dos estudantes sobre a disciplina de Engenharia de Software.

( ) Muito desmotivados

( ) Desmotivados

( ) Nem engajados e nem desmotivados

( ) Engajados

( ) Muito engajados

Em sua opinião, quais são as principais razões dos alunos não se interessarem pela disciplina de Engenharia de Software?

Resposta:

Metodologia de Ensino

Quais mecanismos (metodologia, software e/ou materiais) você tem utilizado para engajar os alunos e apoiar suas aulas em Engenharia de Software?

Resposta:

Quais são as principais limitações dos mecanismos (metodologia, software e/ou materiais) que o impedem de melhorar o engajamento dos alunos e apoiar suas aulas de Engenharia de Software?

Resposta:

EXPERIÊNCIA - PARA ESTUDANTES

Definição de Engenharia de Software

Engenharia de Software (ES) é uma disciplina que cria e desenvolve programas de computador, aplicativos e sistemas de software de maneira organizada e eficiente. É como construir uma casa, mas em vez de tijolos e cimento, os engenheiros de software usam código de computador para criar programas e aplicativos que são usados em computadores, telefones celulares, tablets e muitos outros dispositivos eletrônicos.

Experiência

Em quais atividades você adquiriu ou tem adquirido experiência em Engenharia de Software ou em outros tópicos da Ciência da Computação? *Por favor, marque todas as opções que se enquadram.*

( ) nenhum (nunca participou de atividades deste tipo)

( ) estudei em aula ou em livro (possui conhecimento teórico apenas)

( ) pratiquei em projetos em sala de aula (possui conhecimento teórico aplicado apenas no contexto acadêmico)

( ) usei em projetos pessoais (possui conhecimento teórico somado de experiências práticas individuais)

( ) usei em poucos projetos na indústria (possui conhecimento teórico somado de poucas experiências práticas reais)

( ) usei em muitos projetos na indústria (possui conhecimento teórico somado de muitas experiências práticas reais)

Tempo de Aprendizagem

Em relação à aprendizagem em Engenharia de Software, informe o período em meses:

Resposta:

Educação de Engenharia de Software

Em quais tópicos de Engenharia de Software você tem estudado? *Por favor, marque todas as opções que se enquadram.*

( ) Requisitos de software

( ) Design de software

( ) Construção de software

( ) Reutilização de software

( ) Teste de software

( ) Manutenção de software

( ) Gerenciamento de configuração de software

( ) Gerenciamento de Engenharia de Software

( ) Processo de Engenharia de Software

( ) Modelos e Métodos de Engenharia de Software

( ) Qualidade de Software

( ) Prática Profissional de Engenharia de Software

( ) Economia da Engenharia de Software

( ) Fundamentos de Computação

( ) Fundamentos Matemáticos

( ) Outro: _______________

Engajamento dos Professores

Considerando sua experiência em sala de aula, informe o grau de engagamento dos professores sobre as disciplinas relacionadas à Engenharia de Software.

( ) Muito engajados

( ) Engajados

( ) Nem engajados e nem desmotivados

( ) Desmotivados

( ) Muito desmotivados

Em sua opinião, quais são as principais razões dos professores não estarem engajados pelo o ensino de Engenharia de Software?

Resposta:

Metodologia de Ensino

Quais mecanismos (metodologia, software e/ou materiais) os professores têm utilizado para engajar as aulas de Engenharia de Software?

Resposta:

Quais são as principais limitações dos mecanismos (metodologia, software e/ou materiais) utilizados pelos professores nas aulas de Engenharia de Software?

Resposta:

H.3 Formulário de Execução - Para Estudantes

INFORMAÇÕES DO EQUIPAMENTO

Informe o sistema operacional que está usando:

Resposta:

Informe o quanto de memória RAM seu equipamento possui:

Resposta:

Acesse https://www.minhaconexao.com.br/ e informe a taxa de download em mbps:

Resposta:

Informe o navegador e sua versão:

Resposta:

RECOMENDAÇÕES

- Os procedimentos a seguir devem ser realizados em um desktop ou notebook;
- Verifique se todos programas/aplicações estão fechados;
- Verifique se estão instalados o Discord e o navegador Chrome ou Firefox;
- Realize os passos definidos na próxima página.

TAREFAS

1. Acesse o link **https://evaluation.d32btx1ycdzig0.amplifyapp.com/** em outra janela do navegador de sua preferência;
2. Você tem até 10 minutos para explorar livremente a plataforma;
3. Acessem o mesmo mundo virtual;
4. Elaborem juntos um diagrama de classes de análise que reflita o seguinte cenário:

- Um professor ministra várias disciplinas e cada disciplina pertence a apenas um professor. Cada disciplina fazer parte dos alguns cursos. Além disso, cada turma é composta por alunos.

5. Após concluirem a tarefa anterior, prossigam para a próxima página deste formulário.

H.4 Formulário de Execução - Para Professores

INFORMAÇÕES DO EQUIPAMENTO

Informe o sistema operacional que está usando:

Resposta:

Informe o quanto de memória RAM seu equipamento possui:

Resposta:

Acesse https://www.minhaconexao.com.br/ e informe a taxa de download em mbps:

Resposta:

Informe o navegador e sua versão:

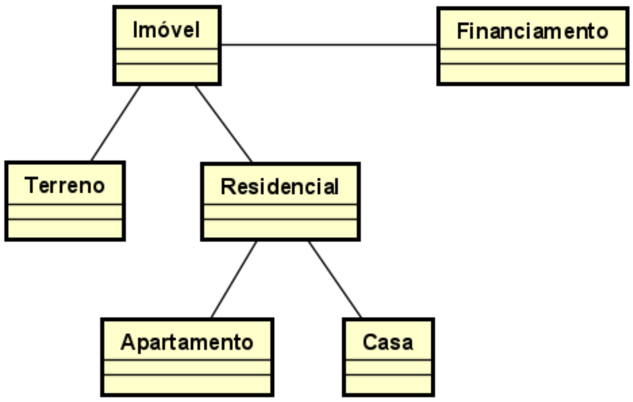
Resposta:

RECOMENDAÇÕES

- Os procedimentos a seguir devem ser realizados em um desktop ou notebook;
- Verifique se todos programas/aplicações estão fechados;
- Verifique se e o navegador Chrome ou Firefox estão instalados;
- Realize os passos definidos na próxima página.

TAREFAS

1. Acesse o link **https://evaluation.d32btx1ycdzig0.amplifyapp.com/** em outra janela do navegador de sua preferência;
2. Você tem até 10 minutos para explorar livremente a plataforma;
3. Acesse um mundo virtual;
4. Elabore um diagrama de classes de análise que reflita o seguinte modelo:



H.5 Formulário de Avaliação

Prezado participante,

Essa é a última etapa. O objetivo deste formulário é obter seu feedback do ponto de vista de usabilidade da plataforma.

Eu acho que gostaria de usar este sistema com frequência.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Achei o sistema desnecessariamente complexo.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Achei o sistema fácil de usar.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Acho que precisaria do apoio de um técnico para poder usar este sistema.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Achei que as várias funções neste sistema estavam bem integradas.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Eu achei que havia muitas inconsistências neste sistema.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Eu imagino que a maioria das pessoas aprenderia a usar este sistema

muito rapidamente.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Achei o sistema muito complicado de usar.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Eu me senti muito confiante usando o sistema.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Eu precisava aprender muitas coisas antes de poder usar este sistema.

( ) Discordo totalmente

( ) Discordo

( ) Não concordo e nem discordo

( ) Concordo

( ) Concordo totalmente

Como foi a sua experiência na tarefa de criação de um diagrama de classes na plataforma?

Resposta:

Em sua opinião, quais funcionalidades devem ser implementadas para melhorar a experiência de aprendizagem em Engenharia de Software a partir de mundos virtuais?

Resposta:

Em sua opinião, quais são as VANTAGENS de mundos virtuais como apoio ao ensino de Engenharia de Software?

Resposta:

Em sua opinião, quais são as DESVANTAGENS de mundos virtuais como apoio ao ensino de Engenharia de Software?

Resposta: