# 1 Introduction

In the Netflix animated series Cyberpunk: Edgerunners (Cyberpunk, 2025), the main character attends courses at a prestigious academy that uses advanced technology to boost education and performance. The students gather in a room with Virtual Reality (VR) headsets and connect to the lesson, which is taught by a holographic (and probably powered by artificial intelligence) tutor. The episode does not show the lesson itself, the entire system fails catastrophically when attacked by malware, but the brief scene highlights the vision many people have of a futuristic classroom, one guided by advance technology and automatization.



Figure 1 Virtual Classroom in Cyberpunk: Edgerunners

Fosler et al, 2024 propose the term “post-digital classroom” to identify the characteristics and trends in education present in a world beyond the adoption of digital technologies. The purpose of this classroom is not anymore to introduce new technologies to students, but to implement them as an essential factor of the learning process. The post-digital classroom is interconnected, social and global. In this scenario, learning goes beyond the physical classroom because it is based on creating relationships between concepts and developing valuable skills rather than acquiring knowledge. It is also a classroom where information is detached from the physical learning institute, and access to facts and sources is, ideally, immediate, ubiquitous and democratic.

The classroom has also become hybrid. There is little distinction between network-based lessons and the face-to-face spaces associated with schools and universities (Goodyear et al, 2009). Hybrid and blended approaches blur the distinctions between learning in an online setting and learning in a classroom. In both instances, information is at hand in the network, students can easily connect to peers and mentors, distance and time constrains are less meaningful and knowledge is presented in a multimedia format that has a technological backbone needed to be created and shared (Rivoltella, 2008, Shank, 2005).

This thesis explores the use of technology in such post-digital classrooms, specifically, Augmented Reality (AR) within the context of mobile computing. Moreover, this research will analyse the creation of effective learning spaces, places where students can build, personalize and control all the activities they engage with (Gourley & Cliver, 2016). Learning spaces are interesting tools at the disposal of students because this are spaces that can exist outside the norm of a typical classroom, they are more fluid, less structured and can easily connect to other similar spaces (Nørgård & Hilli, 2022). The proposal of this research is that AR can be used to boost the way students build and interact with their own learning spaces and can also offer educators another option to be integrated in the construction of a lesson that capitalizes the characteristics of the aforementioned post-digital classrooms.

Within the field of Technology Enhanced Learning (TEL), AR and affine technologies were chosen as a focus of interest because of their intrinsic relationship with space. The initial example scene of Cyberpunk: Edgerunners serves to illustrate the collective idea of what can be achieved in the future with technologies like VR and AR: the possibility of creating and entire new space, suited for the needs of the classroom or the students. It is a space that is shared, in which information and interactions flow between users and that can be controlled at will by students and teachers. In reality, the technology is not quite there yet, especially in terms of fidelity and immersion (Hamad & Jia, 2022, Checa & Bustillo, 2020). What can be explored right now is the creation of interesting synthetic environments that facilitate or allow experiences that are not possible in the common classroom. This process is limited more by the creativity and expertise of the developer rather than by the technology, and therefore can be explored easier and in more detail.

AR, compared to VR, has a more direct relationship with the “real”, physical space and with the context of the user. Instead of an isolated immersion, AR creates a connection with the environment based on image detection, data and visualizations. This natural expression of the technology is where the value of AR can be explored in relation to the creation of innovative learning spaces. The technology not only has interesting capabilities for visualization and interaction, it also allows an easier implementation of shared, social components that can be used to build activities based on cooperative simulations, sharing knowledge and the creation of communities, all crucial elements for the construction of effective learning spaces (Blight & Crook, 2017).

The research is positioned then in the conjunction of these three fields: Learning spaces, TEL and AR. The guiding goal is to understand how students are using technology to learn, and how AR can be used to boost that process. AR shines at creating immersive experiences that can be shared with others and that consider the physical context of the user. I want to use this collaborative space as an educational tool that takes advantage of the inherent social aspects of learning, building and sharing knowledge.

No modern classroom is free of technology, the simple act of taking notes in a paper already implies a set of technological developments needed to put knowledge into written form. Networking and information technologies are just another set of tools at the disposition of any student. A personal learning space can be built around specific software tools, a lot of them now ubiquitous and almost indispensable in any learning activity: text processors, multimedia editing tools, web browsers and document readers, plus any specialized tool that the learning subject requires. But that learning space is also built around more elements, some of them equally indispensable for some students. People need a space to work, access to different amenities, access to textbooks, information and teachers. Some may need a quite space to concentrate, or, on the contrary, may need access to music, to snacks or to a separate place to periodically take a break. The construction of a learning space involves many different elements, some more technological than others, and its effectiveness is based more on the integration of those elements than in anything else. This research aims at identifying how to properly integrate AR in the construction of a learning space, which is already composed by a complex web of many other objects, tools and circumstances.

In the past I have explored the way different technologies can be used as part of those learning spaces, either with tools for online learning scenarios (Gil Parga, 2015, ch 3) or using VR to create a digital space to explore multimedia content (Gil Parga, 2015, ch 4). The current project can be seen as a way to expand on the work done before, identifying ways to adapt a different technology, to apply lessons learned and to explore new avenues of research. In particular, it is an opportunity to expand from personalized learning environments into social learning spaces, and explore the role of the community in teaching and learning.

It was clear in the work done previously and through some notable literature like Richards (2023, p. 46 – 48) and Long & Ehrmann (2005) that the construction of learning spaces is always mediated by the community around us, even when creating a space as personal as possible. Even nowadays that we live in as post-pandemic world and that we seek remote, personalized and secure ways of learning, it has become very clear that the social aspect of learning is a crucial element in the equation (Baber, 2021, De Felice et al., 2023). The aim of this research is to delve deeper into the social elements that influence the construction of a learning space, how the students negotiate the process of learning with others and the benefits of collaboration, as well as the challenges it conveys.

This is also a technological enquiry. Having explored VR in the past, it was clear that this family of technologies offer interesting advantages by using complex visuals, new forms of presenting information and more natural interactions suited for the exploration and experimentation with 3D spaces. They also present curious challenges, especially in the usability front. For instance, the public has not created yet a strong relation or consistent literacy with the technology (Özgen et al., 2021), which creates accessibility problems. And those technologies that leverage common and accessible platforms, like mobile devices, risk carrying with them problems associated with the excessive and pervasive presence of such technologies (Forsler & Guyard, 2025, Petrucco, 2021).

The following introductory chapter will expand this brief exploration of the context and motivation for the research proposed, outlining the main research goal and the reasoning behind the formulation of the selected research questions. There will be a brief exposition of the methodology followed to build possible answers, the significance of this research and why the answers to the questions proposed can provide important insights about the way we use technology to learn and how we design technological tools for the classroom. I will also provide a summary of the results obtained and the contributions achieved, as well as the scope and limitations of the work done. Finally, I will provide a description of the structure of this thesis document.

## Context

AR technologies are positioned somewhere in the middle of the reality – simulation spectrum proposed by Milgram et al. (1995), a model for display technologies used to show digital or physical data in virtual or synthetic realities. The main characteristic of AR in this spectrum is the incorporation of the real world as part of the visualization, making use of different image recognition and composition techniques to identify features in the physical space and overlay them with digital information.

Schmalstieg (2016) adds another layer of analysis to the description of AR-like technologies by using the ubiquitous computing spectrum proposed by Weiser (1991). The model positions different implementations of AR depending on the use of more static or more mobile deployment platforms. In one end of the spectrum are applications that can only be used in singular static terminals, while the other side contemplate platform-independent mobile technologies and ubiquitous systems. Figure 1 shows examples of this distribution as proposed by the authors.

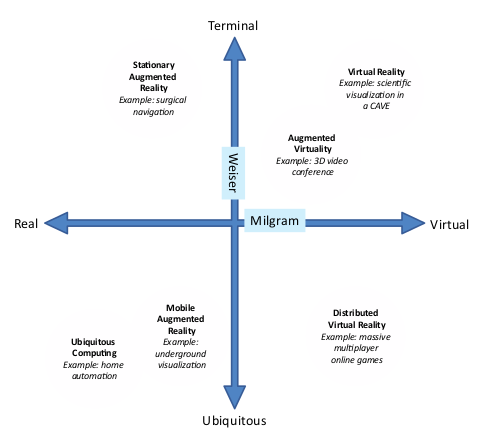


Figure 2 AR in the Milgram-Weiser Spectrum (Schmalstieg, 2016).

In this bi-directional spectrum we can find mobile AR as a family of technologies that offer an in-between mixture of virtual and physical elements in which location, place and context are additional inputs used for interaction with the synthetic reality.

Any technology in the spectrum will offer a variety of characteristics that fulfil one or more descriptions at a time. Mixed Realities, for example, are seen as an extension of both VR and AR, offering seamless interaction and connectivity between the real and the simulated world. It is a blurry line that often must be analysed in a case-by-case approach. No matter what label is used to describe a technology, some agreed upon characteristics mut be present for it to be categorized as AR, as stated by Azuma (1997):

* A combination of real space and digital information.
* Interaction with the simulation in real time.
* The simulation is done in a 3D space.

With these descriptors it is possible to position the used of the technology in different fields, independent of the labels used to identify it. Based on the themes introduced in the opening statement of the chapter, the goal is to analyse AR as software for cooperative work (CSCW). For this task, a useful analytical tool is the classification of CSCW technologies propose by Rodden (1991) in terms of the point in time and space where the collaboration is taking place. Figure 3 shows examples of different systems that can be found in each quadrant of the classification, which define if the activity is synchronous or asynchronous, remote or co-located.

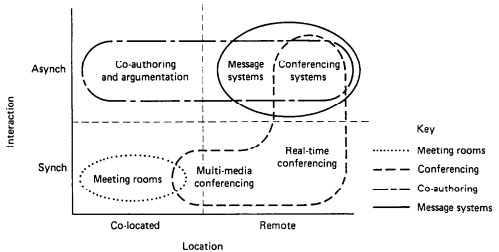


Figure 3 Classification of CSCW Systems

Complementarily, Kiyokawa et al. (2002) offer two important elements present in a collaborative activity: communication and tasks spaces. In the communication space, people exchange information and can sustain formal and informal conversations. In the task space, the actual cooperative work is done. Those spaces can be unified or separated, and they can be physical, virtual or in a mixed state. Independent of the nature of each individual space, both need to be present for collaboration to succeed.

Based on these classification models, it is possible to define the main field of interest of this research as the use of AR in a mixed task space for face-to-face collaborative learning, which implies synchronous activities in a co-located space. In this setting it should be possible to use the capabilities of AR for visualization and interaction with the physical space to “augment” the collaboration process in terms of:

* Activities related to the communication space, the flow of information and the creation of knowledge in the group.
* The use of the physical space as an asset in the collaborative process.
* Management of the collaborative process itself and the structures that can be created to facilitate effective teamwork and cooperation.
* Guidelines to acquire and refine skills related to teamwork and collaboration.

The main proposal is that the unique characteristics that AR provides in the field of Mixed Realities are well suited to experiences in co-located collaboration, and that a learning design that is using a collaborative approach can benefit from and AR tool mediating in the communication and tasks spaces of the activity.

The interest in collaborative learning derives from the analysis of the use of AR in education and the tendencies identified in the available literature. It was possible to note that AR is often used as a tool to explore concepts and practices in hands-on approaches that apply previous knowledge in different situations and contexts. Unfortunately, the technology is seldom used in cooperative scenarios, despite the tendency to use mobile platforms for deployment (Gil Parga et al., 2023).

Collaborative learning is a subject rich in discussion. The conversation can focus on the benefits of groupwork in the classroom, highlighting aspects related to better exposition to different points of view, more complex understanding of a learning topic and an integral development of students (Van Wyk & Haffejee, 2017, Smith et al., 1992). On the other hand, the challenges associated with collaborative work are also amply explored (Baloche & Brody, 2017. Popov et al., 2012, Buchs et al., 2017), and there is plenty discussion around issues related to classroom management, inclusivity, effective assessment and good practices.

Many studies have identified and compiled the advantages of using AR and MR as learning tools. For instance, Penn & Rammarain (2023) offer an analysis of the educational foundations used to design learning interventions. They conclude that most projects converged into constructivist foundations and embodiment theory, opting to create spaces for students to experience and explore the learning subject, with an emphasis on immersion, practice and hands-on interactions. Despite these commonalities, the authors also remarked that most reports do not mention explicitly or do not rationalize the theoretical background of the intervention. They also note that a lot of researchers still hold the idea that introducing a new technology in the classroom is enough to reap its benefits, without caring to build or follow a proper integration plan.

This issue acquires even more relevance now that the mediation of different technologies in the collaboration process has grown due to the Covid-19 pandemic, which forced a quick and often poorly-planned implementation of remote learning (Drueke et al., 2021, Nuere et al., 2021). Over time, this prompted the re-design and re-thinking of how to use technology to support the sudden disruption in learning methodologies and approaches (Fischer et al., 2020, Adi Badiozaman et al., 2020). The forced isolation also highlighted the importance of social spaces in the constructions of learning environments, and the need to provide those social interactions even in online spaces (Walas-Trębacz et al., 2025, McInnerney & Roberts, 2004).

The post-pandemic classroom is dealing now with the need to balance the advantages of online spaces with the problems associated with socialization solely mediated by technology, which tends to be asynchronous and impersonal. There is value in the physical space for the learning process (Petchamé et al., 2021, Thai et al., 2020, Paechter & Maier, 2010), and a technology that is able to connect the physical and the digital is worthy of a deeper exploration to identify proper approaches and successful use cases.

The idea is not to oversimplify the presence of digital technologies in the classroom, nor follow a misguided tendency of selling all the benefits of a technology without acknowledging its problems. If the proposal is to identify the effects of a collaborative learning design mediated by AR, it is important to also identify all the problems that derive from this approach, either because of the issues that naturally come from teamworking scenarios in the classroom or the negative behaviours that the excessive use of digital technologies promotes, especially in the specific environment of mobile platforms.

With that context just detailed, it is possible to summarize the goal of this research as: The construction of an AR tool that serves as aid in a collaborative learning setting by providing help to students to communicate and develop teamworking skills by means of interactivity, visualization immersion and augmentation of the physical space. The following section will expand this idea by providing and introductory analysis of the research structure use in the development of this project.

## Research Structure

The main goal of the research is to develop and AR solution for a collaborative learning environment. By using the definition proposed by Schmalstieg in the Milgram-Weiser spectrum and the classification of collaborative activities exposed by Kiyokawa, the goal can be stated as building a mobile AR software that mediates and helps students in co-located collaborative activities. This goal is justified by an abundance of literature showing the elements of AR used in the past to offer distinctive value for learning, and the open opportunities to explore and understand better the development of multi-user AR experiences for learning and collaboration. The nature of the proposal implies that the research has two main fronts:

* In the **technological** front, the goal is to build a software solution that considers the development challenges of an AR tool in a multi-user and multi-platform environment, and the specific requirements derived from the learning goals proposed in the educational front.
* In the **educational** front, the goal is to identify, describe and develop a case study based on collaborative learning using, and to analyse the behaviours that students develop when learning in a collaborative environment mediated by technology, comparing the use of AR with other tools or approaches.

### 1.2.1 Research Questions

The guiding research questions of this project are aimed at obtaining information of what constitutes an effective collaborative learning design using AR. The answers can be stated in terms of learning goals, interaction design and integration plans with the classroom. The questions also seek information about how AR is creating an effect in the behaviour of the students while using the tool for learning. These behaviours can be related to communication, socialization, planning and engagement with the learning material. The main research question will be stated as follows:

**MQ:** How does the behaviour of a group of students changes when using an AR tool designed to aid in the achievement of a learning goal framed in a collaborative learning scenario.

To guide the implementation of the tool through a strong design, a lot of information can be extracted from current literature and from previous projects using similar approaches. Information gathered from real and incremental usage off the system also offers valuable insights in terms of usability, viability and end-user perception. With this in mind, an iterative development process is proposed to facilitate the exploration of ideas regarding interaction design and fitness to the learning scenario where is going to be used.

The implementation of the tool alone is insufficient to answer the main question. For this purpose, a case study research methodology is proposed with the objective of identifying and describing a strong context in which collaboration is used for learning and in which the implementation of the AR tool can be contrasted and compared to other approaches. In this context it is also easier to observe more natural behaviours from the students and the observations will show results closer to how the tool could be used in a real deployment.

It is very important to carefully select a case study that not only offers unique circumstances valuable enough to be analysed in detail but also has the proper learning context to explore the themes of interest of this research project. Although the specific learning field of a prospective case study is not that important, it needs certain characteristics, independently if it is developed through a single activity, a section of a course or through the whole course. The case study must incorporate all the following elements:

* A clear learning goal, either as a whole or as a step to achieve a more complex goal. Assessment activities alone are not enough because the research objectives require the observation of collaborative learning, not the development of a single teamwork activity.
* A collaborative approach to the learning activity. Students must be expected to work in groups to achieve the competition of the task, or at least, to have access to a space for collaboration in the development of the activity, even if it is individual in nature.

Ideally, the case study also contemplates the process of learning to collaborate, either as its own learning goal or willing to implement such an objective as a secondary goal. This is not essential, but the current proposal borrows a lot of elements from learning designs about developing collaborative skills. If the selected case study already seeks learning objectives in this venue, then the proposed intervention could offer more value.

Is with these requirements in mind that I consider that the selected case study offers an excellent opportunity, not only to experiment with the proposed thematic of collaboration and technology mediated learning, but because it is also a unique and interesting context in terms of learning design and the opportunities for coordinated teamwork, project development and innovative use of technology.

The Industry Project course of the Built Environments program is a complex scenario that provides students with opportunities to develop industry-level skills through a project-based approach. It presents the opportunity to intervene in the whole course and to use the software solution proposed across different stages of development of the course and different learning objectives, an ideal scenario for varied observations and a rich space for experimentation and discussion.

A set of secondary question can be described that will help to focus the data gathering stages of the research, especially those related to the observations and activities in the context of the case study. In relation to the use that the students could give to the AR software proposed, it is important to ask:

**SQ1:** What differences in behaviour can be observed between students collaborating using the AR tool and those that are not.

**SQ2:** What differences the students report in their perception of the activities done in the course between those using the AR tool and those who are not.

**SQ3:** How does the collaboration and communication process change between students using the AR tool and those that are not.

**SQ4:** What differences can be observed in the end results of the course between all the different collaborative approaches observed, especially of those that incorporate the AR tool.

The focus of the observation process should be in identifying behaviours and processes rather than only differences in the end results, that is, the final assessment of the course project. Relying solely on possible improvements to grades or assessments can be a valid but flawed tool to understand the effects of a technology in the classroom (Katz et al., 2017, Dalziel, 1998). Additionally, the selected case study proposes a complex course to analyse, where several and diverse factors influence the work of the students. Taking this into consideration is why a positive or negative result does not tell the full story and why is more important to observe the whole learning process, from planning to development, documenting the behaviours developed to fulfil tasks and reach goals. The objective is to identify if the AR tool proposed is an influence, either positive or negative, and if it provides a more meaningful impact to the learning process as a whole and not only to the end assessments.

Assuming there are actual substantial differences between the students using the AR tool and those that are not, then it is also important to ask:

**SQ5:** What elements of a technological intervention using AR create the most impact in changing the behaviours, perceptions or results of the students.

**SQ6:** What elements of a multi-user AR tool creates the most impact in changing the behaviours, perceptions or results of students collaborating and communicating in a learning scenario.

These last questions are meant to provide an evaluation to the decisions taken in the development of the AR tool, especially the multi-user interactions, and how the tool was integrated to the learning design of the course. It also offers the possibility to highlight elements of the tool that could be polished or reframed in future work.

### 1.2.2 Scope and Limitations

Using a case study methodology, it is possible to approach the research questions through a qualitative lens, which is better suited for understanding the information gathered in relation to behaviours, relationships developed between students and their subjective perceptions of the course, the activities developed, and the results obtained. All those elements would be hard or contra productive to try and quantify. In this light, it is important to acknowledge the limitations in scope and reach derived by the selected methodologies.

In relation to the software development aspect, it is important to establish the scope of the product as a prototype that explores the ideas of collaboration and multi-user AR. A thorough analysis of the design and architecture of the software was conducted to describe different possible approaches and solutions suited to the context and the needs of the tool, keeping an analytical mindset for all the ramifications and consequences derived from the implementation of a particular idea or design.

In terms of the concrete implementation of the software, the work was undertaken by a sole developer and limited in time and resources related to access to the case study. Most of the design and architectural proposals were tested via mock-ups or wireframe prototypes (Coleman & Goodwin, 2017, Sutipitakwong & Jamsri, 2020) in pseudo-structured test scenarios, aiming primarily for quick feedback and impressions rather than structured data. This allowed constant iteration and exploration of different ideas. The final implementation of the software prioritized showing the most critical use cases and the most relevant interactions with the tool, most of them tailored for specific observation sessions. Free use and exploration of the complete tool in the classroom was only possible in the last set of observations.

This approach had an important influence in the structure of the observation process and the nature of the data gathered, fomenting a more guided use of the tool and a more structured response from the participants rather than the free observation initially intended. This was an acceptable concession made to facilitate the development process and to give the participants early and consistent access to the tool, albeit in a more incomplete state. This also minimized the disruption to the students’ academic work while maximizing the opportunities for meaningful observation in the available time.

There is also an inherent problem in the development of a case study in relation to the applicability of the results, generalization and subjectivity. The Industry Project course was chosen because it fulfilled all the characteristics needed for the research, but convenience aside, the course also provides a unique opportunity to analyse a collaborative learning design in action, with scenarios that could be extrapolated to other similar contexts, but also a unique take on the design of project-based learning and assessment, as well as a complex context for implementation and challenges that had to be tackled, all elements worth of a detailed analysis.

Nonetheless, it is important to identify the limitations of using one sole case study, which can be summarized as issues with the transferability and applicability of the data gathered. Other factors that impact heavily the nature of the data are the overall seniority of the students, which were all close to finish their studies and the lack of a concrete study plan of the course, which focused more on the development of the project as its main teaching instrument, offering just a relatively vague and general set of learning goals.

The chapter dedicated to the description of the research methodology will describe in more detail the scope and limitations of the case study, as well as the measures taken to minimize or acknowledge the flaws and restrictions of the chosen framework. For now, these issues can be summarized the main limitations related to focusing the software development into a gradual an iterative progression of a prototype and the validity of the case study in terms of the characteristics needed for the research and the unique value it offers for analysis and discussion.

## 1.3 Significance and Contributions

The technological environment in which we found ourselves right now evolves rapidly and at large steps. Despite critics of stagnation, the classroom evolves and adapts in response and constantly tries to understand how the available technologies can improve the way we learn (Watters, 2021). It is not always a positive relationship, it is often marred by overselling products and forcing a technological implementation without a plan and a proper consideration of the context and needs of the classroom (Odunaike et al., 2013, Cochrane, 2012). Currently, it is also a field that experiences a lot of social scrutiny as we react to the idea that we have become somewhat addicted to digital content and to the devices used to consume it (Liu et al., 2022, Gui & Büchi, 2021).In a context in which we are banning the use of smartphones in the classrooms and obtaining somewhat positive results because of it (Rahali et al., 2024), why, then, rely on a proposal that fundamentally uses that technology?

As Murray & Perez (2014) stablish, exposure to technology does not equal comprehension. In an age in which almost all aspects of life are mediate by digital activities, it is important to create a positive, critical and informed relationship with the technology that we have to use in our daily lives, and that relationship does not develop naturally (Selwyn, 2009, Margaryan et al., 2011). This is a task that can and should be executed in the classroom at different levels of schooling, in different contexts and at appropriate age and field depths. The classroom is the ideal scenario to create and nourish this relationship in a structured and positive way, yet this is a factor that is seen as lacking in education institutes, especially in middle and high school (Burton et al., 2015, Jeffrey et al., 2011).

This project is an exploration of that philosophy, and an experimentation with technological design that uses mobile devices in a healthy approach that promotes the development of skills needed today. Although I firmly believe in the capacities of AR as a learning tool, this endeavour needs to follow a due process. It is important to properly understand how to use the technology and what elements of the design and implementation process need to be highlighted and worked on to create that intended positive impact. The technology does offer a big opportunity to enhance and reframe the way we communicate and work together, but it also has proven to impose certain challenges that have to be analysed, understood and dealt with.

Over the development of this document, I will describe the proposal, design, implementation, observation and analysis activities done in the development of an AR tool for collaborative learning and the test deployment conducted in a case study showing a pedagogical design focused on developing skills related to teamwork and effective communication.

The development of this research was carried in two interlocked steps. In one hand is the design and implementation of the software CollabAR, an AR tool used as a companion in the face-to-face work that was part of the activities proposed for the Industry Project course. Specifically, the software was used during the weekly group sessions of work that the students held for the development of three different assessment milestones in the course-long project.

The development of CollabAR consisted in solving two main issues, both related to the technological front of the research. First, there was a design challenge that required identifying the most common interactions performed in and AR environment for cooperative work. Different use cases were identified that were unique for this context and that posed an interesting design challenge, like sharing information, sharing and coordinating resources, managing the status of the team and coordinating the development of a task. A user-centred interaction design process was used to outlined solutions for the identified use cases which considered important restrictions and particularities of the problem such as the synchronous input of the participants, the physical space in which the activity is taking place and the possible diversity of control schemes between platforms.

This stage was accomplished through a detailed exercise of user-centred design, a process meant to identify ideas and decisions born from the direct interactions of the users with prototypes and mock-ups, a structured process for gathering feedback, integrating the user in the design loop and refining ideas in an iterative process. The results obtained highlighted interesting issues and ideas related to multi-platform interactions, the expectation of users when presented with familiar and unfamiliar controls, complications related to interactions in a 3D space and the integration of the tool in the overall workflow of the students.

The second focus in the development of CollabAR was the technical challenge of creating a multi-user, shared AR space. Several commercially available frameworks and APIs were explored, such as the ARFoundation suit provided by the Unity game engine and the Lightship API provided by Niantic. It was possible to extract valuable insights about the current state of the development of AR tools, especially in the field of education, and it was possible to describe the lessons learned while integrating the development process of the tool with the educational goals of the course. An effort was made to relate the results obtained to those reported in similar studies by identifying common and divergent results and issues, especially those related to finding the technology distracting and the technical development of the tool too detached from the role of the educator.

Parallel to the construction of CollabAR was the development of the case study and the design of the intervention of the Industry Project Course. In the design phase, the course was analysed based on the written material available and on interviews with the teaching staff. This information was used to guide the development of CollabAR and to identify the instances in the progression of the course in which the intervention could create more impact without disrupting too much the academic activities of the students. It was also an opportunity to detail and analyse the learning design of the course and to understand the context in which the observations were going to take place.

During the observation phase it was possible to immerse myself in the full execution of the course through 16 weeks of work. I was able to act as a guest in the teaching staff and interact with the students even when not directly making observations of the tool. I was also able to collaborate with part of the execution of the course by helping in administrative activities and advising students in issues related to team management and efficient work planning. This situation enabled me to have detailed observations of the work done by the students with and without the AR tool, to observe the development of the project through the conception, design and implementation phases, to adapt elements of the tool to better suit the circumstances of the course and to observe the role of the teaching staff in the development of the course and as part of the usage of the tool. This helped to create a rich record to report in the case study and plenty points of analysis and discussion.

The analysis phase used the recorded information from observation stage plus all the material that could be recollected from the execution of the course. This material included the written communication given to the students via the official channels of the course, the workshops executed during the semester as material to help in the development of the project and the final products created by the students, such as presentations, reports and designs. The observations were also complemented by a set of semi-structured interviews to the students and the teaching staff. The interviews focused on gathering better records of issues related to the personal perceptions about the use of technology and the collaborative activities of the course.

From the observations obtained and the analysis of the results it was possible to formulate some possible and satisfactory answers to the research questions. The data points to interesting behaviours promoted by the intervention, such as students creating a more structured work process when the tool prompted or encourage them to do it. It was also observed that this enforced structure helped the students with the organization of activities, prompting good practices for communication and the organization of ideas and plans.

But the structure also prompted some unintended behaviours, like a tendency to create a hierarchical organization of the group around the student managing the tool, which was not in tune with the objectives of the course. The app also forced the students to be aware of their phones more than they were planning or willing to do, highlighting a current trend among students of regulating their phone consumption. It was also noticed that the tool was most useful for teams struggling with their organization and offered little value for those already with a clear work plan.

Data and observations also provided a lot of insights related to the design of collaborative interactions in virtual 3D environments, to the relationships of students with their phones and how students use different resources, properly or not, to sort out the difficulties of a learning project. The case study also opened an unexpected opportunity to analyse the role of the teaching team in the use of the tool, offering a clear path for future work.

## Document Structure

The purpose of this document is to provide an organized recount of the development of this research work, the theoretical background that supported the proposals given and the methodology followed to gather data, analyse it and build a set of answers for the research questions.

This introduction chapter was meant as a summary of all these elements, highlighting the personal motivations behind the chosen research field and the general reasoning that accompanied the design process, the hypothesized and desired results and the methodological pathway taken. Chapter 2 of this document will describe in detail the literature explored that helped in shaping the research questions and that provided the theoretical basis for the educational methods used as anchors for the software implementation.

Chapter 3 details the methodological framework of the research. It briefly explores the research paradigms picked to guide this project and explains the reasoning for choosing them and their relevance to the learning and technical fields this project is based on. The chapter will also offer a complete explanation of the educational front, detailing all the instruments used in the development of the case study. In the technical front, it details the software development methodology followed, especially the reasoning and procedures used for the interaction design process and the methods used to ensure usability, flexibility, expandability and a general user-centred approach.

The description and analysis of the results have been divided in two chapters. The technological front has been described in Chapter 4, where a detailed explanation of the requirement analysis can be found, including use case scenarios and quality objectives. The chapter also details the most relevant elements of the design process, the architectural solutions proposed for the tool and for the interaction design. There is also a general focus on describing the changes or decisions that were made because of the direct test with users or as a response to specific situations of the case study context.

The case study itself is described in Chapter 5, explaining the context of the Industry Project course, the teaching objectives guiding its design and the points of interest for the intervention using CollabAR. The chapter will also provide a narrative description of the observations taken over 16 weeks of development of the course, and a preliminary analysis of the data based on the secondary material extracted from the course, like the written documentation, the work produced by the students and the information gathered from the interviews.

The final analysis is presented in Chapter 6, where I will draw the necessary conclusion gathered from the data and the process described in the previous chapters to propose a set of answers for the research questions. The chapter will detail what elements of the development of CollabAR and the case study supports my proposal of AR as a tool to promote positive learning behaviours and effective collaboration, what important technological hurdles were identified and what surprises were found during the development of the project. The chapter will also offer and outline for future proposals to address the most important issues derived from the research limitations and the problems encountered during the development of the project.