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Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

VIRTUAL REALITY TO ENHANCE SAFETY AND HEALTH IN CONSTRUCTION

ONLINE MULTIPLAYER SERIOUS GAME.

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TREBALL FINAL DE GRAU

This project wouldn't have been possible without the incredible help of Tamas Lovas, Ignacio, Javier and Oscar, thanks for all the hours of patience.

To my mum and dad for coping with me when I was frustrated.

To Carol and Tobi, my two beacons of responsibility and irresponsibility in the best year of my life.

Thank you all.

ABSTRACT

This project is a collaboration with CIMNE in order to develop a Virtual Reality serious videogame with the objective to supply the lack of practice in the courses for students for workers in the construction sector, in the field of safety and health, given that nowadays most of the training is based in traditional methodologies such as master classes and paper learning material. As new paradigms like BIM come out to the industry -to name one of the most representatives-, or technologies such as augmented reality or virtual reality, we wanted to make them taken in account in the future learning methodologies and material. Our approach to this implementation consists on a 3D immersive video game that allows two players to make certain activities –like transporting material or building a wall- while trying to follow all the safety protocols and interact with A.I. bots and machinery. Although several precedent initiatives have been done to explore the possibility of joining VR and safety and health, the innovative online multiplayer component makes it a much versatile tool, which can be used in and outside the classroom, accessible to everybody thanks to new 3D technologies for most of mobile devices, which opens a whole new wide open range of possibilities for the future, given the introduction of the interaction with other students/users, A.I. bots, machinery, and the visual application of the safety measures such as helmets, earmuffs and harnesses, that improve the communication between players and give an extra step towards realism. Although in the end the VR feature was impossible to be added due to compatibility problems with the Networking system that were too difficult to solve within the tight schedule, possible solutions for that are provided, and many future lines of investigation can be started form this point, such as collaboration between numerous players, competition, time efficiency training, realistic complex tasks for teams, and many more.

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MOTIVATION

There are four main reasons that lead me to the decision of starting this project. To be honest, I never expected to be doing something like this, but after all if you embark on an adventure such as this, into a field that reaches far beyond your expected knowledge, it better be something that you enjoy:

- First of all, during my student years in UPC I learnt that due to different facts –such as the construction bubble or its posterior crisis- the safety and health technologies on the construction sector never upgraded at the same rate as they did in other sectors. The opportunity to try to change that was a challenge that I wanted to accept.
- In a more personal and subjective way, the second reason is that I loved videogames as a child, and I still like them now. I never had any console of my own, but when I got the chance to play as a kid in my friends' houses, I always had a blast. So when the opportunity to learn about videogame technologies came to me, I was thrilled. There is something that I think most of the kids have told their parents at least once, and it is: "When I grow up I want to develop videogames". Well, that was probably my only opportunity to fulfil this dream, and even more if it is in something as innovative as Virtual Reality.
- Moreover, on autumn 2016 I made a short A1 Revit course to start to learn about BIM technology, and this TFG seemed like a good way to refresh all the BIM concepts that I had forgotten, even though at the end I just had to open the program once or twice.
- And the last but not the least, this project allowed me to learn the Unity engine software and to code in C#, which although it sounded like a huge challenge, I was sure that at the end those would be good skills to have in my pocket.

Finally, I wanted to make this tool a realistic alternative to the passive learning that the students for workers have to take nowadays, given the fact that most of work prevention aspects are learnt at the building site and not in the classroom. Getting the workers to gain their experience on safety regulations by VR instead of putting themselves in a real risk environment is a step forward in the sector that can prevent a lot of accidents.

For all of these reasons I started this journey on an uncharted world for me, and in the end, I was glad to see that I met again the 14 year old kid I still have in me.

CHAPTER I

INTRODUCTION

The formation of construction workers in safety and health has followed the traditional principles of education during decades and most of the training in the field is built on methodologies of master classes and paper-based learning material. Although there is a consistency below the organization of the topics, the construction workers need to gain their experience in safety and health in the construction site. This is a risk, because the workers will only get their experience if they start working, and at that point they are inexperienced, leading them to making mistakes and being vulnerable in situations that more seasoned workers would handle safely. The alternative to taking that risk is to have laboratories for practical explanation where students can get themselves acquainted with the risks of the construction site while being totally controlled, and therefore gain the necessary practical knowledge to start their jobs, but nowadays in Spain there are only a couple of centers – "Centro de Prácticas Preventivas" of "Fundación Laboral de la Construcción" in La Rioja and "Instituto Tecnológico de la Construcción" of "AIDICO" in Valencia-, and the majority of students have no access to it.

Therefore, the main goal of this work is to recreate a 3D environment in virtual reality technology featuring the most common risks in the construction site, where the students will have the task to make certain activities while following the safety and health rules. It will have a building in construction imported from Revit and a realistic environment feeling with the application of stereo sound, textures, materials and animations.

This goal can be split in other secondary objectives:

- Review the current critical issues for safety and health in construction in terms of training.
- Evaluate how VR experiences can improve the effectiveness of the formation in safety and health.
- Recreate a 3D construction site environment in Virtual Reality, including Collective Protective Equipment (CPE), Personal Protective Equipment (PPE) and dynamic machinery.
- Include different agents (other users/workers/practitioners/students) in the virtual building site, with capabilities to interact with them by using multiplayer and AI bot features.

- Include collaborative aspects for the multiplayer system and in the VR experience.
- Test the application both technologically and functionally.
- Make this application easily accessible for all the students through regular mobile devices.

The document is structured in the following way:

- Chapter 1: It is where we find ourselves now. It includes the *motivation* of the study as well as the *introduction* where all the aspects of this project are displayed.
- Chapter 2: It is a background. It breaks down all the key concepts regarding the *digital world* –BIM and digital twin-, the state of the *safety and health courses nowadays*, a dissertation between the benefits and disadvantages of the *experiential learning vs guided learning* and an introduction to *virtual reality*, including a short economic analysis of its possible impact in the economical field.
- Chapter 3: This chapter includes a summary of the *technological Unity key features for VR experiences in construction*, along with a slightly more technical approach that explains the innovative features of this project, as long as its *methodology of implementation* with a step by step structured analysis and an explanation of all the problems found in the way.
- Chapter 4: Here is where *Virtual Reality Experience* is developed, with an explanation about the integration of the main features and innovation, videos of its testing and results, the construction site map and some in-game captures. It also includes the description of my experience in the *ORP Congress in Cartagena de Índias, Colombia*, where I was part of the team of CIMNE presenting in it.
- Chapter 5: Finally in this chapter the *conclusions* are presented as well as some potential *future lines of investigation*.

CHAPTER II

DIGITAL WORLD

Building Information Modelling

The Building Information Modelling (BIM) is a methodology of work in the construction sector based on the use of digital systems that allows the user to gather all the information of a project and use it to analyse and effectively manage all the life cycle of a building, from its initial phase with the design to the demolition, always with a full collaboration between the different parts involved in the process.

The name comes from the following reasons: [1]

- Building: Referred to the complete life cycle of the building. All the phases of the project can be considered in BIM, from Urbanism, Project and Constructive Phase to Rehabilitation and Demolition.
- Information: Probably one of the key points that make BIM so powerful in its field of action. All the information gathered during the project can be an input that includes blueprints, energetic calculus, structure analysis, bills, 3D views, maintenance of the building, etcetera.
- Modelling: It is a model where all the different aspects of a project can be worked with: Architecture, Structure, Urbanism, Economic Viability...

The BIM technology is the process of generation and management of the building's data during its life cycle, using 3D modelling softwares and in real time, to diminish the loss of time and resources in the design and construction. All this powerful tools are at hand for all the stakeholders involved in a project:

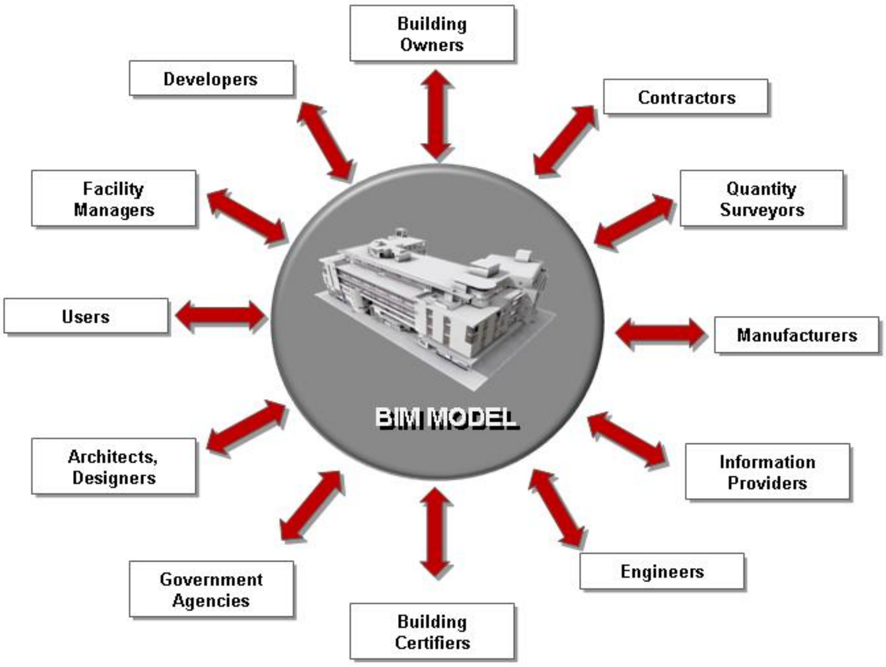


Figure 1: Stakeholders involved in a BIM project [R.R. López, Introducción al BIM]

BIM systems can unify or link an architectonic model with all the other features of a building like the energetic studies, structures, topographic maps, etcetera, making the coordination between teams much easier and saving time and money, thanks to a cloud save system that can be accessed and modified in real time.

With this type of models we leave behind the 2D models with lines and layers, and we enter in a 3D perspective with groups of constructing elements with their properties and characteristics, such as colour, price, weight... Nowadays BIM systems recognize a door or a wall as an object and not as a set of geometrical entities when we draw them, making the softwares and the project's visualization much more intuitive and rich.

Several countries have already understood the advantages of the use of BIM in their public projects to save money, time, and meet the environmental expectations according to the 21st century. Here's a list of some of them: [2]

- Germany: BIM is required for projects worth more than 100M € since 2017.
- Australia: BIM is required for all projects since 2016.
- Denmark: BIM is required for any project worth more than 2,7M€ and any public project worth more than 677.000€ since 2011.
- South Korea: BIM is required for projects worth more than 50M $.

- Catalonia: BIM will be required in 2018 for projects worth more than 2M €.

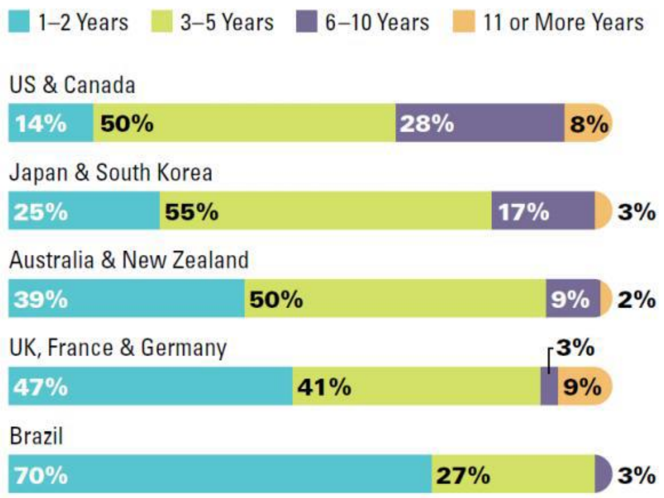


Figure 2: Length of Time contractors have been using BIM (by region/country) [McGaw Hill Construction, 2013]

BIM works in a level organization. The UK government accepted this methodology to represent the grade of collaboration and cooperation in projects to fully take advantage of all the capacities of BIM. It's obvious that the way of working in the construction industry cannot change overnight and that some transition time has to be done. Also the old and new generations have to be trained, and this process takes time. These levels can be understood as milestones in the process to reach the full cooperation. The levels have been ordered from 0 to 3, and although there's a bit of debate over which are the limits of each one of them, they can be defined as the following: [3]

Level 0: Work state where there's no collaboration at all. The drawing and representing methods are in 2D, and the communication is done with blueprints and paper. The technology used is CAD.

Level 1: Mix between 2D and 3D works with CAD. The 3D has the aim to show the project in a more visible and understandable way, and the 2D is used to hand in the project's documentation, from a more technical and detailed point of view, in order to get the project approved. This is the level at which many companies are operating now, although there is no significant cooperation between parts and all of them work with their own information.

Level 2: It introduces the collaboration between parts which is the key to the BIM. Everybody works with their 2D-3D in CAD or BIM projects but no necessarily under one same shared document on the cloud. Every software used though, has to be capable of be exported by means of a standard type of data exchange archive, like the IFC (Industry Foundation Class).

Level 3: Total interoperability and cooperation between stakeholders in a single shared model in the cloud, accessible from any part of the world. This level is also known as OpenBIM, and UK aspires to reach it by 2025.

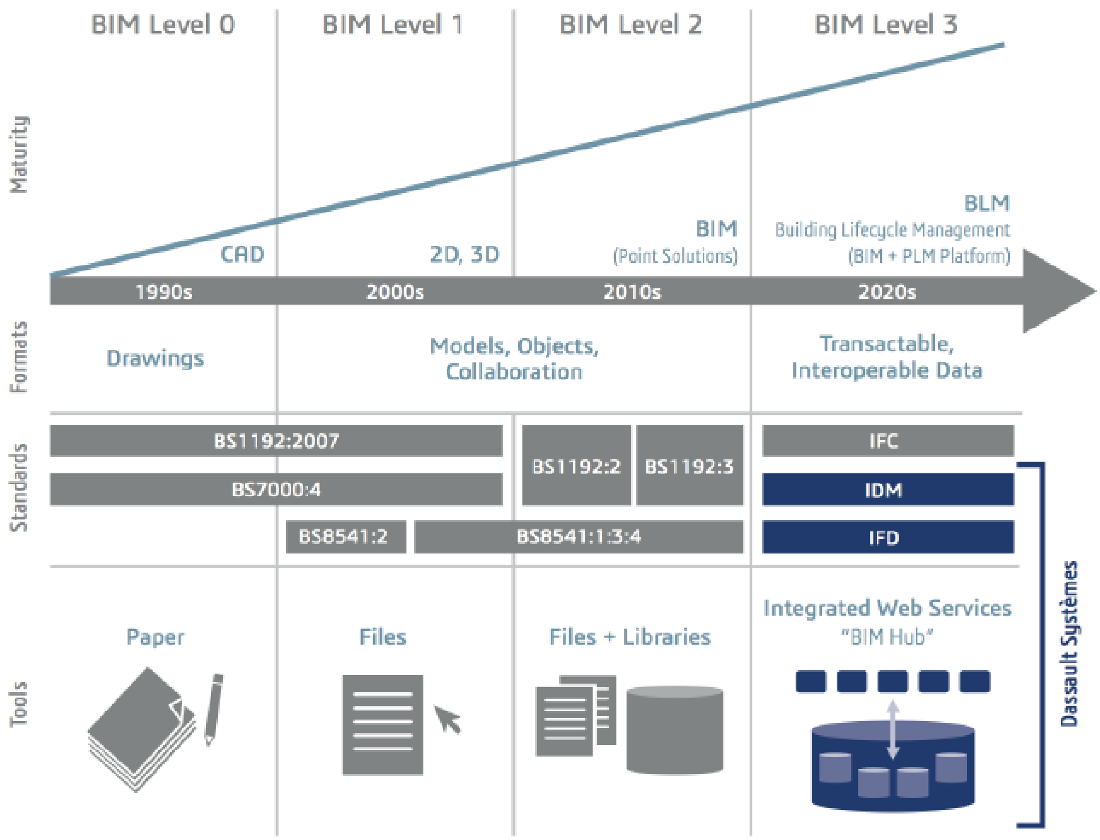


Figure 3: Model showing the evolution in the BIM levels regarding Formats, Standards and Tools. [R.R.López, Introducción al BIM]

Digital Twin

Digital Twin is a technology based on virtual replicas of objects or processes that simulate the behaviour of their real counterparts [4]. Its objective is to analyse its performance in certain environments to increase its efficiency. The informatics engineer Michael Graves already introduced this idea on a talk in 2002 in the Michigan's University, where he mentioned the possibility to create digital representations of physical systems that would be connected to their real entities along all their life cycles.

Rolls Royce, on their aero spatial division, has taken this to the next level. They have not only digitalized all the designing of their engines, but they also test them virtually. As a result, this makes them safe time, money, and the number of built engines to test.

The digital twins are connected to what is called "The internet of things". In 2020 there will be an expected number of 21.000 million digital twins, which will help understand how products are used and how to improve them.

A digital twin learns continuously. This is possible because it contains technology like Artificial Intelligence (A.I.), machine learning and software of data analysis. As the director of Data & Analytics KPMG in Spain says "[digital twins] will combine with other technologies, such as augmented reality and artificial intelligence.

If the construction sector successfully develops a strong culture with the Digital Twin technology, it will have the chance to reproduce not only the life cycle of buildings as in BIM, but also digital representations of it that will learn from its own procedures, giving a feedback on the works being done that can make constructions more efficient.

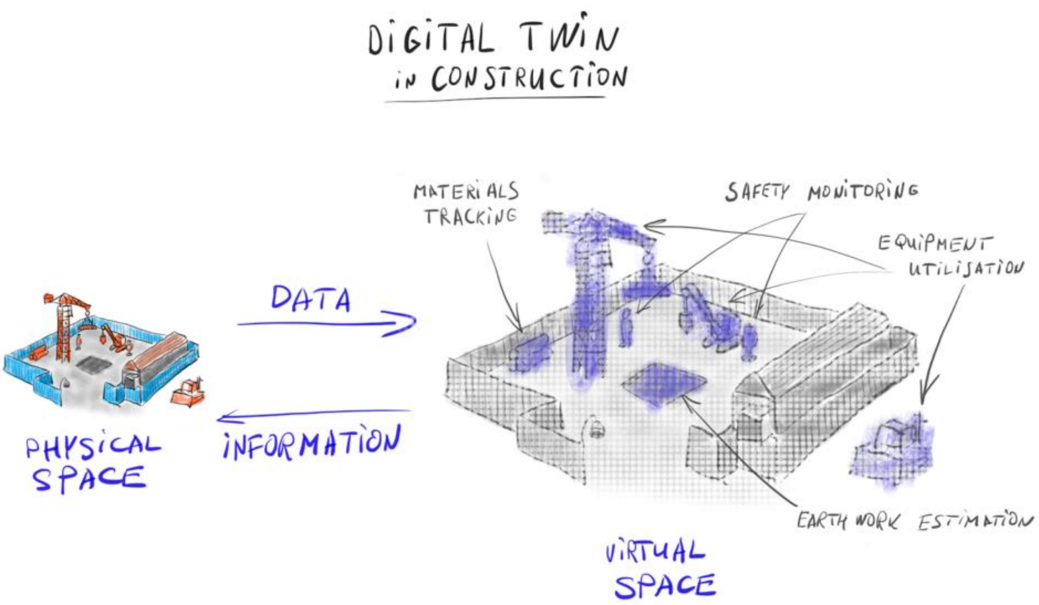


Figure 4: Schematic drawing of the data/information flow in a real construction [5]

Imagine having the 3D model of the building as in BIM, with all its information, but also all the information related to the building process, such as the smallest details on every tool, material or person working on it. What if we could know every bit of data in every moment and in everything, such as the moment when we need to automatically order supplies to make them get to the site in the moment we run out of materials, or know if a beam is correctly installed?

Nowadays data is being sent to the digital twin by sensors that continuously monitor changes in the environment and report back the updated stat in the form of measurements or pictures [5].

With the digital twin of a building, teams can work against the BIM4D schedule, trying new techniques or methods in order to make the real process faster, since the simulation of the digital twin will give them the necessary data. If this technology was joined with the VR, teams of designers and workers could see in advance almost all the possibilities for a construction site in an immersive way, making the whole process safer, and the digital twin could even be able to alert of the riskiest processes or moments in the construction, due to an accumulation of machinery, lots of workers, bad weather, etc.

SAFETY & HEALTH COURSES NOWADAYS

The formation of the workers is a key for any company, in order to establish the necessary competences and abilities for the jobs that they are going to perform. Nowadays there is a wide range of options with lots of offers really well adjusted to the needs of the companies and to the job profiles too, but not all of them have the same quality and provide the same value to the necessities of organizations.

In safety and health formation, the companies form the workers with the objective to stablish good habits in the jobs to be performed. What the sector may need to consider in safety and health formation is the change in the traditional habits. It is being proven that traditional formation (designed to interiorize only theoretical knowledge) isn't effective enough because the change of habits require changing the neuronal structures below. In safety and health, where the emotional aspects that intervene are related to the acceptance of obligations, responsibilities, the change of behaviour patterns and the feeling of guilt, the intellectual comprehension isn't enough to make a change in the already learnt habits. In order to do that it is required to restructure all the intellectual habits, emotions and conducts [6].

The objective of a good formation in safety and health is not only to give the workers the necessary confidence and technical inputs for the job they are going to perform. We need to give those persons the necessary abilities to let themselves be the judges of their own initiatives and introduce changes in their behaviour, so that they can make their job in good safety and health conditions.

Our focus should be on making the working day normal for all the employees in their job centres, to make them work naturally choosing for the "safe way".

There are several methods of formation although we'll go in depth in one:

- *According to the article 19 in the law 31/95*: The formation is an obligation to the employer, and needs to ensure the safety and health of the workers. This formation needs to be theoretical and practical, and has to be focused on the specific job of the worker, adapted to the evolution of risks and repeated if it is necessary. In case that the company cannot provide the formation it can use external specialized companies to do it. This law though, limits the formation through new technologies, everyday more present in our daily lives, and that have been proved as a better way to interiorize concepts than the traditional classroom, professor and presentation. A great example of the new technologies and new methods is "gamification", under the idea that "the game is something inherent in humans and an inexhaustible source of learning and satisfaction" [6]. This gamification tries to turn something routine like a course of formation in something dynamic and entertaining.
  Playing makes us aware of our knowledge and abilities, but also of our lack of them. Since it is an active and participative learning it contributes to change the habits of the workers, our objective since the start.

In June 2017 *GA Consultores,* a reference company in the formation sector with virtual reality and augmented reality, made a study about the repercussions on the workers that tried this kind of experience. Keep in mind that this study doesn't show the effectiveness of VR in formation, but how do the workers feel about its implementation after trying it. 8104 persons between the ages of 20 and 55 tried it. Here are some of the results [6]:

- 90% thought the course was good or really good.
- 94% thought the content was adequate or really adequate.
- 85% learnt something new.

- 72% wanted to participate in more activities like it.

In a similar study performed with 100 workers, it was shown that the retention of information with augmented reality is better than with simply a video, confirming our initial intuition that a formation joining the traditional methods and VR/AR is more effective.

EXPERIENTIAL LEARNING VS GUIDED LEARNING

In this study we wonder which of the two possible experiences fit our goal the most:

- An application to train the workers that guides them through the interphase –with a list of steps or a voiceover to help them follow the “storyline”, avoiding making mistakes -.
- An application that within the storyline lets them “explore” the surroundings and interact on their own with the 3D model according to their instincts and perception of the activity to complete, and at the end of the training, give them a feedback based on their performance.

Experiential learning

The experiential learning could be defined as the “learning in which the learner is directly in touch with the realities being studied”[Keaton and Tate, 1978]. The subject learns through reflection on doing. In this view of the experiential learning, the emphasis is often on direct sense experience and in-context action as the primary source of learning [7]. It may not have the content and substance of a guided learning experience, but it’s more focused on the technique and the process. It offers the foundation to pursue a framework for strengthening the critical links between education, work and personal development.

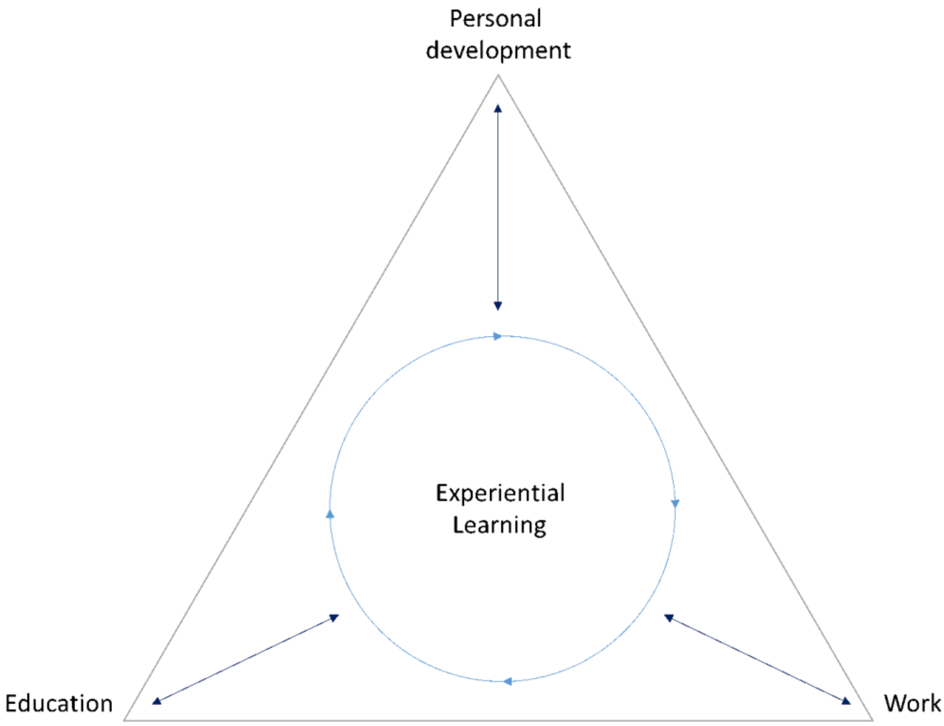


Figure 5: Experiential Learning as the process that links Education, Work, and Personal Development [Kolb, 1974]

Experiential learning has been a topic of discussion since the ancient world. Aristotle, in 350 BCE, wrote in the *Nichomachean Ethics* "for the things we have to learn before we can do them, we learn by doing them"

One example of experiential learning is going to the zoo and learning about the animals by looking and interacting with them, instead of reading their behaviour from a book. Another example would be learning to ride a bike, by simply jumping on it and trying not to fall. Kolb illustrated this process with his four-step experiential learning model:

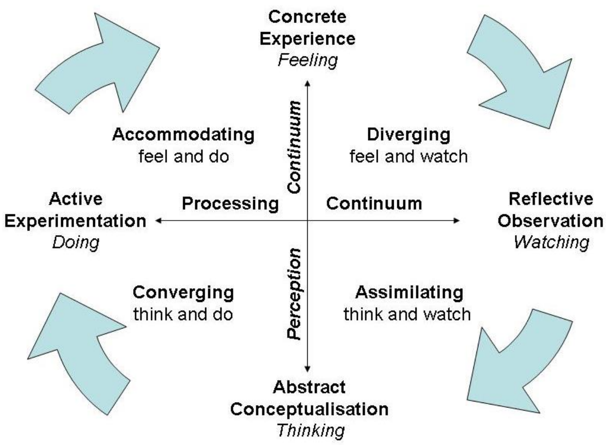


Figure 6: Klob's model illustrating his four-step experiential learning model. [Kolb, 1974]

Following with this example, in the "concrete experience" phase, the learner jumps on the bike and rides it, gaining experience. This experience is the foundation to the "reflective observation", where the learner can consider what is working or failing. Then by thinking of ways to improve the next attempt, the learner is completing the "abstract conceptualisation". And finally by applying this knowledge to the next attempt, he is doing the "active experimentation".

Kolb found four types of learners while studying the experiential learning:

- Assimilators: The ones who learn better when presented with sound logical theories to consider
- Convergers: who learn better when provided with practical applications of concepts and theories
- Accommodators: who learn better when provided with "hands-on" experiences
- Divergers: who learn better when allowed to observe and collect a wide range of information

Also he stipulates four characteristics that the learner needs to have in order to achieve a good learning level. The learner must be willing to be involved in the experience (has to jump on the bike), has to be able to reflect on it (understand why he-she is doing it and the benefits from it), the learner must possess and use analytical skills to conceptualize the experience (riding the bike but then skipping the observation of your own mistakes or avoiding the thought of solutions won't show any progress) and finally the learner must possess decision making and problem solving skills in order to use the new ideas gained from the experience.

Also several studies like the one from Barton D. state that active learning –a similar approach to learning as the experiential learning- is more beneficial to students because the retention of information is higher when the student is involved in the task being studied, instead of just listen to lectures and receive information in a passive attitude.

It could be summarized as the intentional construction of skills, abilities, or knowledge through participation or contribution.

These are the reasons why we have taken into consideration the experiential learning method for the 3D VR experience. Sometimes learning by heart a list of personal safety equipment, safety directions and other instructions related to health and safety regulations can be not just boring, but easy to forget or underestimate their importance without the background that an experienced worker may have.

By leaving the learner alone in the VR application we expect him to gain the experience of being in a construction site and learn about its risks without being endangered at all, and at the same time, learn the necessary concepts of health and safety regulations faster, better and in a motivational way. The goal is to make the experience the closest to the real life without being the real life job.

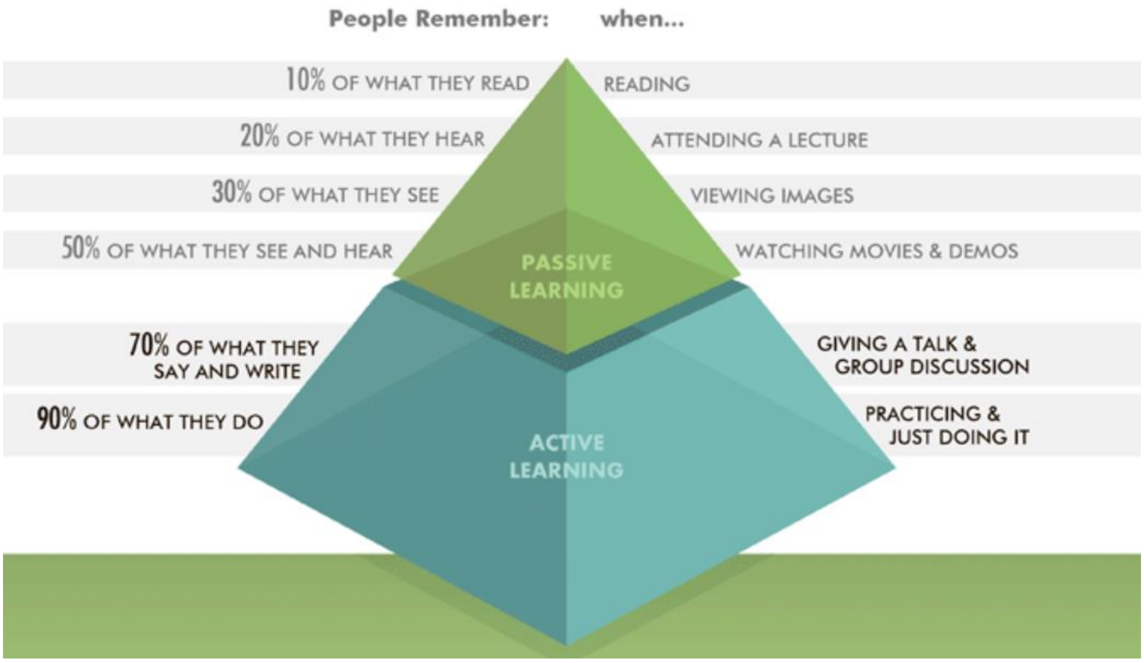


Figure 7: Pyramid of the two learning types with its percentages and actions [8].

Guided learning:

Buchmann and Swille (1983) argue against the experiential learning, and propose that the purpose of formal, guided learning, is to overcome the biases inhered by the experience process of learning. The learner plays a passive role in comparison to the experiential learning. They cite numerous sources of error in judgements due to the experience, and agree that the memories and first-hand experiences tend to be overused. Vivid experiences tend to be weighted highly than objective data.

Although the guided learning has the drawback of being a passive learning method, it has its bright side too. The guided learning is a really organized and well-paced process, where all the topics are taught and there's no risk of skipping any important issues. Moreover it gives the reassurance to the learner that all the work he is doing is set in the right direction thanks to the guidance of the lecturer.

That's why we considered to mix both learning processes, but instead of using them in the usual academic way –lecturer gives the theory and explains the topic and the exercises in a passive way, and then the students practice alone and get involved in an active way-, we'd do it reverse: The learners would be in the VR experience without any directions except for the task to do, they'd do it according to their intuition and their previous knowledge, and after it they would get a feedback from the application with an evaluation of their performance and some indications for the future. This way we get the best of both learning methods: the retention capacity and the benefits in the learning process from the experiential-active method and the guidance with topic by topic evaluation to correct the errors in judgement or point out conclusions that the learner may not have gotten to.

VIRTUAL REALITY

Virtual Reality (VR) was a tool was born in the 1860's, when artists began to create 3D panoramic models. With time this technology evolved and in 1962 Morton Heilig made the first step into what was going to be an immersion inside a VR environment, with the invention of the "*Sensorama*", a machine that had a 3D stereoscopic view, stereo audio, wind and aromas [9]. From that point on, several improvements on the technology were made, resulting in the devices that nowadays are on the market, such as the "*Oculus Rift*", a head set that allows the players to have a 3D stereoscopic experience in a VR world, in a first person view, being able to interact with the environment. Those three key characteristics –*immersion*, *interaction* and *first person view*- made VR really attractive to video game developers. With the grade of precision in the game closer and closer to reality every day, the player has control of the surroundings and a level of immersion never seen before. In the construction sector VR has not been strongly implemented yet, but other sectors have already begun to take advantage of this chance to represent the real world with an extremely high accuracy. More and more every day, different projects count on the VR support in order to take their efficiency to the maximum, especially in enterprises with very little margins, in which inefficiencies, mistakes in the initial plans or last minute changes can throw away millions or have bad consequences, resulting in terrible losses. Some of those sectors are healthcare and medicine, manufacturing and logistics, or even retail, just to name a few.

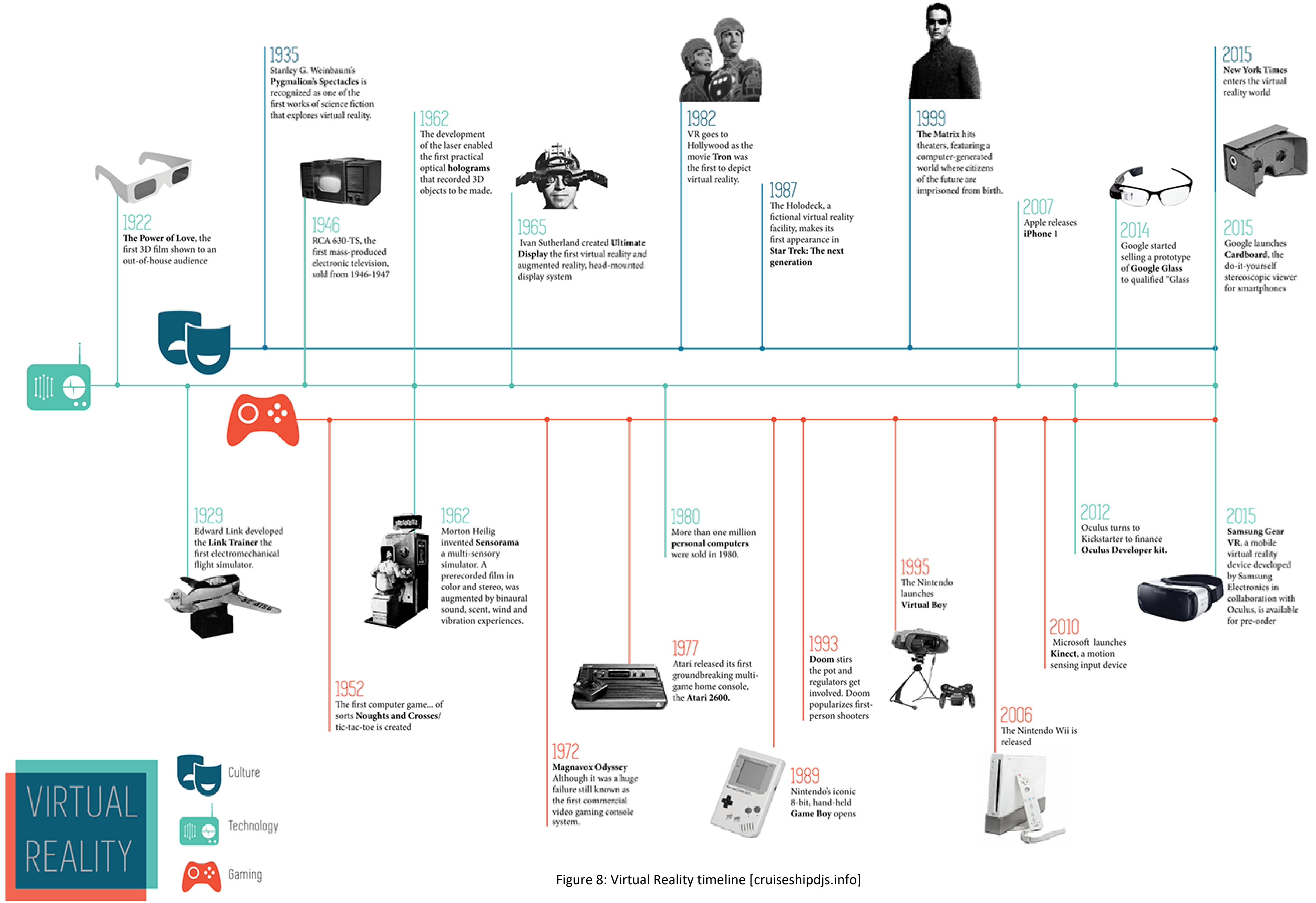


Figure 8: Virtual Reality timeline [cruiseshipdjs.info]

One of those sectors is, indeed, Construction. Most of the problems found when constructing a building, are related to the inability of field personnel, architects, engineers and designers to truly embrace the magnitude of the project before it is built. Getting guidance from 2D plans and bad communication between teams usually causes the project to be stopped due to problems that couldn't be seen on paper. Although now computer-aided technology has stepped in with CAD, and 3D plans are starting to move their way in the sector, -especially since several countries are starting to make Building Information Modelling (BIM) projects obligatory for public tenders -, they don't give the level of knowledge and self-awareness of the site that Virtual Reality can provide, because certain faults related to design and construction can only appear when the construction process has already started, creating delays, activities re-assessings, etcetera.

Moreover, this problem in representing reality can even affect business relationships between the client and engineer/architect, due to the difficulty of communicating the client's desires in a 2D platform, capturing them in a project and then bringing them to life, as sometimes the outcome is not as the desired one.

Virtual Reality on the other hand, can immerse a person inside a virtually constructed environment. Nowadays BIM projects have had an outstanding improvement and development, with several platforms and programs to work with, like Revit, Archicad or CypeCAD, to name a few. These programs can now be adapted to VR tools, joining the architecture 3D models and its information –the characteristic that makes BIM so essential-, with the immersion, the fully virtual representation of an idea and first person interaction of the place. No need to say that the application of this technology is at a very low cost compared to the current alternatives, such as the experimental labs.

To put it simple, the VR allows the "players" to have a 360 view of the virtual surroundings, in this case the building to be constructed, thanks to a head set that gives them the 3D view. Depending on the head movement of the person, the VR headset will act as if the person was moving inside the "virtual world".

Figure 9: Fictional recreation of what a person feels when using VR, in this case inside a construction [VRroom]

Obviously the major interest of VR in the construction sector is to save money, thanks to the unlimited number of tests that the designers can do before the construction project starts. The effect of changing the time of an activity in the BIM model can be seen in the VR experience; the potential collaborative problems that can appear between teams can be tested with months in advance without implying a huge cost; and the final locations of every detail can be previewed by both designer and client, before any brick is put into place. The level of accuracy can be sustained from the first day of construction until the last piece of furniture is put in place, making the input and feedback of the client much easier to understand. Entire realistic electric systems could be manually checked from inside the VR model to avoid mistakes that wouldn't have ever been found in a 2D plan or in a computer, or pipe lines or joints in beams. If the collaboration between client, designer, engineer and contractors was one of the many key parts of the BIM, it could be said that the VR is the extension of it that allows everyone to make sure that none of the parts had any misunderstanding on the final appearance of the project –potentially improving the relationships between parts-.

In this first introduction there have been mentioned several points where VR implementation inside BIM models can be extremely successful, such as reducing rework, lowering costs, meeting deadlines, resolving potential issues faster and improving quality. But there is one of them that hasn't been mentioned yet, which is the last but not the least, and it's ***improving safety.***

Until now the VR models have only been focused in its use for owners and designers in the offices, but not in the construction site for the workers. Even so there is a new branch that can change the history of work accidents forever. By training workers on specific activities inside the VR we can make them aware of the risks that they are exposed to in the construction process. Working at height, moving objects, having noise environment, etcetera, are a series of risks that can be put to test for the workers without any risk of damage for them. They can be trained to be conscious of their own safety whilst being on a 25th floor without safety net, or security lines, things that cannot be tested in a lab, and they can understand the importance of the personal safety material after they have “virtually died” due to a truck that they were paying no attention to, and why not, they can learn all of this while improving the way they do their job, faster and better. The coordination with other workers doing other activities can also be part of the VR model, in case we have several people involved in the same activity or in the same place.

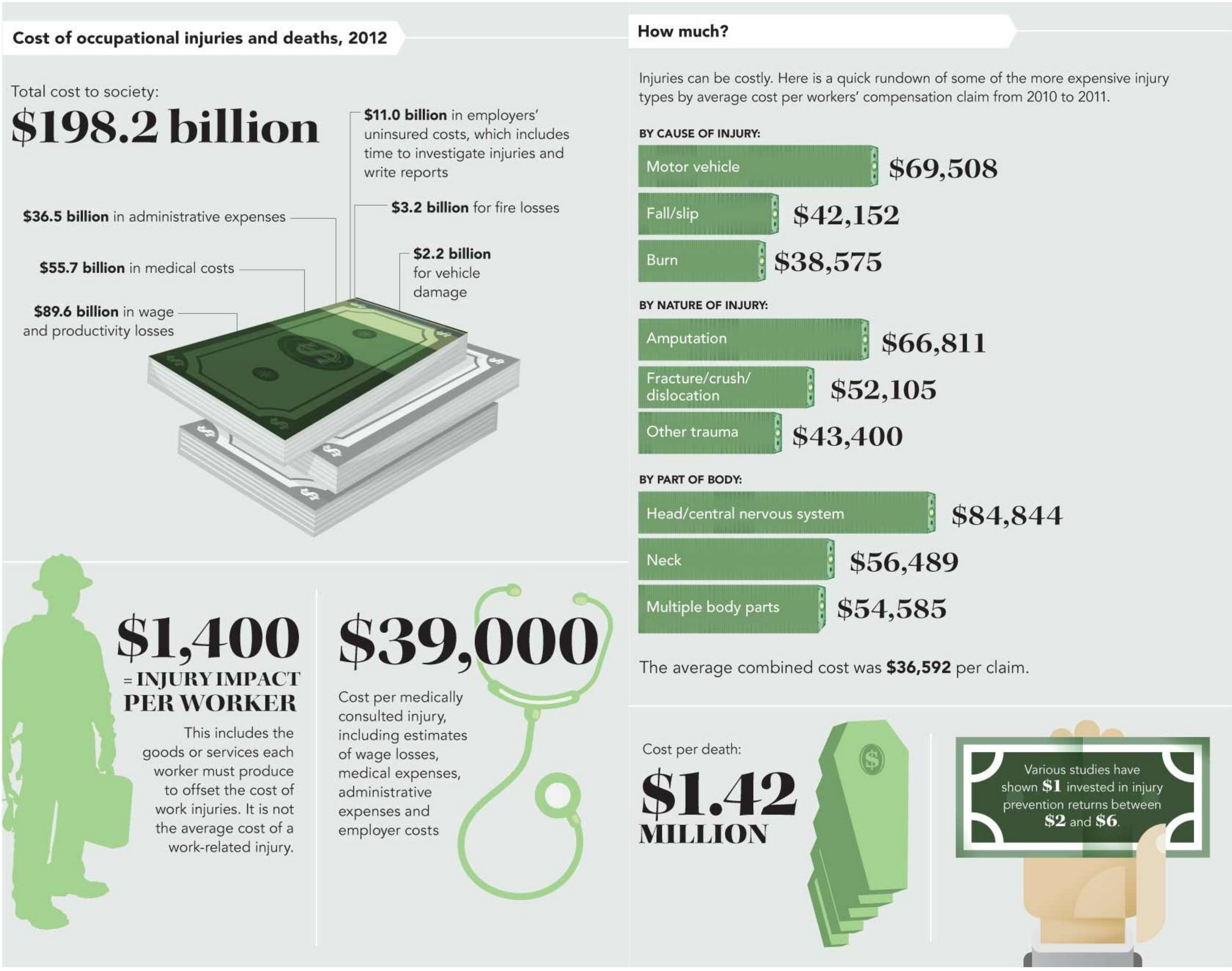
Effectiveness of VR in Safety and Health in economic terms

Investing money on VR training and equipment for Safety and Health can seem a risk too high for companies that already have a program that sticks to the legality to train their workers in such matters, but several studies show that actually it is a way of getting midterm profits and to help improve the security of the workers. Let’s look at all the variables:

On an article published on the renowned magazine “Safety + Health”- edited by the National Safety Council of the USA (NSC)-, Kyle W. Morrison differs from the nowadays way of thinking, and writes “The return on investment of safety” [10].

First of all, to consider if it is worth or not to invest on safety, we have to know the actual average cost of an injury/death. Several methods are used to estimate the costs, depending on whether you count only the hospital costs or the total cost to the society. The NSC puts that cost for society at 1.42 million dollars for a fatal injury. Morrison says that the number can seem high enough, but actually it is even higher because it only takes in account the direct costs, like workers’ compensation, medical expenses, civil liability or litigation costs, and property loss. The indirect costs though are much higher. The NSC estimates that for every dollar in direct costs, the indirect ones can go up to 2.12$. These indirect costs include workplace disruptions, loss of productivity, worker replacement, training, increased insurance and attorney fees... This means that for a single death, the value skyrockets from 1.42 million dollars to somewhere around 3 million dollars. And NSC states that this is the lower side of the scale, because other studies conclude that the indirect costs of injuries in the construction industry can be 17 times higher than the direct costs.

So safety can have a lot of economic impact if handled properly. To put some real world examples of companies that have already tried it, Schneider Electric had a rate of 3.6 injuries per 100 full time workers in 2002 [10]. It was below the average in their sector, but they still wanted to improve the safety of their workers by identifying possible hazards that could hurt someone. In 10 years the company saw their rate drop to a 0.5, meaning 900 fewer injured people and their savings rose to 15 million dollars in direct costs only. Other companies as Alcoa have seen their earnings increase from 0.20 $ a share to 1.42 $ in five years, and their sells grew a 15% each year during that period thanks to investing on the safety of their workers.



*american billions: 1.000.000.000 $

Figure 10: Cost of occupational injuries and deaths in 2012 in the US [NSC, "Injury Facts", 2014]

Moreover, the UK government estimates that between the years 2014/2015 and the 2016/2017 there were more than 0.4 million of work days lost due to workplace injuries in construction, and that its cost to society was 0.5 billion £. That cost can be explained for example as the monetized amount of extra time that people have to use an old inefficient infrastructure –like a secondary road- due to a delay caused by a work accident – that affects the ending time of the new highroad-.

Figure 11: Cost of workplace injury and new cases of work-related health in the construction sector (2015 prices).

[Labour Force Survey, 2014/2015 – 2016/2017 and HSE Cost to Britain Model, 2015/2016]

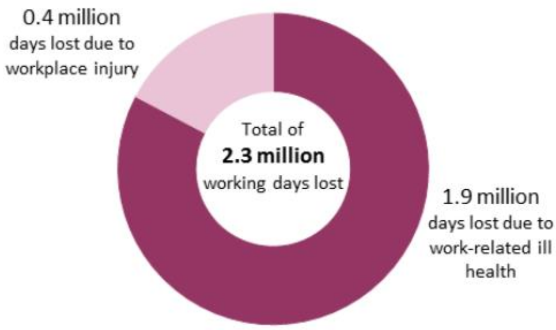


Figure 12: Estimated working days lost due to work-related ill health and workplace injury in construction in the UK.

[Labour Force Survey, 2014/2015-2016/2017]

So now it's clear that investing on safety has a lot of importance, not just for its human side but also for the economical part.

How can a combined project with BIM and VR be a good investment?

There aren't many studies in the construction industry regarding the effectiveness of training workers with VR, whereas in other sectors this has been already tried. The results show that the performance of the person practicing with the VR is improved, as happens for example in the study conducted by Dr Neil. E. Seymour and his colleagues, where they checked if "Virtual Reality Training Improves Operating Room Performance" [11]. They concluded that students that trained with VR were faster in a gallbladder surgery, and that they made 6 times fewer mistakes than the non-VR trained students (1.19 vs 7.38 errors per case). This is a reduction of the 83.8%. Obviously in a surgery the pressure and precision needed are much higher than in most of the construction situations that a worker may find himself in, but it gives a general idea of the potential of this technology.

So let's say that VR can achieve a 30% reduction in the injuries and accidents in the construction sector. How much money would that mean for an average company in the sector?

Spain's Institute of Statistics shows that in 2016 the average number of injurie leaves in the construction industry was 7217,2 every 100.000 workers, and that the mortal cases were 8,62 every 100.000 workers. If we imagine a fictional project a year long with 100 workers, that means that there will be on average 7,2 injury leaves –and hopefully no deaths-. According to the NSC studies, that means that the sum of direct and indirect costs for the company caused by these injuries is:

36592 $ (average direct cost per claim) *** 7,2** (number of injuries) *** 2,12** (low scale indirect cost per direct dollar spent) **= 557.578,656 $**

That is more than half a million dollars lost due to these injuries. Now let's look at how much would be the profit if the number of injuries could be reduced a 30%:

36592 $ (average direct cost per claim) *** 5** (number of injuries) *** 2,12** (low scale indirect cost per direct dollar spent) **= 387875,2 $**

557578,656 - 387875,2 = 169.703,456 $

Just by investing on a better Safety and Health formation, this company would have been able to safe up to 170.000 $.

CHAPTER III

TECHNOLOGICAL UNITY KEY FEATURES FOR VR EXPERIENCES IN CONSTRUCTION

Unity is a cross-platform game engine [Wikipedia]. This means it is the software that hands the necessary features to create a video game in a quick and efficient way to the creators in a bunch of different platforms.

The structure of the game engine has several basic areas for the developers to use. They can import art and assets (such as blueprints and models in 2D and 3D) from other kinds of software (like AutoCad, Revit, Blender, Maya, 3Dmax and many more), then assemble all these assets to form scenes and environments, add lighting, audio, special effects, physics and animation, interaction and logics, and edit, optimize and prepare this content for other platforms.

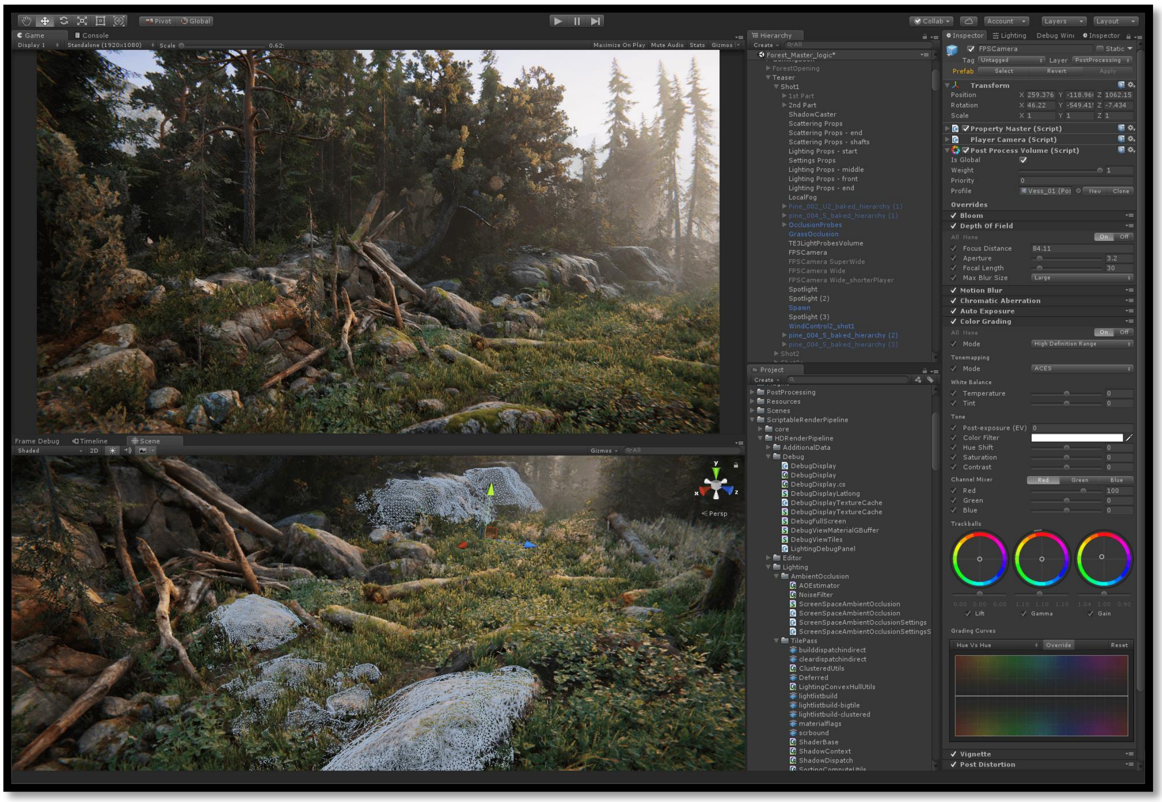


Figure 13: Unity is a powerful game engine, capable of rendering amazing scenes to achieve the maximum realism.

[Tim Cooper, Unity Blog, 2018]

Unity has 6 main pillars that support its structure:

- Graphics: They are the reason you can "see" the game. Renderers on Unity are really accurate and the final effect on lighting and texture can be truly breath-taking, completely immersing the player in the experience.
- Audio: Audio is the other key feature on realism in any video game. Unity allows the developer to create, import and code audios to take the game to a new dimension.
- Physics: Physics are run by Unity's physics engine. They are really flexible, which make the developer have all the control over them.
- Graphic User Interphase: The GUI are the images and buttons that the players see in their game window.
- Scripting: They are the pieces of code that define the logic of the game, adding behaviours to its components. They allow the developer to control players, cameras, objects, physics, **animations**…
- **Networking**: Unity's newest feature that makes possible the connection between players.

All the features above were used in projects and VR experiences done before by CIMNE, but there are two of them still unexplored:

- <u>Animations</u>: The animations are the key to apply realism to a multiplayer video game. In order to see other players move and interact with objects, it is necessary to implement certain animations to make transitions and interactions smooth. In this project the players will see animations for walking forward, backwards, picking up objects, and many more things.
  The animations are controlled through 4 things:
  - Animator Controller: It's the controller that the Unity Engine will use to play the animations.
  - Animator View: It is a view in Unity, related to the Animator Controller that will play those animations, where the developer drags all the animations necessary and stablishes the relations and transitions between them depending on certain properties like triggers, boolean values, integer values or float values. Each of those will have a tag. The transitions between animations will check if those properties are true, false, or comply with the values, and then will play the animation or not according to that.

- Script: The script that will set values for the properties of the transitions. It will send information to the tags, such as "isWalking" boolean is true, and then the Animator Controller will play them or not according to the relations stablished in the Animator View.
- Animator/Network Animator Component: The component to be attached to the game object necessary to make it play the desired animations. It needs an input of the mesh to be animated and the Animator Controller that will animate that mesh. In the case of a Networked game, the Network Animator will be added too to sync the animations through the network, with the input of the Animator, to know which Animator to sync.

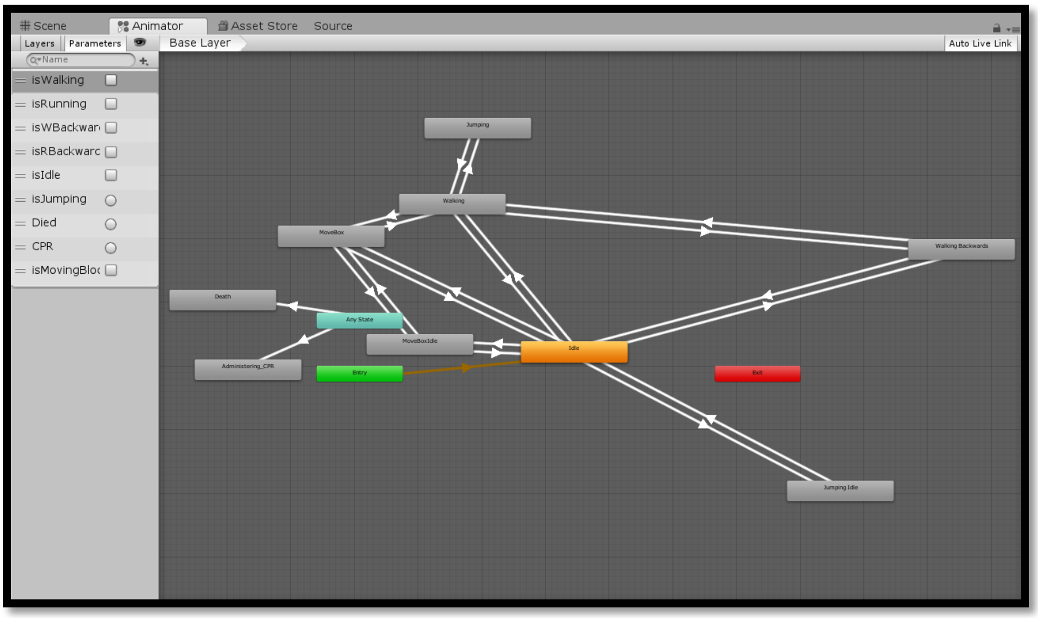


Figure 14: Animator view from the project showing the tree of transitions between animations and its variables.

- <u>Networking</u>: Networking is the feature that makes this game so special. It synchronizes all the information of the users playing in different computers/devices and distributes it to make the game work as it should in an online multiplayer environment. It consists of five main Components:
  - Network Identity: It is the Component attached to a game object that will exist in the Network. That means that it can change its properties due to interactions, and that those properties have to be updated and synced through the network. It has two check boxes:
    - Server Only: That will make the game object spawn only on the server, so the clients won't be aware of its existence.

    - Local Authority: Gives authoritative network control of this game object to the client that owns it. The player game object on that client has authority over it. Other components such as Network Transform use this to determine which client to treat as the source of authority.
- Network Transform: Synchronizes the movement and rotation of game objects across the network. Note that the network Transform component only synchronizes spawned networked game objects (that means that they must have a Network Identity).
- Network Animator: See above in "*Animations*".
- Network Lobby Manager: This Component will have to be added on an empty game object on the Lobby scene. It is a specialized type of Network Manager that provides a multiplayer lobby before entering the main play scene of the game.
- Network Manager HUD: The Network Manager HUD is a simple and quick way to provide the basic functions that players of your game need in order to host a networked game, or find and join an existing networked game. It displays a collection of simple UI buttons which appear in the Game view when the Editor is in Play mode.

Networking also changes the way scripts behave. In order to make a script work in the network you have to specify that you are "using UnityEngine.Networking" and that it is a "NetworkBehaviour". Then the scripting system will allow you to use the characteristics of the network to synchronize states and data through the Network. This works in the following way: Let's say we want our player to pick up a certain object, like a helmet, and we want it to be placed on our head. This helmet on our head is already put there, but its renderers aren't set as enabled, to make it invisible until we put it on. If we coded this in the "usual" way, "*locally*" to be more precise, what we would see is that in our view we would indeed pick up the helmet and have it in our head, but the other clients would never see it, and for them we wouldn't have a helmet on. Why does this happen? This is the way the Unity Networking System works:

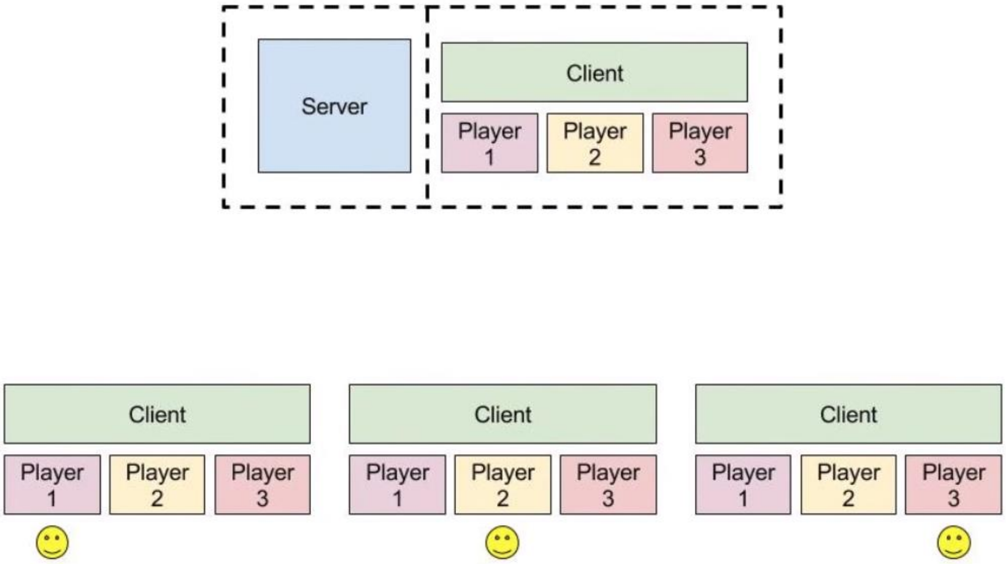


Figure 15: Scheme of the parts involved in a networked multiplayer game (Server, Host, Client)

For Client we can understand that it means "computer". So every person playing is a client. The Server is what runs the game. It updates positions, movements, animations, etc. Finally we call Host to a Client that is also acting as the server, as would be the case of our project.

We can take the example above. We have three clients controlling three different players, and a Server that could have also a Client and then would be acting as a Host, but since it doesn't have a Player 4, it isn't.

Usually the most common actions, like movement, position or animations, are automatically synced through the Server thanks to the Components attached to the game objects (Network Transform and Network Animator). But in our case we want players to do certain actions that we programmed through script. Since Clients don't connect directly to other Clients, all the info goes through the server, which updates the data to the rest of the clients. In order to tell the Server that it has something to update, we use **Commands**. And if we want to tell the Server to update something on all the Clients, we use **ClientRPC**'s.

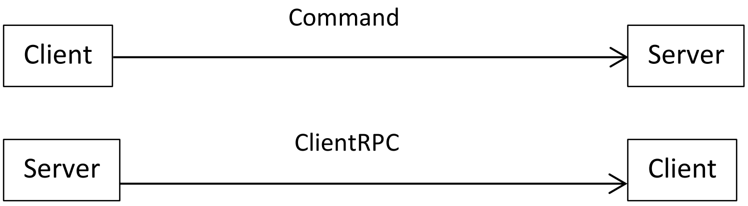


Figure 16: Functions that send information between Client and Server.

So if we used this script to pick up the helmet:

```
public GameObject helmetHead;

void Update ()
{
  if (Input.GetMouseButtonDown(0))
                {
                    CmdHelmet();"
                }

}

[Command]
void CmdHelmet()
    {
       RpcHelmet();
    }

[ClientRpc]
void RpcHelmet()
    {
       helmetHead.GetComponent<Renderer>().enabled = true;
    }
```

We would be saying: “On left click, run the Command CmdHelmet”. Then CmdHelmet would say “Server, run the RpcHelmet”, and the RpcHelmet would tell all the Clients “enable the renderers of all the copies of **that** helmet, put on **that** player”, in the following way.

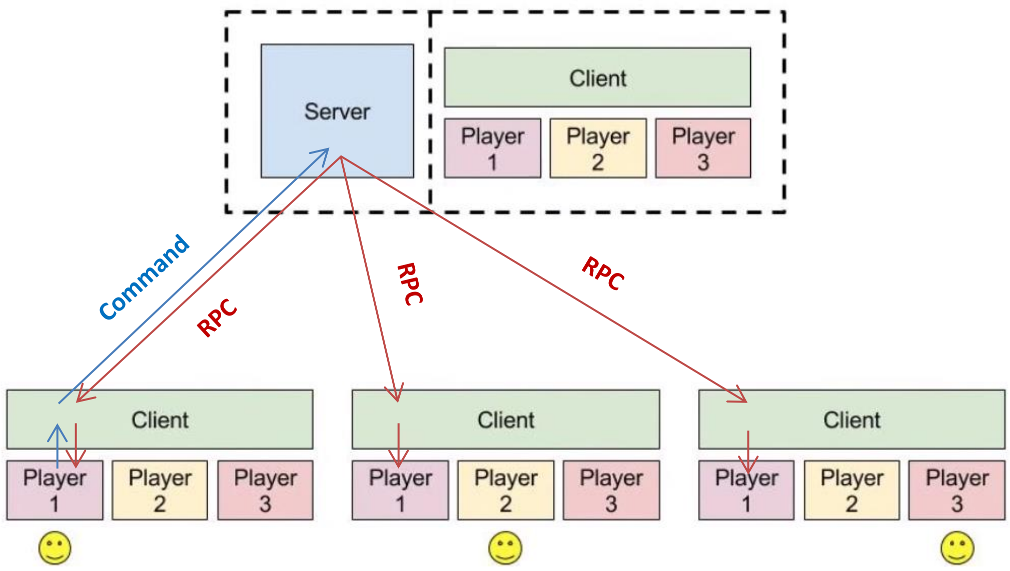


Figure 17: Scheme showing the synching of information from one Client, to the Server, and to the other Clients.

This is, in a much summarized way, how the Unity Networking System works, and how it is applied to the game.

METHODOLOGY AND IMPLEMENTATION

The project started by learning the possibilities that the Unity Engine has. After realising that it can successfully import 3D models from Revit and that it can develop a networked game, the frame where the whole project would be in was defined.

The first step was to learn the interface of Unity –how the views worked, how the assets were organized and the whole variety of options and controls that it has-, with the Roll a Ball official Unity tutorials. Then I had a look at the scripting Documentation and I was set to go.

The different phases in which I divided the development of the project were the following, and they were organized like this:

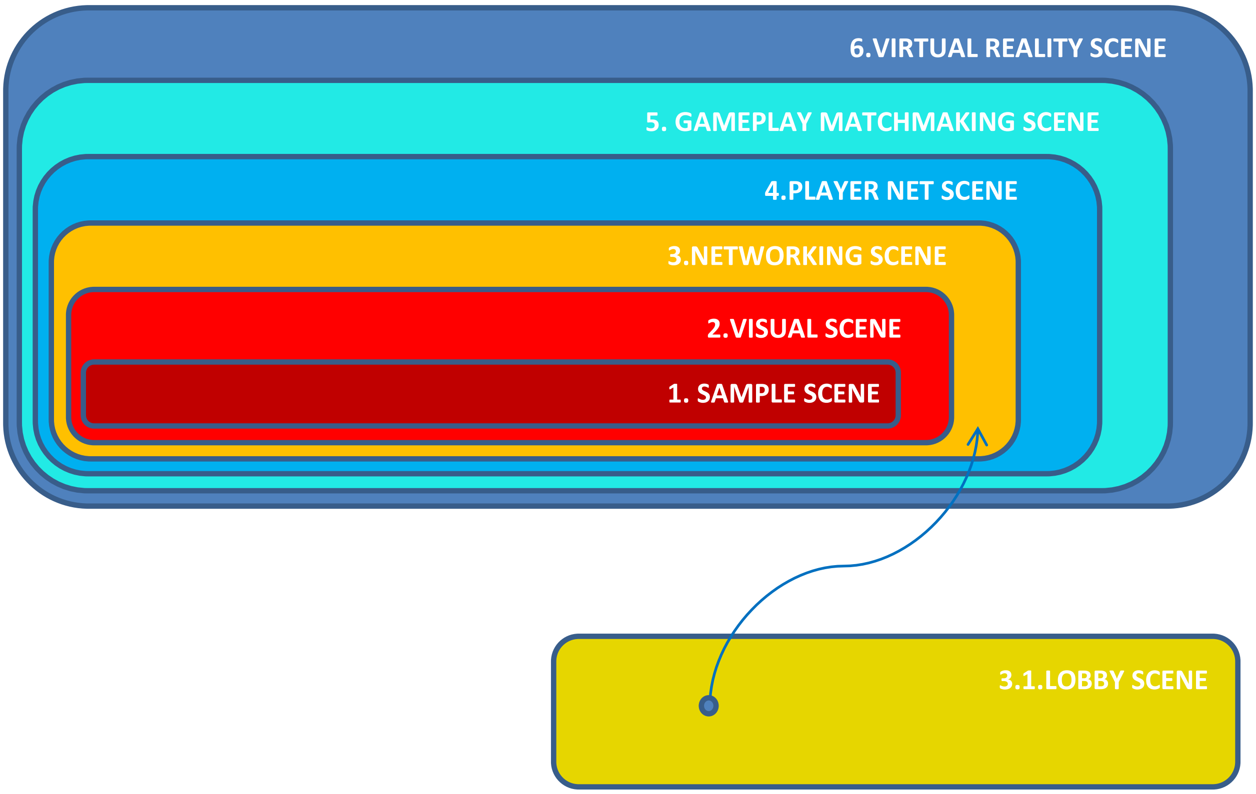


Figure 18: Graphical representation of the scenes' organization in the development of the project

- *Sample Scene*: Simple offline game with only a ground and a Character Controller that consisted on a Camera, a First Person Controller and an Audio Listener, that I programmed to do a tax simple as lifting a box on click enter and transporting it.

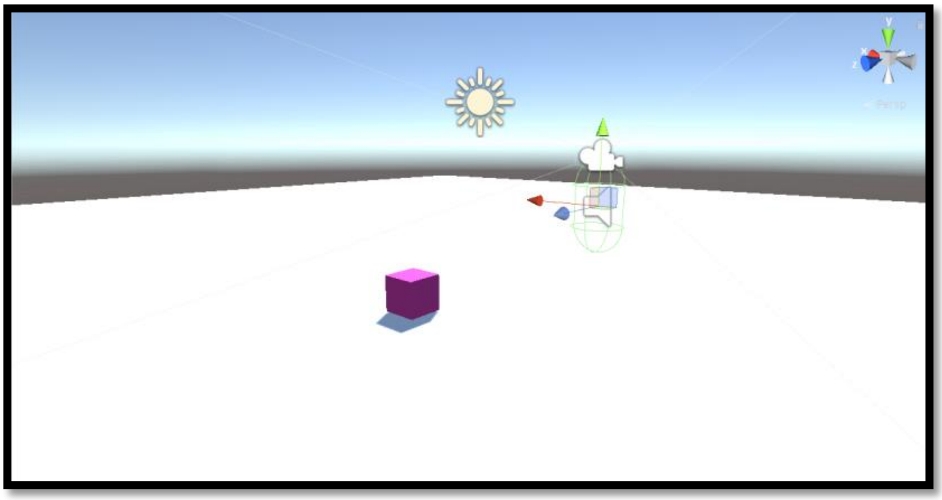


Figure 19: Sample Scene displaying the Character Controller and Box.

- *Visual Scene*: I went on several tutorials on YouTube and hundreds of threads on Unity forums to learn how to do the first innovative feature of the project: Animation. I ended up developing a really neutral character called Ybot. Since I didn't want to have all the characters in the game with different physical features due to the extra work that it supposed I used a humanoid. It had a quite complex animation tree, that I basically programmed to practice and learn how to properly handle the Animator Controller, which had forward and backward animations, crouching forward and backwards, idle and crouching idle, running forward and backwards and jumping. All those animations had smooth transitions between them according to the parameters that I scripted.

  I also imported a 3D BIM model of a building to have something to work on.

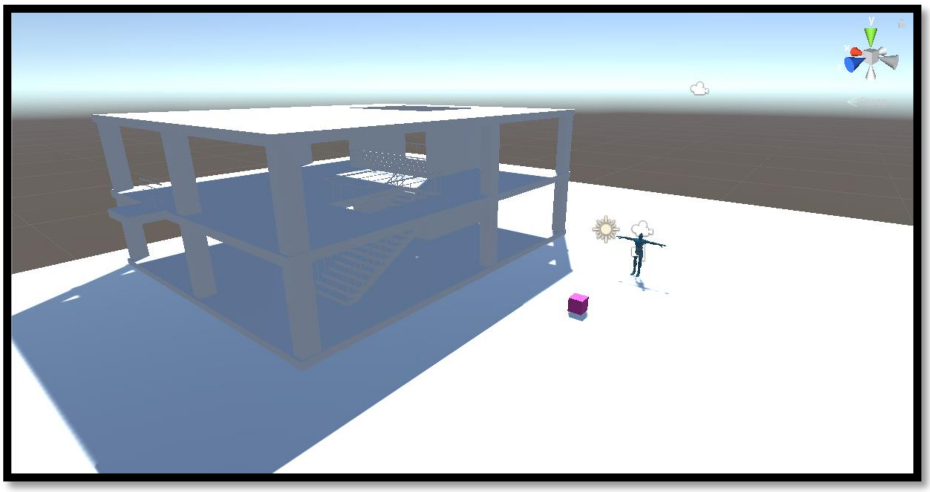


Figure 20: Visual Scene displaying the Ybot, the Box and the BIM model.

- *Networking Scene*: Thanks to a really well-explained tutorial on the Unity networked game tutorial "Tanks", I developed the Lobby for my game -it is technically a Scene, but it is only used as the mean to put the online players together to start the game, and it is a very mechanic process with no special value to be explained-, allowing me to spawn my player prefab in a Server and play online. Here is where I found the first problems. Although on my screen I could see my player moving with animations, its movements weren't updated on the client. After some research I found the answer, which was adding the Network Transform and Network Animator components. There was a bigger problem though: When picking up the box with the Host everything worked fine, but when doing it with the Client the box's transform wasn't synching correctly, and snapped to its position before being picked back when being left to fall. I stuck with this for at least a month –while I researched on more networking features-, and after a long time I came to two possible conclusions:
    - Unity's Network Parenting system doesn't work well. I read several forums complaining about this issue and they were never solved.
    - Using RPC's to update the box's transform while updating it with the Network Transform made the same information travel at different rates, causing the flinching, snapping and other issues.

I finally yielded and I moved on with the defeat of not being able to transport things through the network. Later I'd solve the issue with a quite elegant solution.

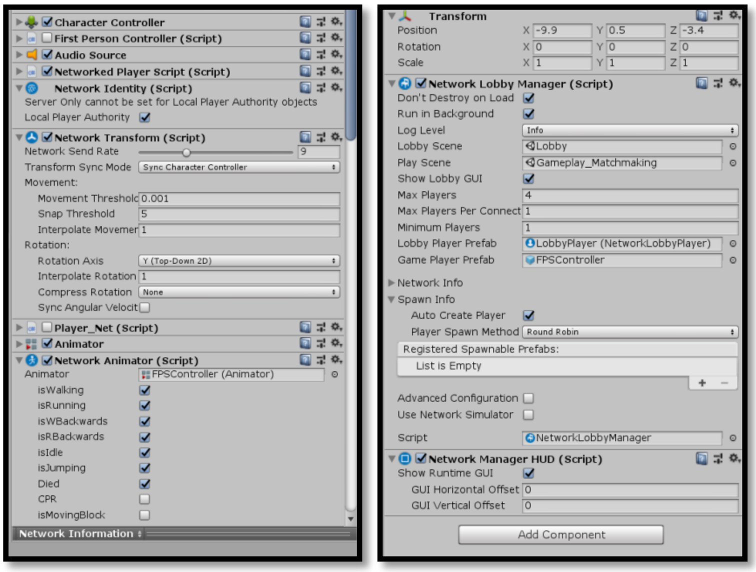


Figure 21: Inspector for the player prefab showing the Network Identity, Network Transform and Network Animator Components (left) and the Inspector for the empty object in the Lobby scene showing the Network Lobby Manager and Network Manager HUD.

- *Player Net Scene*: After moving on, I had to start getting some results to get the game going, because until that moment I only had some online players moving on a gigantic white square. The 3 milestones where:
  - Safety Equipment: That was my priority. I wanted to make my players able to equip the necessary Personal Protective Equipment (PPE), because to me that was the crucial first step in any course about safety and health. I downloaded the assets of a helmet, earmuffs and harnesses. What I did to make the effect of equipping an item was to make 2 versions of the same game object. I put one helmet with the renderers enabled so you could see it and pick it up, and then another already equipped on the player but with the renderers disabled. When picking it up I made the switch between enabled and disabled for both of them. I used the same process for the earmuffs and harnesses, and it actually gave me the idea of how to transport things. But that "picking up" was run only locally, so I had to learn a lot on Commands and RPC's to make the instance of the **same** helmet get set active on the **same** player that had picked it up across the network. A nice twist on this was the programming of the life line: I put a set of invisible walls circling the perimeter of the building, with its colliders disabled. In case of a player connecting to the life line, those colliders would set active, and therefore the player wouldn't be able to fall.

Paradoxically, after trying for so long to sync actions through the network, I had one action that had to be performed only locally (because only the player that connects to the life line can get the wall colliders active to prevent his falling).

- Health, Points and Time: Having the Safety Equipment correctly scripted and networked I went on what probably was the biggest challenge in Unity. I had thousands of minor problems and two major ones. The first was the actual scripting of the health system. There were not many tutorials and threads on the internet talking about networking and more specifically networking health, and since at this point most of the games were quite complex, they were all using references to other scripts that behaved in different ways than mine, which made the already small amount of tutorials existing useless. The second problem I found was that since the Health and Points systems were related to the UI of the player (the images that display the time, points, health bar, etcetera) and I had only one UI on the player prefab that was spawned in the network, data was flowing in crazy ways. At some point I had a game that behaved completely random. I could have a player jump from a 2nd floor, have its health variable down to 25/100 but leave its health bar full and have the other online player suddenly die to the damage of the first one. Chaos. But at least things were happening, the scripts weren't working well, but they were working. After watching maybe ten times the YouTube Unity tutorials "*MerryFragmas2.0*" and "*MerryFragmas3.0*" I found the clue that would solve everything. Enable UI's, scripts, components and several other things only on the Local Player through the function "OnEnableLocalPlayer". This way each networked copy of the player prefab would have only one UI, and the UI's for the copies of the other players seen on the Client would have none of those. Then Health and Points flowed amazingly. The only "but" I would give to the scripts is that these variables are Client controlled instead of Server controlled. That means that the data is not shared by the clients. If I wanted to make the game end for Player1 and Player2 at the same time on the death of one of them for example, I would have to make a really complex script to share the data, while if I had been able to control the data from the Server the flowing of RPC's would have done that way easier.

For more information on my Networked scripts and how do they work between each other see the Annex.

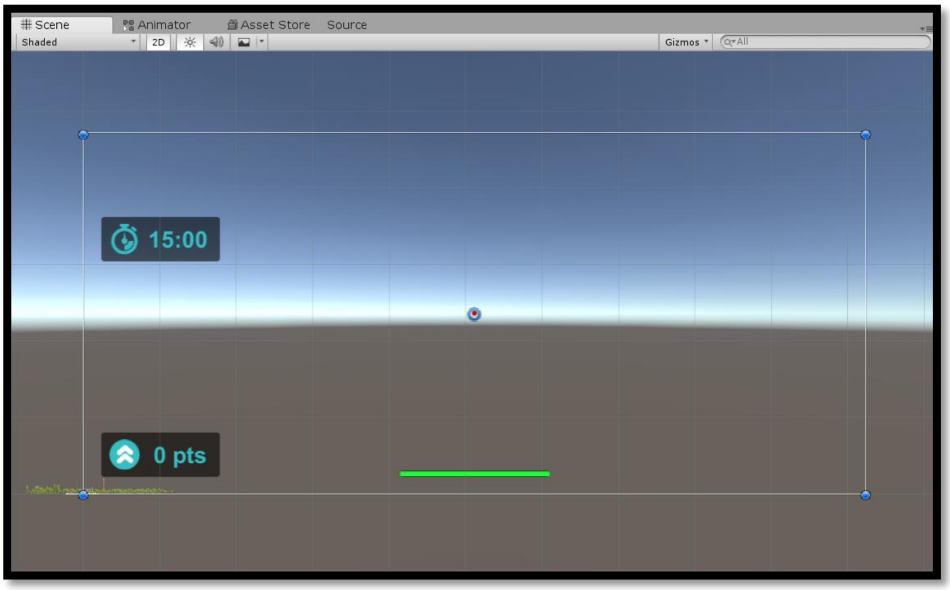


Figure 22: Image of the Health bar, Points and Time features in the player UI after being successfully coded.

- Activities: I decided to code two main activities. Transporting the material to build the walls and then build the walls. At this point I already solved the transport problem; I used the same technique as with the helmet. The script to build the walls was also based on the same principles, the only trick being putting the un-built invisible walls on the non-collide layer I created, so that the players wouldn't collide with an un-built wall. That is because if I had used the SetActive(false) line in the script, the Raycast wouldn't have been able to hit the wall collider and therefore it would have never been set as active. The Raycast is an invisible ray coming out of the camera that when hits an object at a certain distance gathers its information, for example its tag. That's how my scripts could know how to interact with objects. By putting the walls in the non-collide layer, I made the Raycast able to hit the wall but let the player go through it in case it was not built yet.

- *Gameplay Matchmaking Scene*: Here most of the essential work was done. I programmed the A.I. bots –excavator, crane, and two workers- to do certain activities or move following paths. I made some research on the new particle system manager of

Unity and I got to make the sparkles resulting of the work of one of the bots. Having then all the pieces set in place I started adding the scripts referencing the health and points scripts and controlling the amount of damage that was done when getting burnt by the sparks or run over by the excavator. Finally I made some changes on the "FallDamage" script because sometimes players were getting hurt when going down the stairs and I worked on the textures of the materials.

Figure 23: Gameplay Matchmacking Scene displaying all the game objects, AI bots, paths, terrain, textures, etcetera.

- *Virtual Reality Scene*: This scene was the scene where supposedly the virtual reality component had to be included, but that was impossible due to the following problems.
  - Android: Our first approach was to include the VR for the Android system, through the Google Cardboard. The problem that we had was that in the Lobby Scene, when trying the game with the VR, nothing was to be seen. This happened because the Network Manager HUD (the custom GUI that allows the player to have the necessary buttons to create a match and join games in the Lobby) is a special GUI provided by Unity. This special GUI doesn't have all the usual characteristics of other GUIs, which include changing their location between the World Space and the Local Space. The Network Manager HUD is set as Local Space, and that means that it always stays in the same position with respect to the camera. When moving the headset to interact with it, since it always moved with the camera, there was no way of "reaching" it. When we

found this problem we tried to set it to World Space, so it would be still in the same point, but the option was nowhere to be seen.

Moreover this GUI is always put in front of all the other GUIs, so the reticule of the VR system wasn't displayed either.

The solution to that is to create a custom Network Manager HUD from scratch, which is possible, but when this problem appeared there was no reaction time left.

- HTC Vive: After gathering some information we discovered that this issue was not a problem with the HTC Vive headset, but then another problem appeared. In order to use them all the controls would have needed to be changed, involving scripts, tags, game objects, etcetera. This was again an amount of time that we didn't have.

CHAPTER IV

VR EXPERIENCE

For the VR experience we wanted to make it fulfil certain aspects. First of all it had to make the player feel inside a real construction site. The obvious solution to that was to use the virtual reality, in order to feel the immersion and make the environment as real as possible to supply the lack of technology simulator centers. The other main objective was to recreate the construction site activity with the best precision possible, and that means having other people around, having a surrounding that changes constantly due to the comes and goes of the workers and their activities. That is why it was decided to use Networking. The possibility of interacting with another person playing with you makes the experience more similar to the real life, where most of the time workers are in teams performing the same activities. Also it provides the chance to train in distance and with multiple persons. In addition to that the textures and the audio had to feel real, and that is why all the audio is stereo. Also one really important part on construction sites is machinery. With some scripts we made a crane and an excavator that move and interact with the players inside the game. Moreover that led us to think that, since our experience was designed for two real persons, we could program some other workers that are not real players but A.I. bots, and that also perform their activities and interact with the user. Another goal that we set was to make the users learn for themselves, not through a series of inputs similarly to what they would do in a classroom. The objective was to join the experiential learning and the guided learning in order to get an efficient but organized learning.

A part from that, in the other simulations developed before, the only risk displayed was the fall from height. Now that there were A.I. bots and machinery around, we could take that a step forward and also program damage due to the machinery or by the work of other people. Finally the capacity to play with other people opened the possibility to make them compete and collaborate, just as in any construction site where to contractors have to do their jobs as fast as they can but depend on one another to do them.

With all of those goals set, we proceeded to design a storyline for the users to follow.

Storyline

Two players will enter the construction site, connected online. Their objective will be to build four walls in total, two in the first floor and two in the second floor. They will have to do it by transporting the blocks from the pile to the platform of the crane, and then pick them up on the top floor to build the walls. Their aim will be to do that in the least possible amount of time, and they will earn points every time they complete a task correctly. They will also earn points if they follow a safe conduct, equipping themselves with the helmet, earmuffs and harness if necessary, that will allow the players to connect themselves to the life line. They will lose points in case they lose life, and they'll die if their life score gets to zero. They can be hurt by falls to different level, by impacts or collisions against the excavator or the crane's platform and burned by the sparks resulting of the work of one of the AI bots. The two players will have complete freedom in the organization of their tasks. When the task is done they will have to exit the construction site.

The paths followed by the excavator intentionally intersect with the path that the players will have to follow to transport the materials from the pile to the crane. This is unusual in a construction site, and it would probably be indicated with alert signs, but for the sake of the learning in this very short experience it is done like this to train the workers to be focused all the time.

Main features and Innovation

- *Online Multiplayer*: Possibility to create tasks to be done by more than one person, where the actions of one can affect the other –putting someone at risk, altering their performance with their decisions, etc. -. Option to play and train from home due to the variety of 3D options that mobile devices have nowadays, playing alone or in group, even with a supervisor inside the game watching over everyone's performance.
- *Visual Application*: The new animation system and the recreation of all the actions in a graphical way allows not only an extra level of realism but the chance of communication between players to alert each other of possible mistakes they may be making (not wearing a helmet, being in the path of the excavator…).
- *Collaboration/Competition:* Objective of getting the maximum possible points in the minimum amount of time where collaboration is key (after all one person can do all the work by himself, but the amount of time would be way bigger than two persons collaborating, even if that means sharing the points). In more complex environments this can simulate the coordination between teams/workers/contractors which have to make certain activities with a limited amount of time and they have to share equipment, or depend on the activities of the others to perform theirs. The competition to finish in the least amount of time and the collaboration to be able to

keep on with your job make this feature a good reproduction of what may happen in a real construction site.

- *Non-Guided Experience*: No special instructions will be given except of the controls and the task to realise. No hints or inputs will be displayed inside the game or by any external person the help the players have a better performance. The objective is that they learn by themselves, by making mistakes, and that try after try they get all the necessary habits, like equipping the helmet, connecting themselves to the life line or not getting too close the machinery to win a few seconds to the clock. They will have total freedom in the paths to choose and to decide who is doing each task. At the end of the experience they will have a summary of their performance displaying the time, points and life, and in case of having a supervisor looking over he would give the players his feedback.
- *Team Training*: Overture to design training for teams of workers in dangerous situations, to simulate and practice coordination between machines or to enhance the performance of teams doing critical activities, helping to achieve a new level of efficiency and security in the construction site.
- *New Risks Included*: The virtual reality experience will have not only the fall to different level risk, but also the possibility to get burnt by the A.I. bot, to have an excavator run over you or to get hit by the moving platform of the crane, simulating then the three most common causes of injury in construction –falls to different level, hit by a moving vehicle and injured handling a workplace tool-.
- *A.I. Bots*: Scripted game objects acting as workers or machinery that can affect the performance in the game and that the players constantly interact with. In the full version you can play on-line with the A.I. bots, but it can always be turned down because the A.I. bots acting as workers are not essential for the job to be done, although they enrich it. Experiences can be had playing in multiplayer with no bots, with no multiplayer and bots, and with no multiplayer and no bots.

Construction Site Map

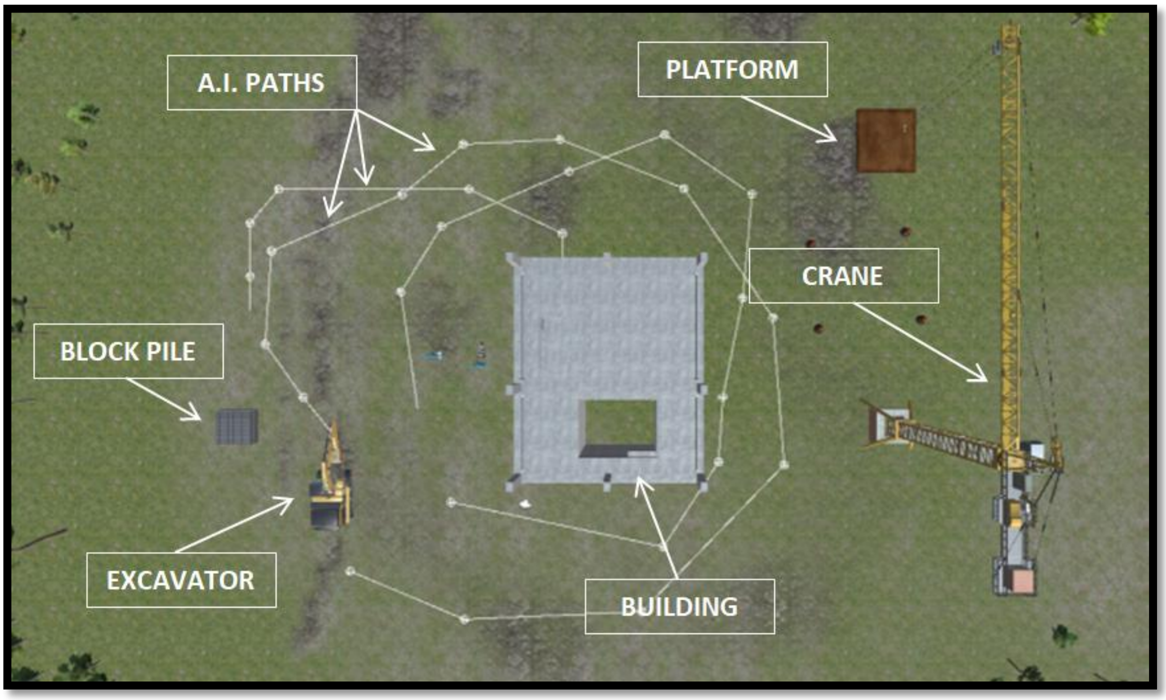


Figure 24: Top view of the construction site displaying the different parts of it.

In the image it can be appreciated the two storey building in construction in the middle, with the walls to build still invisible. There is an excavator that will follow one of the paths drawn in a white line, with white dots in the points where it changes direction. Looking closely on the image, at the left of the building, there can be seen the starting points of the two other AI bots. On the left of the Excavator there is the pile of blocks from where the players will have to take the material to the crane. Although the crane is also an AI its movement it's controlled by the clicks of the players whenever they load or unload the blocks from it.

In-Game Captures and Videos:

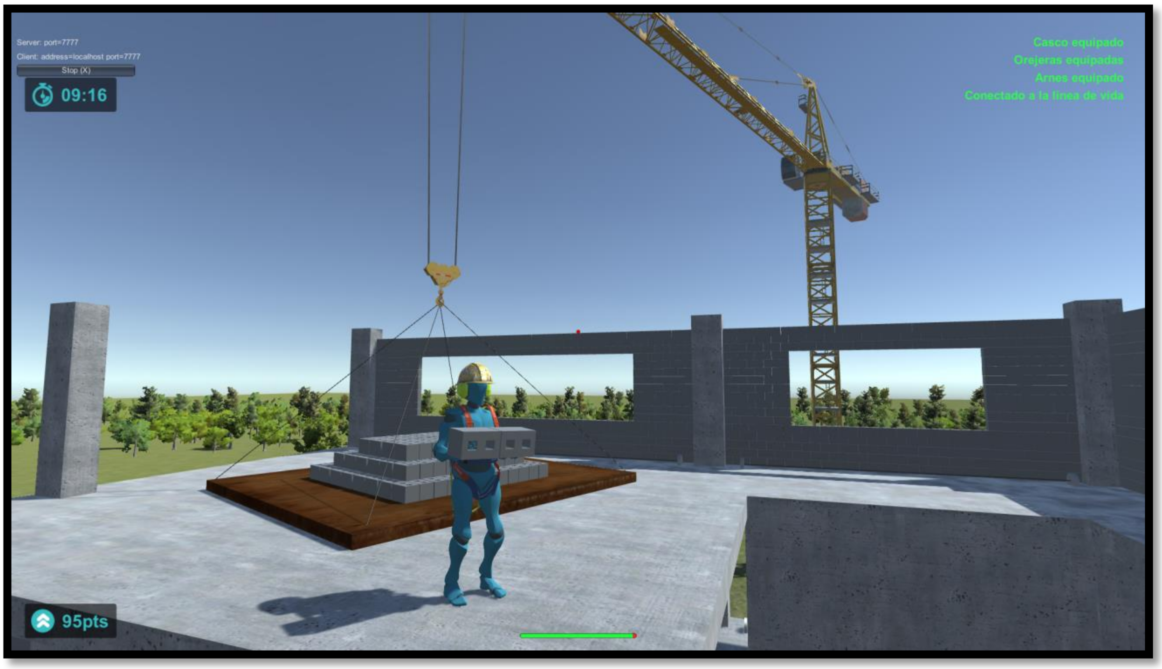


Figure 25: In-game capture of one of the players while it is building the wall from the view of the other player. It can be seen in the screen that the player we are watching has the helmet, earmuffs and harness equipped. On our player view we can also appreciate on the top right corner how it also has the helmet, earmuffs and harness equipped, and that it is connected to the life line. Also it can be seen that it has accumulated 95 points, that there is a remaining time of 09:16 minutes to complete the task and that at some point it lost a little bit of Health (Health bar at the bottom).

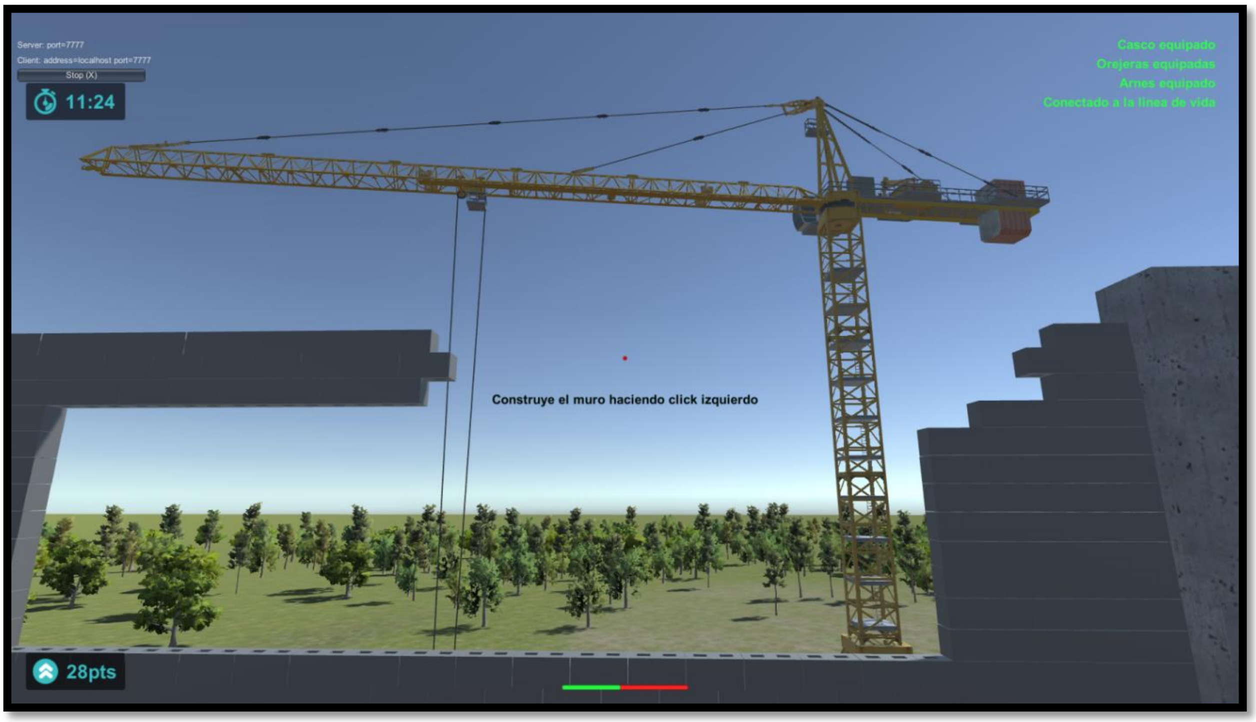


Figure 26: In-game capture of one of the players building a wall in the top floor. Since he has collected the blocks from the platform of the crane, when pointing to the wall to be built he is given the option to build it. It can also be appreciated that he has lost more than half its life for some reason.

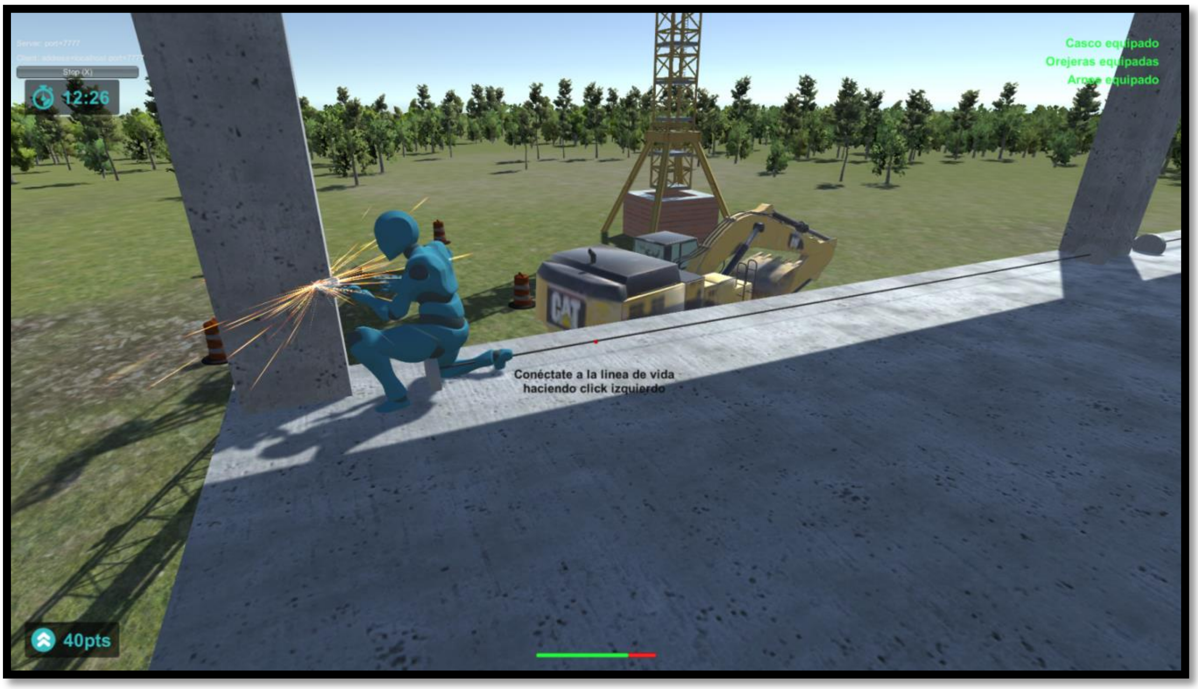


Figure 27: In-game capture of one of the players watching one AI bot perform a task. The particle system is a new feature in this project, and if the player gets too close to the sparks, it gets burnt and loses Health. It can also be appreciated the option that the game gives to the player to connect itself to the life line.

https://youtu.be/I6inIz8-wzY

Video 1 *[Recommendation: Watch the video with headphones. This way you'll be able to appreciate more the muffling effect of the earmuffs and the 3D sound changing directions as the camera –the player's head- changes its orientation]*: In this video we can see how to start the on-line game in the Lobby with two networked players. Then both of them enter the office and equip themselves with the necessary protective equipment. One of them goes to the top floor to await the materials being carried by the other player and lifted by the crane. In the process we can see how the player gets injured when it gets too close to the sparks and when the platform of the crane hits it.

https://youtu.be/-ZC3SYYaUCs

Video 2 *[Recommendation: Watch the video with headphones. This way you'll be able to appreciate more the muffling effect of the earmuffs and the 3D sound changing directions as the camera –the player's head- changes its orientation]*: Here you'll see how both tasks are performed through the view of one of the players. Also note how when the player is connected to the life line it cannot fall when it is on the edge.

https://youtu.be/uIc9FqX0hCY

Video 3 *[Recommendation: Watch the video with headphones. This way you'll be able to appreciate more the muffling effect of the earmuffs and the 3D sound changing directions as the camera –the player's head- changes its orientation]*: In this video it is shown how a player that's not wearing the harness and that is not connected to the life line can fall and die. When this happens, a small box with information about time, life and points will be displayed. It's also displayed when the time is over and when the work is finished.

ORP CONGRESS IN CARTAGENA DE ÍNDIAS, COLOMBIA

Due to the potential that the project was showing in joining VR with Networking, my supervisors proposed to me to present it in the international congress ORP in Cartagena de Indias, Colombia. Even though in the end we couldn't bring it because of the unexpected last minute incompatibility problem between the VR and Networking systems, I was able to travel there to help Ignacio Valero and Oscar de Coss with their tasks and presentations. During the week that I stayed there, I got the chance to meet a lot of important persons in the sector, share ideas with them and attend discussion tables where the most interesting topics were presented. I made lots of contacts of people that I really want to hear from again, given the energy and the passion that they put to their work. I also had the opportunity to learn from Oscar working by his side and helping him to introduce his project, and I'm sure this knowledge will be key in my future investigations regarding VR.

I was also glad to see that in one table of discussion there was a mention to the necessity of a multiplayer system when training workers with VR, which gave me a lot of moral, knowing that I had chosen a good path. That motivated me to explain to the assistants –whenever possible- my line of work, even if it was not presented in the congress, and the feedback was truly helpful.

I had an amazing experience at Cartagena, and I will never forget this opportunity. From the week I spent there I got 3 main conclusions:

- There were a lot of interesting ideas, but they desperately need to be implemented. They cannot end in a theoretical approach just floating in everybody's mind but never being applied. In the field that concerns me I think that VR is already past this point, but several companies asked for more concrete experiences related to each sector. Maybe it's time to put it to test in a regular construction site, get results, apply the feedback to improve it and listen to the companies that want personalized experiences, so that we can prove that the confidence that we have in this technology is well placed.
- Safety and Health is in good hands. Everybody in the congress had great ideas and pursued innovation to make the formation more effective and the work environment a safe place.
- VR is an attractive technology. Our stand was one of the most concurred, if not the most, and we got a lot of people coming to try it and asking for information about it. If

our development can meet the expectations and excitement of the companies, there is a bright future ahead for VR in the sector.

Figure 28: Me at the ORP congress in Cartagena de Indias, Colombia.

CHAPTER V

CONCLUSIONS

In this project we wanted to recreate a 3D environment in virtual reality technology featuring the most common risks in the construction site, where the students had the task to make certain activities while following the safety and health rules. After finishing the study, we can say that we have achieved almost all the proposed objectives.

In the review of the current state on safety and health formation we have seen the necessity to improve the way workers learn in order to prepare them in the safest possible way, since the methods nowadays haven't updated at the same rate that the industry has. While construction methods such as BIM and the digital twin concept keep gaining importance in the sector, the persons involved in it are stuck with the same formation that was taught decades ago. As can be seen in Chapter II, Virtual Reality is an asset that has helped in other sectors, and that can improve the performance of the people that trains with it. Therefore it is strongly advised to implement this technology in the future courses of safety and health and even in the industry as a whole.

The development of the 3D environment with the inclusion of the PPE and machinery was a success. The surroundings are detailed, with well-built textures, materials and sounds that provide the necessary realism to the experience. The interactions between player and machinery are accurate, and the crane was even programmed to react to the player's actions.

Probably one of the best achievements was the Networking multiplayer feature. The added value that this property gives to the project sets a wide range of possibilities for this kind of experience to grow. This implies an extra work to be done in the scripting and set up of the Unity inspector, but in the end the results are worth the effort. If until this day the challenge was to replicate real life activities in the construction site, such as the transport of materials or building walls, now the spotlight is on the capacity to make those activities happen at the same time in a collaborative action, in the same way as it is in reality, because after all a construction site is like a complex gear set that has to be as precise as possible, and this complexity can be – and has to be- trained, not only for the efficiency of the construction but for the safety of the workers. Moreover, the creation of AI bots is another step forward in the complexity of the scene. In this project the activities that they are performing are not putting the players in a huge risk, but still can make some damage to them, and with more development they can be key in future versions.

The collaboration system that we used in the project was a success too, giving the players the chance to participate in the same actions together but also to compete between them though a system of points. Again this feature is only possible thanks to the Networking, and it is interesting because the competition between different contractors can sometimes be a factor of risk in the construction site. Teaching workers to collaborate between each other to be efficient while competing with their colleagues in a safe environment is another aspect that can't be taught or practiced in a class.

Sadly the Virtual Reality feature couldn't be added due to the last minute problems related to its compatibility with the Networking system provided by Unity. It is a really interesting characteristic that should be added in future versions, and the only reason why it is not in this project is the fact that we had to develop first the Networking system to then realize that there was a compatibility problem. Unity "prefabricated" game objects and components are really helpful for starters, but at some point they lack the flexibility that custom complex games need. The two issues that were the most problematic were the Character Controller (a player controller that Unity provides so that starting developers can have a player immediately set up for testing), because its colliders doesn't have the usual characteristics of a collider (for example it collides with every other collider, but when coding it only detects the collision if the character controller is facing the collider that we are colliding with, completely ignoring the rest of directions), giving issues that would be easily avoided with a custom player controller built from scratch. The same happens with the previously mentioned Network Manager HUD or the Network Transform component, which has some trouble updating the transforms of parented objects through the network.

The testing of the application was divided in two parts:

- Technological: The application behaves perfectly in the network, either with LAN connection or in a match between different internet lines. The movements of the players are synched smoothly, as well as all the animations. The movements of the camera are precise and the amount of lag between the players is almost imperceptible, so the game experience is not affected. The resolution is HQ and the interaction of the person playing and the objects in the game is easy to understand, controlled mainly with the keyboard and the mouse, given the lack of the VR component. When played with low performance computers the game has low frame rates, but it works with most of the computers tested (the usual computers that can be found in any home).

- Functional: This functionality could not be tested because of the lack of VR, but after all the information gathered and the feedback from the ORP congress we can be optimistic about is functionality.

FUTURE LINES OF INVESTIGATION

Compatibility between Virtual Reality and Networking

This is one of the secondary objectives that due to the complexity of it was impossible to complete. It was an issue that could only be appreciated in the final stage of the developing process, when it was too late to go back and make the necessary changes in the prefabs, scripts, game objects, etcetera. For a true immersion and the optimal results, this is the most important next step to take in this field, and can provide the full potential of this project.

Detailed scripting and programming of a dangerous/complex machine

Reproduce the controls, movement and important characteristics of the desired machine. This would allow companies to train workers in those fields without risking either lifes or assets. Then it could be introduced in a VR experience as part of a multiplayer game (just as if one player was in charge of moving the crane on this one).

Prefab of Activities

In the same way you can create prefabs for Unity of your GameObjects, it would be incredibly helpful for the development of the VR concept and its implementation in the industry that the programming of activities for real-life constructions was done through script prefabs. That means that the programmer in charge of developing the experience would have a library with the scripts already written for most of the activities that can be performed in a construction site, in network behaviour and with all the necessary information commented in them (such as necessary properties of the game object/s the script is attached/referring to, tags, etcetera). This way the process of building a virtual environment to train specific workers for real life situations would be a fast job, consisting on importing the BIM model to Unity and preparing the properties of the objects that will interact with the players.

Training of Teams

Prepare specific multiplayer situations for complex or dangerous activities where the members of a team of work can practise to make the construction safer and more efficient. It could be supervised inside the game by the supervisor.

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