LAB University of Applied Sciences
Faculty of Technology, Lappeenranta
Double Degree Program in Civil and Construction Engineering

Michael Elstner

Use cases of Extended Reality in the construction industry

Thesis 2020

Abstract
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LAB University of Applied Sciences
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Instructor: Timo Lehtoviita, LAB University of Applied Sciences
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The thesis aims to give an overview about different use cases of Extended Reality in the construction field. With the latest hard- and software, there is a large space for pushing along the digitalisation. One objective of the research was to determine the dataflow from modelling programs to environments that support Extended Reality. The other purpose of the study was to collect and cluster the application of this technology. With the aim of a uniform classification, a new table schema was elaborated and supplemented by a lucid graph.

The study was carried out on a very general level that gives an overall understanding about Extended Reality. The information was gathered from own experience in the field and enriched by several online sources. The data was carefully selected to cover a preferably wide field. The idea of the thesis is based on the outcome of the education in Saimia UAS from the summer 2019.

A final result of thesis was that Extended Reality should be focused in research nowadays to improve the construction world. Based on the findings, the development is in progress but far below its potential. Further study is required to accompany the development constantly and keep the information up to date.

Keywords: Extended Reality, Virtual Reality, Augmented Reality, Augmented Virtuality, Mixed Reality, Use case

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Glossary

Technical terms for defining Extended Reality

The role of the observer describes the possibilities that the user of Extended Reality has when accessing the environment.

An active role is defined by editing existing content or creating new content.

A passive role is defined by only viewing and overlaying the content.

A showroom describes the environment where Extended Reality takes place.

A virtual showroom takes only place in a purely virtual environment.

A combined showroom takes place in the real and the virtual environment the same time, the ratio between them can vary between the extreme situations.

A real showroom describes the reality itself.

Types of Extended Reality

Extended Reality is a preamble for Virtual Reality, Augmented Virtuality, Augmented Reality and Mixed Reality.

In Virtual Reality content can be viewed inside a virtual showroom in the role of a passive observer.

In Augmented Virtuality content can be changed inside a virtual showroom in the role of an active creator. “Augmented” refers to the role of the observer.

In Augmented Reality content can be added to the perception in a combined showroom in the role of a passive observer. “Augmented” refers to the showroom which is upgraded.

In Mixed Reality the showroom as well as the role of the observer are “augmented”. Content can be changed in a combined showroom in the role of an active creator. Through that, it is the most advanced type of Extended Reality.

File formats

In a CAD-Format the boundary representations define the main structure and additional metadata is attached to this hierarchy.

The Mesh-Format is an optimized geometric saving option for rendering that is not including metadata about the structure.

General

Digital Twins are a virtual copy of real-world systems with fully parametric functions and include bundled data from multiple sources.

A Game Engine is defined as the basic software environment for developing computer games and other applications that base on the same principle.

A Head-Mounted Display is the preamble for all devices that are worn on the head and have a display for digital content built-in.

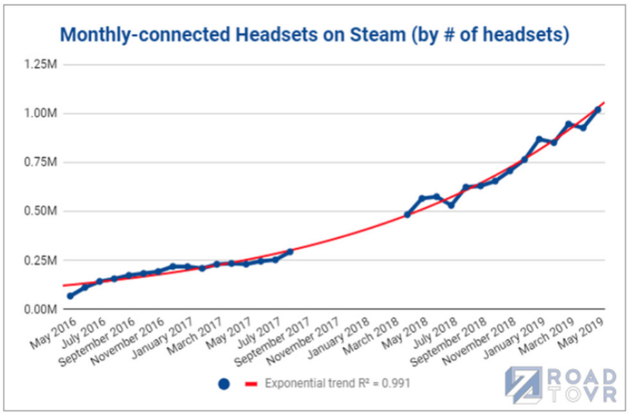
A Use Case is the specific application of a product solution in a certain manner.

1 Introduction

Extended reality experiences will change the everyday life of many people. That is foreseeable and definitely more tangible than a vague prediction. Considering the potential application fields, the presence will increase rapidly. This thesis will convey the necessary technical background with the aim of understanding data-flows. Deliberately the term Extended Reality (XR) is used, since there should be no containment on purely virtual devices. The distinction can be found in the Glossary and in chapter 2.2 Definition of XR categories. Especially for engineering purposes, the whole product spectrum is promising. It is useful to keep in mind that insights for the development are coming from many business sectors. For example, the gaming and film industry profits especially from the spreading through an increased interest in their products. It is funny enough that movies have predicted this possibility earlier and provided in promising before it was realised. However, it should be paid attention not to get lost in speculations. Bugs and restrictions will still belong for a while to the application. It remains to be mentioned that Extended Reality is growing together with Digital Twins. If these two aspects are combined, the profitability of each will be noticeably higher compared to a stand-alone treatment. In chapter 3 Enumeration of use cases, different initiatives are listed which have the impact to be a reference point. These detailed exemplifications are conveyed in a library format that is reappraised uniformly.

2 Background to Extended Reality

Extended Reality is one of the efforts to create a digital construction industry. Figure 1 shows the trend of connected headsets with the most famous operating platform Steam from the company Valve. It is obvious, that the growth is relevant and continuously raising.



Data gap from seven months of data misreported by Valve

Figure 1. Trend of Extended Reality (Forbes, 2019)

The application fields are incredibly various. In early stages, cinematography and military development have been in the foreground but nowadays it expands to many more aspects of private and work life. Engineering projects are getting easier and faster with having more efficient planning tools. The depiction of data is becoming an even smaller problem. Traditionally, the construction industry has been lagging in digital workflows. This seems to be in a change. Digitalisation in the office and on site are marching on with every new solution that is developed. In the following chapters, basics are mediated to have a sufficient background for the discussion afterwards.

2.1 History of Head-Mounted Displays

Extended Reality was not invented from one day to another. It took a long time of continuous improvement to enhance the ideas and come to a practically usable version. The underlying phenomenon of three-dimensional perception is binocular vision. This describes the way how our brain combines the picture from each eye to a single one and how it creates a feeling of depth. Stereopsis uses this effect for creating a 3D view out of 2D original. It has been Sir Charles Wheatstone in 1838 who has been able to design an apparatus for readjusting it. The function is very simple and shown in Figure 2. Two different images placed opposite to each other are reflected by 45 degree turned mirrors towards the eyes of the observer. Later in 1935, the first fictional glasses have been contrived by Stanley G. Weinbaum in his short story “Pygmalion’s Spectacles”.

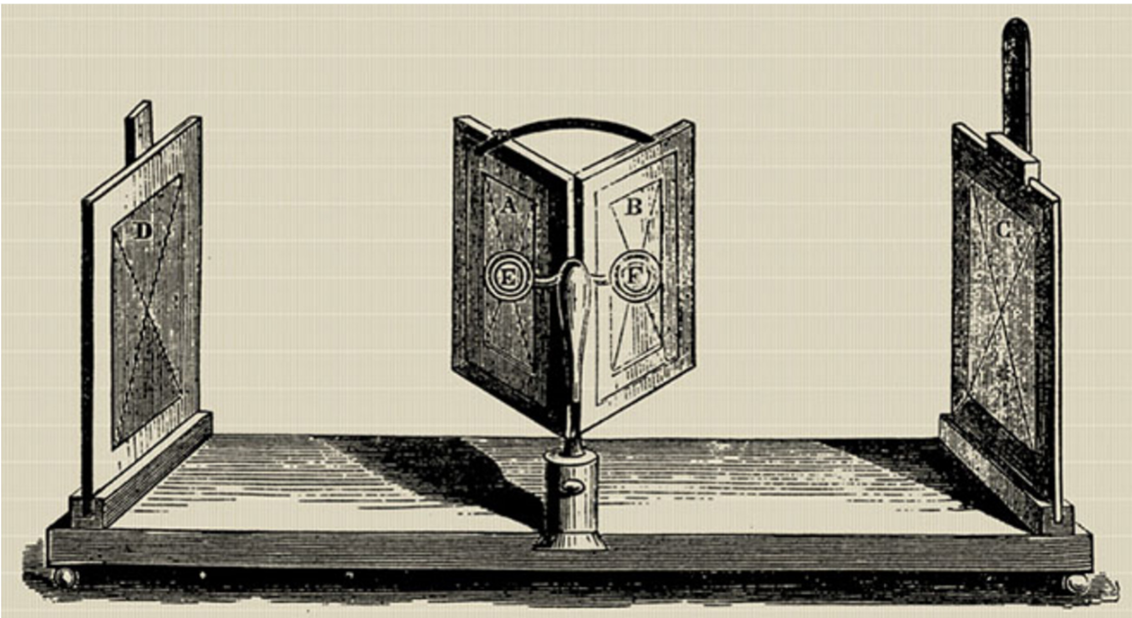


Figure 2. Stereopsis with a simple apparatus (Barnard, 2019)

The cinematographer Morton Heilig is the crucial inventor for virtual goggles that have been translated into action. On the 4th October 1960, he obtained the patent in the United States of America for working out the world's first Head-Mounted Display (HMD). It was able to create a three-dimensional vision supplemented by sound stereos but without motion tracking at this stage. The technical drafting for it can be seen in Figure 3 (Cross section) and Figure 4 (Spatial sketch).

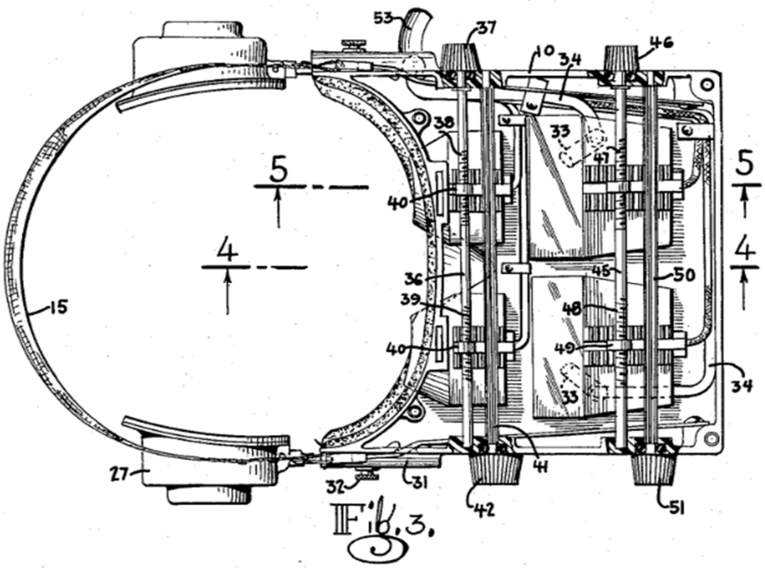


Figure 3. Cross section of the Head-Mounted Display (Heilig, 1960)

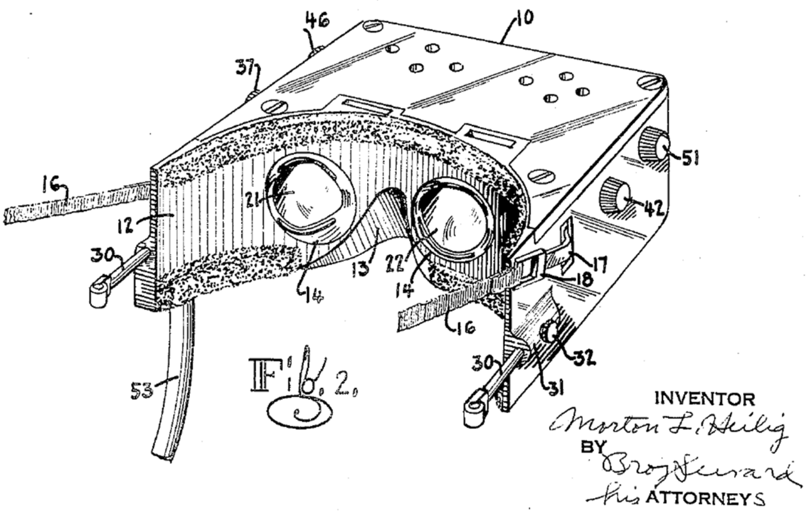


Figure 4. Spatial sketch of the HMD (Heilig, 1960)

In 1962, Morton Heilig patented also the Sensorama, a big VR box. He realised the idea of a large cabin with visuals effects and even more gimmicks. The sophisticated construction included atmospheric components for stimulating all the human senses.

Motion tracking was then invented in 1961 by the Philco Corporation engineers Comeau and Bryan. Their HMD called Headsight was affiliated to a remote camera which was displayed in the built-in video screens for each eye. The purpose was a military one, same as for the following development from Thomas Furness. He constructed the first flight simulator for the Air Force in 1966. The used 3D maps were generated by a computer and were including real data in the fields of avionics, radar and infrared. His efforts were taking a long while and culminated with the release of a flight simulator called “The Super Cockpit” in the 1980’s.

Ivan Sutherland was a pioneer in computer graphics and Harvard professor. The name for his Head-Mounted Display was nothing less than “The sword of Damocles” (view Figure 5). The displays from the glasses were connected to a computer which created frames with simple shapes when moving the head. Unfortunately, the only version was implemented in his lab and no other people than visitors came into the lucky circumstances to experience this milestone.

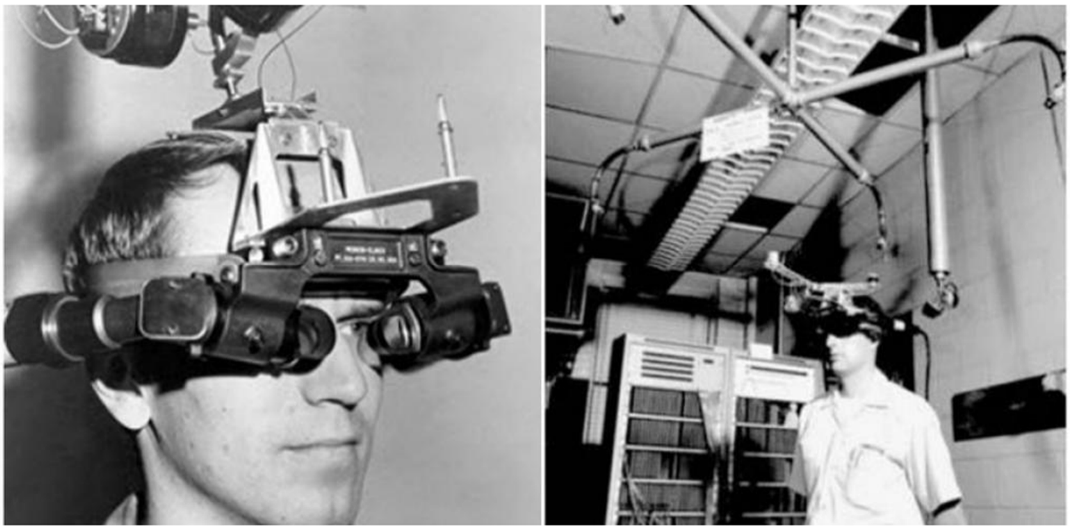


Figure 5. The Sword of Damocles from Ivan Sutherland (VRROOM, 2016)

For the formation of the term Virtual Reality especially Jaron Lanier needs to be mentioned. Together with Thomas Zimmerman he founded the company VPL Research Inc. which was developing and selling goggles and gloves for Extended Reality. (Barnard, 2019)

2.2 Definition of XR categories

Apart from the reality several different subtypes can be distinguished that all firm under the preamble of Extended Reality (XR). Since the demarcation varies widely in the common use and there are no standardized definitions currently declared, this thesis makes a proposal how to establish a clear-cut explanation. As characteristics are chosen the showroom where the observer is located and the role which he can occupy. The research is based on considerations from the company Unity which have been clarified, thought through and transformed into a uniform overall concept (view Unity3D, 2019a). The developed chain of arguments differs from some circulating opinions but makes the most sense in its conclusiveness. The single use cases will be classified according to this scheme.

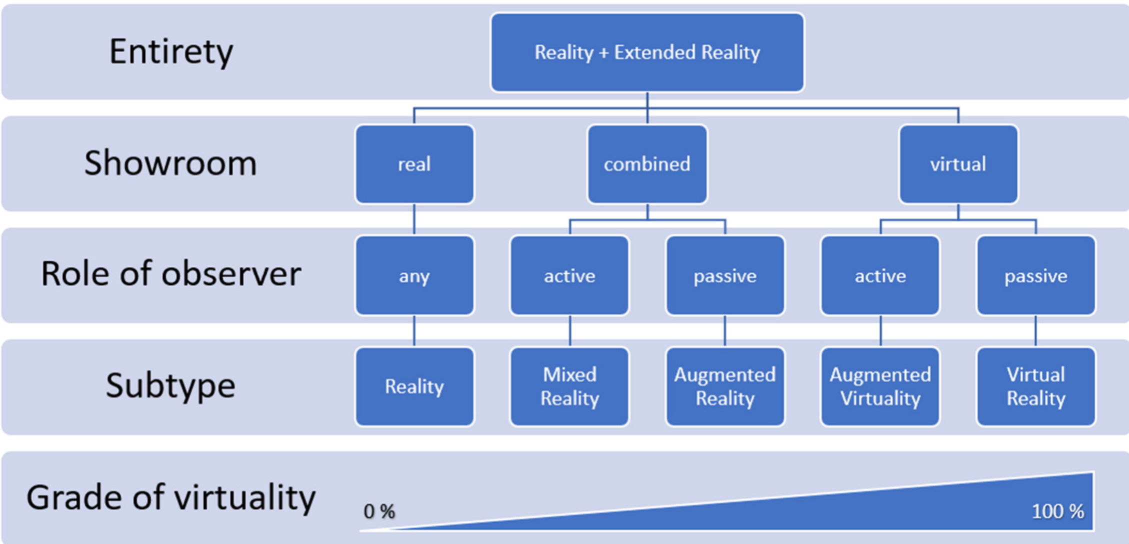


Figure 6. Demarcation of subtypes

Out of Figure 6 it can be seen that Mixed Reality is located nearest to the Reality and provides thereby the most helpful tool for the construction industry since the final aim of every project is the practical implementation. Augmented Reality differs from Mixed Reality in the way that the observer has the possibility to view and overlay content but not to make changes with it. In contrast to this passive role the active one is characterized by the deployment of methods like editing existing or creating new components. With both variants the sharing of content is feasible if the viewing devices support this function. Virtual Reality in the proper sense and Augmented Virtuality only take place in a virtual showroom that is completely sealed off from the usual perception. The two types differentiate themselves only through the role of the observer.

It would be desirable, if these stipulations prevail and find general recognition. Examples for the respective categories can be found in the classification table of the use cases that are following in chapter 3. All definitions can be read up in the Glossary and are considered from this point onwards as a basis for the discussion. An even bigger immersion can be achieved with using earphones. When applying the categories of Extended Reality for head-mounted displays, the biggest difference is between headsets for combined and for purely virtual showrooms. If besides Augmented Virtuality and Virtual Reality also a combined showroom should be supported, it is either necessary to have cameras built-in or guarantee a direct view trough the device. Controllers, joysticks or voice recognition are then defining if a device can be used only passive or also active. Since the active use includes already the passive one, Augmented Virtuality includes Virtual Reality and Mixed Reality includes Augmented Reality. Beyond that it is possible to overlay the real component in a combined showroom with most of the devices so that's why Mixed Reality mostly also enables Augmented Virtuality and Augmented Reality enables Virtual Reality.

Following is a more detailed definition of each subtype:

Virtual Reality (VR) takes place in an environment that is fully predetermined. The observer disconnects from the real world and dips into a fictional surrounding. Though the vision can be copied from the reality, the observer has no influence on it. Example: Walking through an animation of a project in planning

Augmented Virtuality (AV) is the progression of Virtual Reality where the observer interacts with the environment. The experience is not purely virtual anymore because the user influences directly (in real-time) the fiction. The description "augmented" needs to be understood in relation to the role of the observer. Example: Working on a project planning by drafting in the virtual environment

Augmented Reality (AR) differs from Virtual Reality in the point that the base is also the real world ("augmented" refers to the showroom). The real view gets revalued through the insertions but compared to Mixed Reality the content can't be changed inside the environment. Example: Fading in user manuals to the perception when executing maintenance work

Mixed Reality (MR) is understood as a combination of Augmented Virtuality and Augmented Reality where both, the showroom and the role, can be seen as "augmented". The real and virtual world are combined and the observer decides about the composition of them and is freely possible to design the elements. Example: Join erection planning and real view on site to do quality assurance

2.3 OpenXR standards

Similar to the efforts in the field of BIM, there is the interest to create common standards for the workflow with Extended Reality. In BIM the arrangements are for example the listing of the “Common BIM requirements 2012”, the initiative “Open BIM” and the file formats “IFC”, “COBie” and “BCF”. (Buildingsmart Finland, 2016). The connector for Extended Reality is the operating platform between the game engine and the viewing device(s). For creating smooth data flow, the Khronos Group has formulated open source interfaces. On one side the OpenXR Application Interface (API) regulates the communication between the operating platform and the game engine. And on the other side the OpenXR Device Plugin Interface determines the connection to devices from different hardware providers. This principle is graphically recorded in Figure 7. As an annotation, it does not make a difference if the end user accesses via application (first line) or directly via game engine (second line). In both cases, the game engine handles the commands and acts as the central knot on this level. All companies that are participating in the OpenXR initiative are listed in “Appendix 1. Participating companies in OpenXR”. (Khronos Group, 2019a)

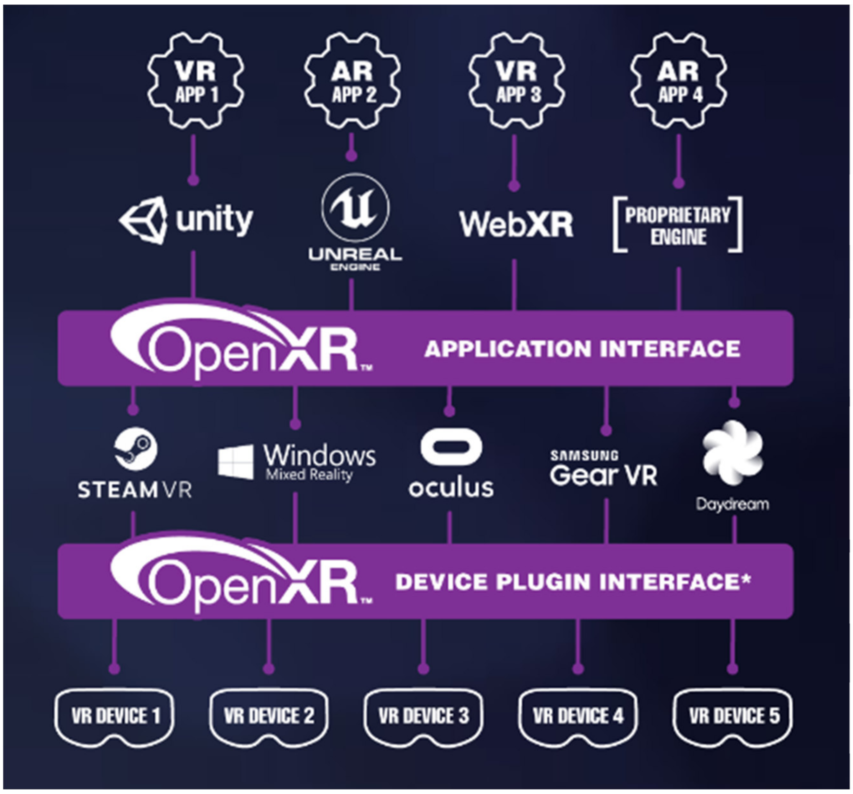


Figure 7. OpenXR concept (Khronos Group, 2019a)

To give a short statement about the formation of the Khronos Group, it can be mentioned that over 150 leading hardware and software manufacturers have united to an open industry consortium which is working out royalty-free standards. Apart from Extended Reality, other processed fields comprise 3D graphics, 3D asset authoring and machine learning. (Khronos Group, 2019b)

2.4 Visualizing devices

There are several different ways for visualizing Extended Reality experience. Depending on the showroom for which the viewers are made and the roles that the observer can take in, they are suitable for different types of the virtual spectrum. For a combined showroom, the headset needs either to be built with a direct view through or affiliated and synchronized with a camera. The role of the user is determined by the complementary equipment of controllers or voice recognition for working with the displayed view.

It is meaningful to cluster the devices after their functionality. The overview is not containing only head-mounted displays but also other visualization tools. Following is the list of different options:

- Any kind of XR
  - Head-mounted display with direct view or affiliated camera
- VR and AV (Showroom: only virtual, Role: optionally active or passive)
  - Head-mounted displays with sealed off view
  - CAVE (recursive acronym for CAVE virtual environment)
- VR and AR (Role: only passive, Showroom: optionally combined or virtual)
  - Mobile Phones
  - Tablets
- Only AR
  - HUD (head-up display)
  - VRD (virtual retinal display)
  - Smart glasses
- Only VR
  - Mobile phone powered headsets

Examples can be looked up in “Appendix 2. Viewing devices”.

The arrangement in a table enables a good overview:

Devices	Role: passive	Role: active
Showroom: virtual	**VR** - Sealed off HMDs - Mobile phones - Tablets - CAVE - Mobile-phone powered HMD	**AV** - Sealed off HMDs with controller - CAVE with controller
Showroom: combined	**AR** - Mobile phones - Tablets - HUD - VRD - Smart glasses	**MR** - HMDs with direct view or affiliated camera with con-troller

Table 1. Viewing devices sorted after their functionality

The devices differ a lot in their technical specifications and in the grade of devel-opment. Important key facts are named in the following:

- Display type (LCD/Dual LCD/OLED/AMOLED)
- Resolution (pixel x pixel, pixels per inch PPI, pixels per degree PPD)
- Refresh rate (frames per second FPS)
- Optics and Colours (infinite contrast ratio)
- Field of view (FOV)
- Tracking (Eye-, Face, Head-, Motion-, Position-)
- Headphones (Built-in/Off-Ear, possibly with spatial sound)
- Controller (need and interoperability)
- Operating platform
- Connectivity (wireless?)
- Expandability

2.5 Operating platforms

There is the need of a specific platform which allows to translate commands between the software of the game engine and the one from the viewing devices plus controllers. This central processing unit acts as a translator for demands from both sides and is thanks to the OpenXR standards compatible with almost every manufacturer. This operating software needs to be not only familiar with the most common features but also with every special capability that is offered by at least one device. All the head-, face-, eyes-, hands- or motion- tracking is recognized by the viewing software but the consequences need to be calculated from the game engine and transferred back to the viewing software. All this communication is running for a better compatibility over the operating platform. As mentioned in the OpenXR standards, it is a good hierarchy if every level of the software structure only communicates with its direct neighbours and uses standardised language. Following, the operating platform gives a common contact spot for addressing visualizers. If several sources are used, this is also the place where they are controlled centrally and synchronized with each other. In Plugins it is sometimes not visible that an operating platform is running but this is owed to a hidden execution in the background. A list of popular operating platforms can be found in “Appendix 3. Operating platforms for XR”.

2.6 Game engines

The most popular game engines for Extended Reality are Unity and Unreal Engine and beside of better renderings their main advantage in use is having dynamic models. The so-called rules are predefined settings that allow to give obstacles a certain behaviour. Unreal Engine seems in this manner more intuitive to use with the graphical Blueprint Editor. A unit within this visual programming language is a Blueprint Macro. Freely selectable functions can be bundled within this package and reused at any other place of the code. For the flow control and the management of global events, Blueprint levels need to be defined and considered when creating the global graph. Many ready-programmed sets of functionalities can be purchased from the Marketplace in Unreal Engine. In Unity the corresponding library is the Asset Store. (Unreal Engine, 2019a)

Figure 8 shows just one example how to define the behaviour of an object. The exact details from programming these rules are not relevant for this thesis. The advantages of game engines for construction purposes are significantly constituted by the possibility of defining intelligent rules that cannot be set with traditional software. With sufficient IT-knowledge, this is an attachement point to create improved planning tools. For example, analysis calculations can be integrated through coding within the game engine and visualized with its appropiate tools. The defining of rules creates a new path where Digital Twins go hand in hand with Extended Reality. Game engines can bring technologies together because their functionality and extendability is very huge. The platform which they offer for creating applications that can be linked together is incredible and allows to consider so many facets at the same place.

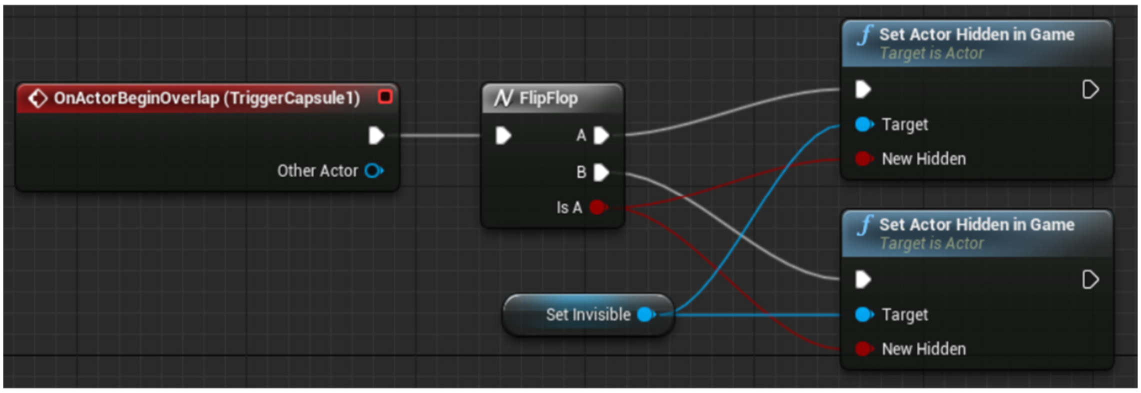


Figure 8. Examplary Blueprint for a switch (Unreal Engine, 2019a)

Unity and Unreal Engine as well as some other reputable ones are listed in "Appendix 4. Selection of some appreciable game engines". It is showy that companies from the United States dominate the business. Subsequently a range of viewing options is added in "Appendix 5. Compatibility of the Unity game engine with different viewer". An extension tool for game engines will be presented in the next chapter that allows the efficient conversion of CAD models to game engines by synchronizing them with each other. PiXYZ simplifies the dataflows and astonish with its functionality. Afterwards a software called Unity Reflect will be introduced that provides a specialized platform for many use cases that use game engines for their workflow. (Unity3D, 2019c)

2.7 Extensions for game engines: PiXYZ

This software has a very wide range of importable formats and at the same time a wide palette of viewers is compatible. More information is packed into ”Appendix 6. Compatibility of the Unity game engine with different viewer”. The big advantage to other converter programs is the live-link to game engines without any loss or duplicate of information. Furthermore, the program allows within the synchronisation also several purification methods. To understand, how PiXYZ is working, it is good to have a look on the format units. In general it is possible to distinguish between CAD and Mesh-Models as shown in Figure 9.

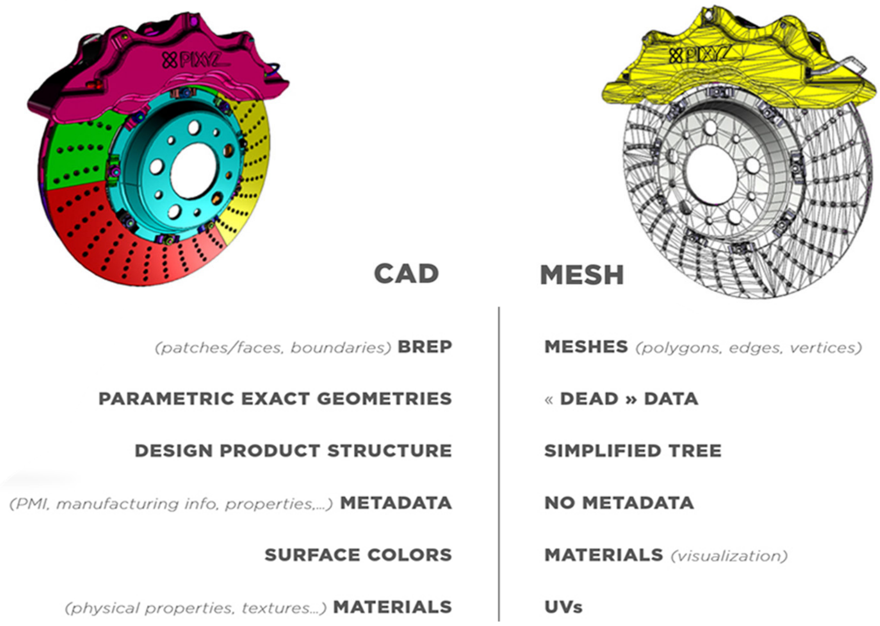


Figure 9. Difference between CAD and MESH format (PiXYZ STUDIO, 2018)

Mesh Models are reduced on geometric information but therefore specialised on the visualisation. CAD models are based on Boundary Representations (BREP) and contain additionally metadata like Product Manufacturing Information (PMI). When storing the data, the technical expertise needs to be stored in a CAD model and linked to an optimized visualization model in the MESH format. PiYXZ does this job and allows furthermore the export in various formats. The full list can be looked up in ”Appendix 7. Export formats supported by PiXYZ”. The synchronisation principle is illustrated in Figure 10.

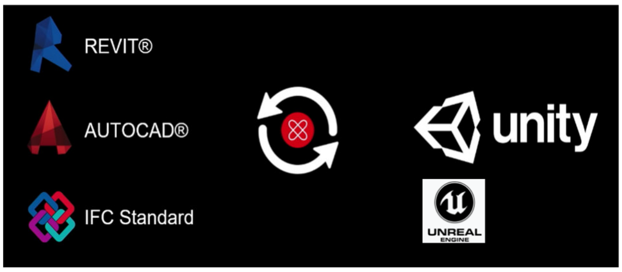


Figure 10. Synchronization with PiXYZ

In the following, several aspects will be named to demonstrate how models can be imported to PiXYZ in detail.

- Defining scale
- Set coordination system
- Select metadata wether to be imported
- Set UV settings for textures
- Select shader for optimizing rendering
- Create prefab folder where objects for reuse are stored
- Set Live Sync Mode with BIM software according to preferences

Depending on the choice of using the studio version or the Plug-In, the workflow is little bit different and less or more functions are provided. Different stages from an example project of Unity are portraied in Figure 11. For Unreal Engine the process would be similar. (Unity3D, 2018a)

Figure 11. Workflow from CAD-drawing to a fully rendered file (Unity3D, 2018a)

2.8 Extensions for game engines: Unity Reflect

Unity Reflect is a product which allows amongst other things the bidirectional transfer of data between construction software and visualisation software. The name "Reflect" is owed to the function as a synchronisation server which mirrors the models. Since the server keeps the structure of the files, different layers can be activated or disactivated. The principle is shown in Figure 12.

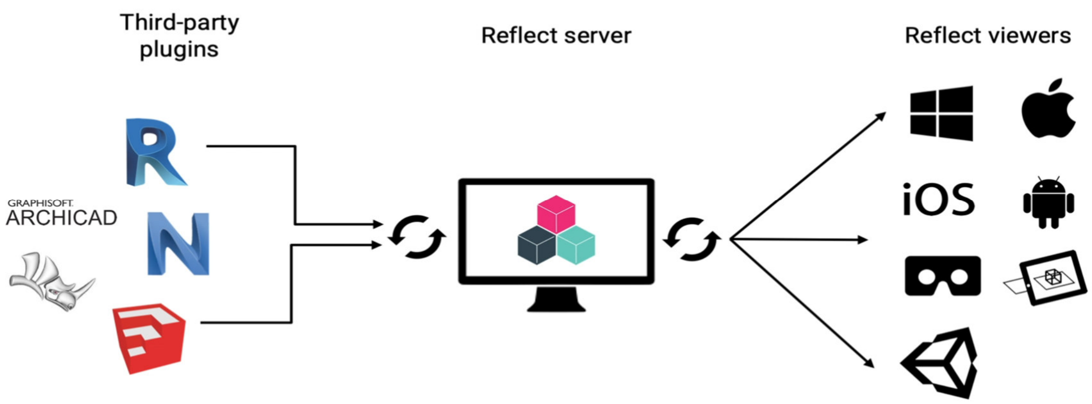


Figure 12. Schematic concept of Unity Reflect (Unity3D and SHoP, 2019)

The product is brand-new on the market and was just released in fall 2019. The mode of operation has several advantages, for example the interoperabilty of design tools from different environments and the integration of game engines in the development process. Thanks to the live-link and its structure as multi-platform, repitition of work by virtue of incompatibility is avoided. Time after time, this platform will be extended. The company has created an online workspace where new ideas are collected and brought into development. These are a few:

- PlugIns for ArchiCad, AutoCadCivil3D and 3DS Max
- Integration of the BIM360 platform
- Two-way link to other game-engines
- Point clouds in an integrated format
- Construction sequencing
- Importing drone photogrammetry and comparing to as designed-models
- Live-monitoring of cities for maintenance

(Unity3D, 2019c) (Unity3D and SHoP, 2019)

2.9 Workflow from CAD models directly to Digital twins

Digital Twins are a virtual copy of real-world systems with fully parametric functions and include bundled data from multiple sources. Unity cooperates with its verified solutions partner "Unit 040" for developing digital twins with the help of Extended Reality. The software-solution Prespective is advertised for merging virtual and physical worlds in a manner that is easy imitable. Following are some examples for data that can be stored together in a digital twin model: CAD, CAE, CFD, BIM, GIS, Sensor data, Point clouds, LIDAR, RADAR and GPS. With the information, monitoring can be carried out and many analyses can be evaluated. The way of using Prespective is presented in Figure 13 and is exemplary for the process of bringing CAD models to a Digital Twin file.

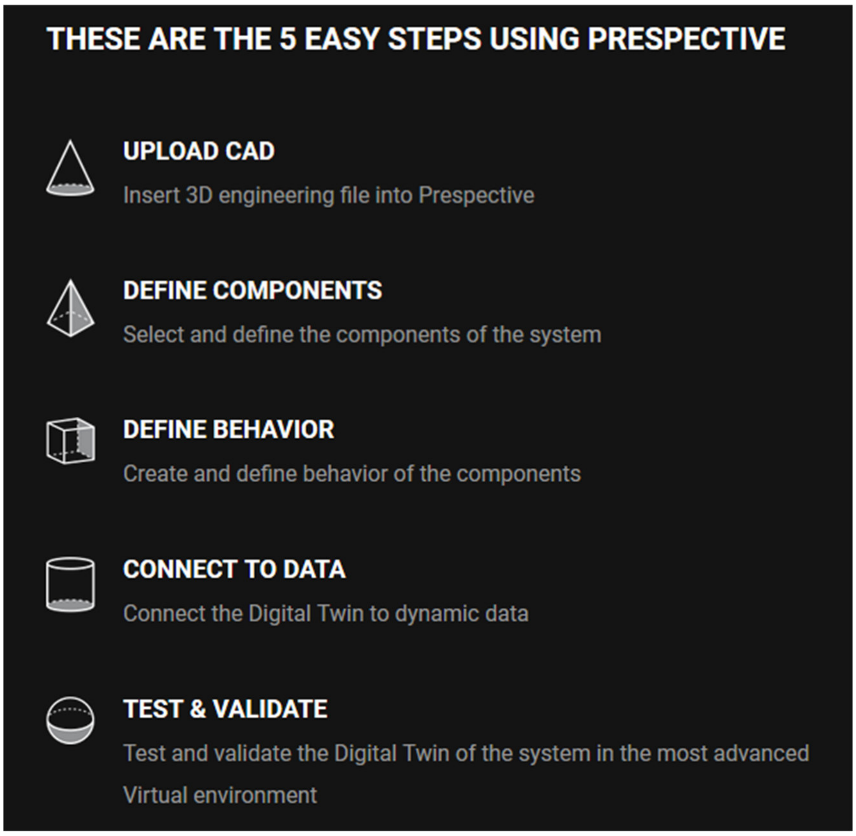


Figure 13. Steps of using Prespective (Prespective, 2019)

It can be resumed, that Unity is currently the platform of choice for creating digital content. The programs PiXYZ, Prespective and Unity Reflect represent valuable extensions of the functionality that cover a very wide range of useful application tools that can be also used together. (Unity3D, 2019d)

3 Enumeration of use cases

Before the different use cases are explained more precisely, it is a good idea to have in mind why uses cases are so valuable. It is nothing new that there is a difference between the theory that is taught in educational institutions and the practical knowledge that is needed when working in the industry. Especially for civil engineering this conflict is remarkable since most of the administrative work requires expertise from both worlds. Use cases help to build bridges and to avoid talking past each other. A foreman on a construction site has the best expertise about the usability whereas a developer of a BIM-tool knows very well the implementation of a solution. In the end, the simplicity and intuitiveness decide about the rentability of a system. This is one reason why user experience (UX) should be considered for developing. A very helpful tool therefore is the evaluation of use cases. They break down the logic from the technical hierarchy to the operability.

Bauen Digital Schweiz (Construction Digital Switzerland, BDCH) initiated a project to collect use cases and harmonize their structure by using a common template for all of them. This process is still ongoing but the first results are already visible. Several categories are used to cluster the instances. The first subdivision is made between Building Construction and Infrastructure. Very meaningful might be also the stage during the lifecycle: Concept Design, Developed Design, Technical design, Construction, Operate and Dismantling.

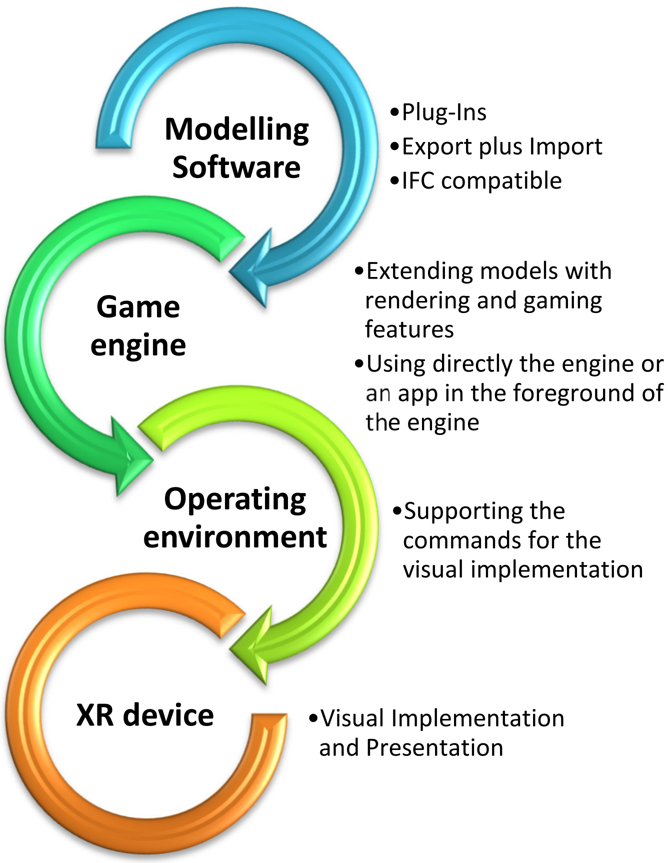


Figure 14. Process map for XR workflows

In a flowing text, different paragraphs give a further explanation about the use case: basics, description, benefits, objectives and distinction. It seems obvious to take the same kind of clustering in this thesis. Additionally, some use cases contain a process map for the workflow (view Figure 14). (Bauen Digital Schweiz, 2019)

New criteria have been added to give a more specific classification. In detail it is the year, the company which develops the XR application and the one which executes it. This allows an assessment about the future orientation. As an example, Fortum has a suite that includes a fully developed workflow (view Figure 15).

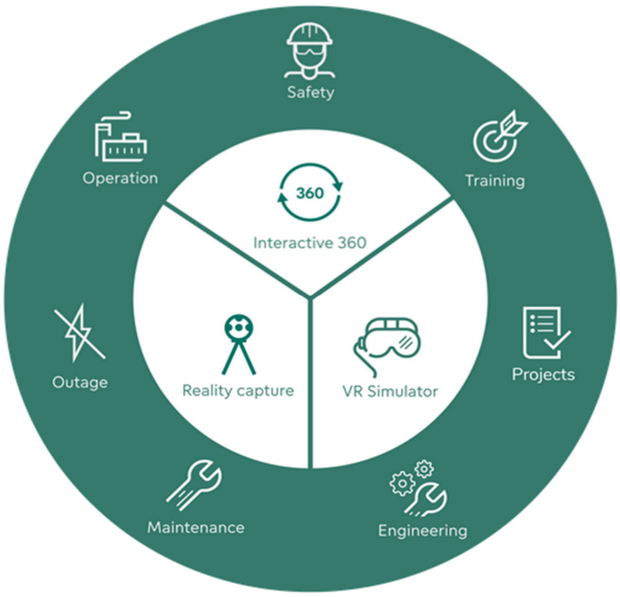


Figure 15. XR solution package eSite from Fortum (Fortum, 2019)

Another important distinction is the addressee who mainly uses and profits from using XR. Facts like the used equipment, the modelling software, the gaming software and the type of XR complete the classification of hard- and software. Last but not least the probably most useful difference is made between the purposes and the steps of working. The value of a solution can be estimated with the specification between the possibility of viewing, editing, creating and sharing. And the purpose can be the improved prediction of the user experience, the visualization of options for voting, the improvement of the marketing, the reduction of planning errors, the assistance in execution and the enhancement of safety. Not relevant answers are greyed out.

3.1 Evacuation simulation (Fire Safety Engineering)

Basics

The location for the study has been the tunnel system that will be built for the Future Circular Collider (FCC) from the European Organization for Nuclear Research (CERN). Since the tunnel will be between 300 m and 600 m deep under the earth, the way out is long and complicated. It is expected that the perimeter of the accelerator will comprise almost 100 km.

Description

Fire hazards can never be locked out completely. There will be always a remaining risk that fire occurs somewhere and people have to leave this area as fast as possible. If simulations have been done for different kind of scenarios, the behaviour of the affected humans can be evaluated ahead and used for intelligent signposts. Evacuation routes can be displayed according to the specific situation.

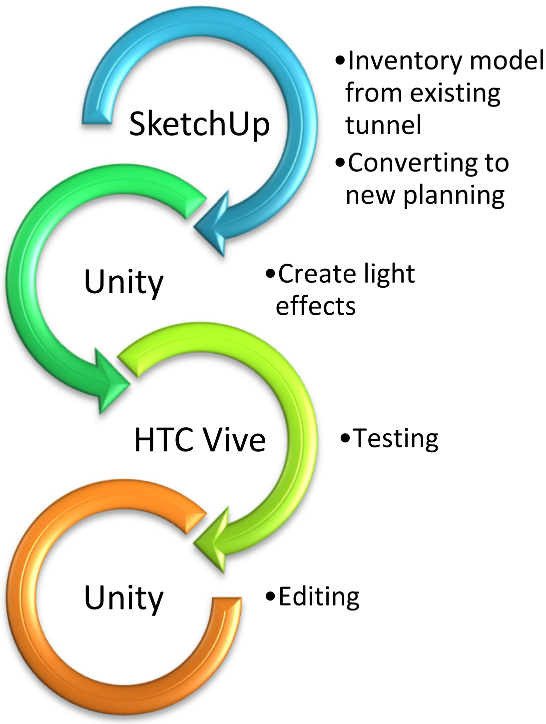


Figure 16. Process map

Benefits

If different routes for fleeing from the fire are tested with people that have the same view as the victims, they can give hints where to optimize the way-finding systems. Different concepts can be simulated and tested for their visibility. Furthermore, several way routes can be compared and dangerous localities tracked down.

Objectives

Fire evacuation concepts are getting much more practical when they have been tested with lifelike readjustment. Reactions of try people are much more meaningful compared to concept drawings. The predictability of human behaviour in fire hazards is increased and also the interaction between several people who are exposed to the same situation.

Distinctions

Compared to other use cases, the focus is on the marking of the way-leading signposts. They are based on light signals that are adjusted by the surveyors (view Figure 18 and Figure 19). Other methods, like sound announcements are not investigated. Furthermore, there is also no simulation how rescue workers can enter the tunnel and help the trapped people.

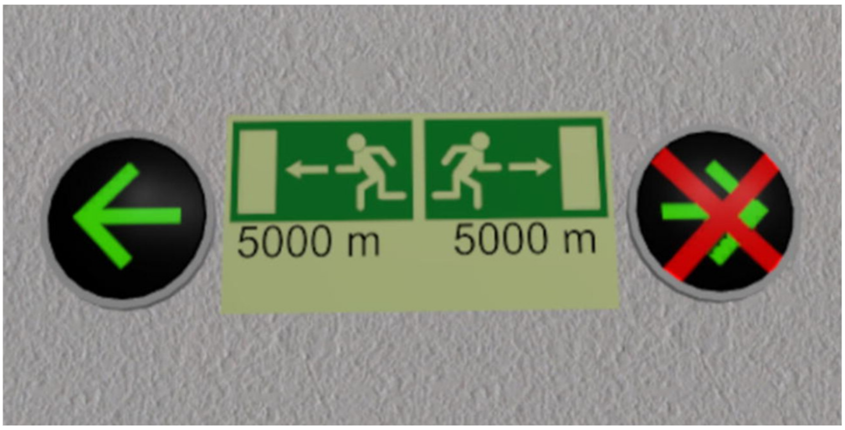


Figure 17. Dynamic way-leading (Silvia Arias et al., 2019)


Figure 18. Signposts near a door are tested for their visibility (Silvia Arias et al., 2019)

Classification table

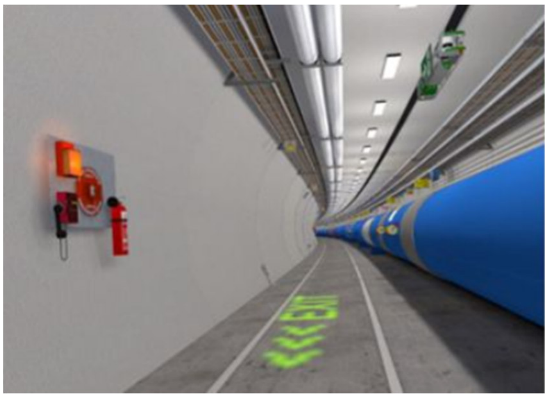
<table>
<tr><td>Object</td><td colspan="4">Future Circular Collider (FCC), Geneva, Switzerland</td></tr>
<tr><td>Subject area</td><td colspan="4">Fire Safety Engineering for Tunnels</td></tr>
<tr><td>XR-Developer</td><td colspan="4">Department of Fire Safety Engineering, Lund University</td></tr>
<tr><td>XR-Executer</td><td colspan="4">CERN, European Organization for Nuclear Research</td></tr>
<tr><td>Year</td><td colspan="4">2019</td></tr>
<tr><td>Picture</td><td colspan="4"></td></tr>
<tr><td>Field</td><td colspan="2">Building Construction</td><td colspan="2">Infrastructure</td></tr>
<tr><td rowspan="3">Stage</td><td colspan="2">Concept design</td><td colspan="2">Construction</td></tr>
<tr><td colspan="2">Developed design</td><td colspan="2">Operation</td></tr>
<tr><td colspan="2">Technical design</td><td colspan="2">Dismantling</td></tr>
<tr><td rowspan="2">Addressee</td><td colspan="2">Planner</td><td colspan="2">Worker</td></tr>
<tr><td colspan="2">Seller</td><td colspan="2">Owner</td></tr>
<tr><td rowspan="3">Purpose</td><td colspan="2">Predict user experience</td><td colspan="2">Reduce planning errors</td></tr>
<tr><td colspan="2">Visualize options for voting</td><td colspan="2">Assist in execution</td></tr>
<tr><td colspan="2">Improve marketing</td><td colspan="2">Enhance safety</td></tr>
<tr><td>Showroom</td><td colspan="2">combined</td><td colspan="2">virtual</td></tr>
<tr><td>Role of observer</td><td>Active</td><td>Passive</td><td>Active</td><td>Passive</td></tr>
<tr><td>XR Type</td><td>MR</td><td>AR</td><td>AV</td><td>VR</td></tr>
<tr><td>Equipment</td><td colspan="4">HTC Vive</td></tr>
<tr><td>Game engine</td><td colspan="4">Unity3D</td></tr>
<tr><td>AEC software</td><td colspan="4">SketchUP</td></tr>
<tr><td>Source</td><td colspan="4">(Silvia Arias et al., 2019)</td></tr>
</table>

Table 2. Classification of use case 3.1

3.2 Safer construction sites (Safety Training)

Basics

The whole study bases on construction sites from Skanska and their employees. The agency OutHere worked as external service provider but the meetings were held in a joint team with equal participation from both sides.

Description

The workers on construction sites are exposed every day to a lot of dangers. Safety-training programs help to enlighten them from time to time to refresh the relevant topics. Regulations on paper or recorded videos have helped in the past to fulfil this intention. With programmed happenings that can be experienced life-like, people get a much better understanding about the far-reaching consequences from carelessness.

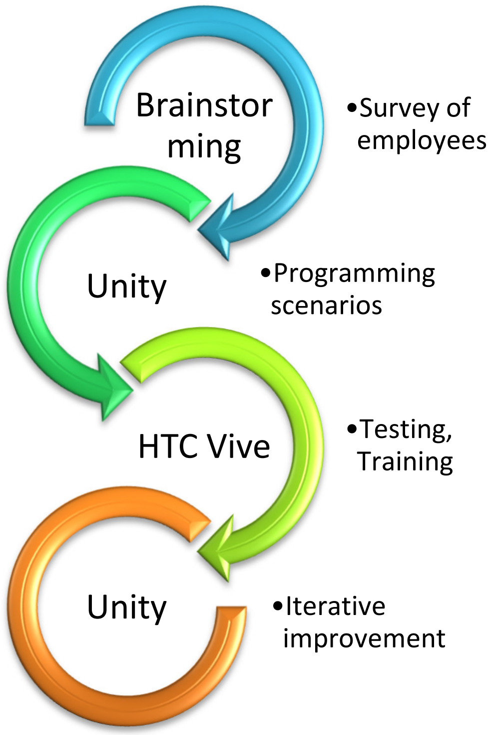


Figure 19. Process map

Benefits

Workers are getting aware of crucial safety factors after testing them in the virtual environment. The simulation is so realistic, that it creates memorable emotions for the viewer. When you have experienced consequences of accidents yourself, it is much more probable that you create associations with it. Resulting from that, workers can change wrong attitudes about safety and keep it better in mind during daily routines. It should get through these exercises their own motivation to reflect hazardous behaviour.

Objectives

The aim is to increase the safety on site by benefitting from already occurred cases. They can be analysed and communicated to everyone. Risks are not constantly the same. Workers should be able to recognize when they appear and disappear. As a side effect, also the work productivity can be boosted.

Distinctions

Different to other trainings, participants are getting challenged and need to make decisions in potentially risky situations. The earnestness is much higher than in other concepts. Prototypes are tested for accuracy and realism in many iterative steps with the help from affected workers. The produced models are interactive and react to the decisions of the user. This is a very unique improvement compared to the demonstration of determined show cases.

Figure 20. Simulations for safety training (OutHere, 2018)

Classification table

Object	Different exercise localities in Sweden			
Subject area	Safety Training for construction sites			
XR-Developer	OutHere, Gothenburg, Sweden			
XR-Executer	Skanska, Sweden			
Year	2018			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	HTC Vive			
Game engine	Unity 3D			
AEC software	No information found			
Source	(Unity3D, 2018b) (OutHere, 2018) (Skanska, 2018)			

Table 3. Classification of use case 3.2

3.3 Immersive hospital design (Furnishing planning)

Basics

Mortenson construction is a US-based company that is under the top 20. Their visual insight team has developed the design process of hospitals with AR planning tools. Two big clients are the University of Washington Medical Center and the Kaiser Permanente. The same progress in XR is also made for other big projects such as airports, universities or hotels.

Description

Client stakeholder and developer work together in a team which uses real-time 3D visualisations with interactive control. Through that, all staff members can participate in the planning, whether they are doctor, nurse, project manager or technical personnel. Amongst other things, work areas, medical instruments and light booms can be moved and placed in an enhanced way. Decisions about room dimensions, ergonomics, aesthetics, functional systems, and workflow efficiency can be matched very early from all participants.

Benefits

The benefits are obvious. Medical staff can scale their own workspaces and experience them in a stage when changes are still possible. Inconsistences can be discovered by the real experts and the ergonomics for staff and patients streamlined. The cost for creating physical models is inapplicable.

Objectives

New complexes can be approved by clients much better when it is possible to have an experienceable visualization. Collaboration gets way better when diving together into the 3D space.

Distinctions

Special about the usage of Unity is the integration of wide-ranging additional features to comply with even the most specific demands. The C# API is one of these extras that allow to integrate many different further developments.

Classification table

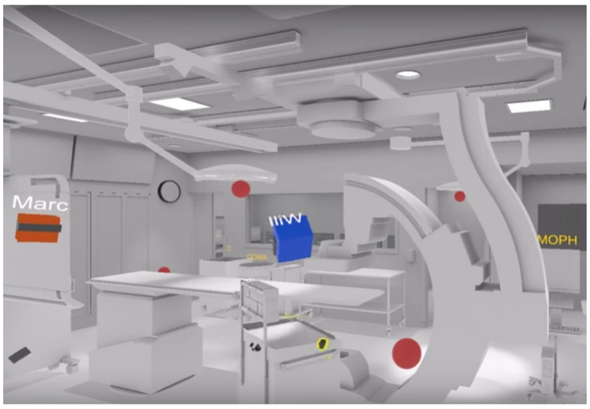
Object	University of Washington Medical Center, Seattle, USA			
Subject area	Furnishing planning for large-scale projects			
XR-Developer	Mortenson			
XR-Executer	Mortenson			
Year	2018			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	HTC Vive, Oculus Rift, Oculus Go, HoloLens, 360 video			
Game engine	Unity3D			
AEC software	3ds Max, SketchUp, Rhino			
Source	(Mortenson, 2018) (Unity3D, 2018c)			

Table 4. Classification of use case 3.3

3.4 Immersive airport design (Concept development)

Basics

Brisbane Airport Corporation (BAC) commissioned Aurecon Group with the planning of a new way finding system for the Brisbane Airport. Unsigned Studio is a team of global experts of Aurecon.

Description

For the arrival area at the International Terminal, the entry control point facilities have been brought up to date. A model of this space has been made and designers have tested it from the view of passengers. In the domestic terminal, a skywalk has been integrated. For this, special functions have been implemented to adapt the prevailing equipment and allow standardized modification tools.

Benefits

Adjustments can be done instantly during the virtual tour. Signage and markings can be tested for their formation and relocated with the help of the controller. Decisions are easier to make in the virtual environment than by viewing blueprints. The client can give immediately feedback about the changes.

Objectives

In the designing process, the end-user and his viewpoint are considered. For the client, this means less risk about bad assessments from passengers that are claiming about missing needs and disorientation.

Distinctions

The investigation has only been done for a new way concept and not for a complete airport planning. This makes it an example for the adaption of revised concepts for existing complexes. Since many airports will have an increased number of passengers, it will be very helpful to use it for the improved usage of old structures and if necessary, also for efficient extensions.

Classification table

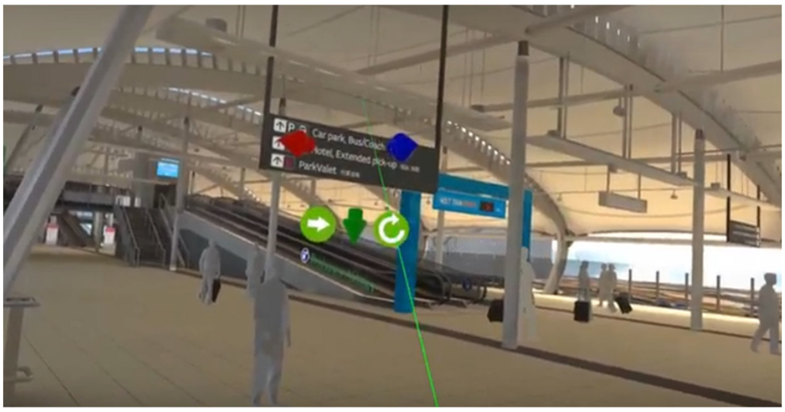
Object	Brisbane Airport, Brisbane, Australia			
Subject area	Concept development for large-scale projects			
XR-Developer	Aurecon Group			
XR-Executer	Aurecon Group			
Year	2018			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	HTC Vive			
Game engine	Unity3D			
AEC software	No information found			
Source	(Aurecon Group, 2018) (Unity3D, 2018d)			

Table 5. Classification of use case 3.4

3.5 Residential building in Lahti (Architectural model)

Basics

Vedenvälke is a residential building in Lahti which was designed and constructed by YIT Finland. For the poll about the building plans, Teatime Research created a VR tool to visualize different parameters that are important for the construction. This is also very usable for marketing purposes.

Description

In the early planning stages, the spaces and dimensions were visualized to set up the room list. A matching scenery was added to evaluate the view from the different apartments. Later on, interior details were included by the architects and materials and themes could be compared with each other.

Benefits

Interactions with the model helped to have an easy planning tool where changes could be proven through an advanced visualization. The model is so easy and intuitive to use that the implementation planning gets much simpler.

Objectives

The objective of the research is to get the whole process to an XR environment and save time in the preparation of the execution plans. Also, different themes can be tested and approved for their effect on the tenant. Wrong planned obstacles might get sorted out before they are brought to site.

Distinctions

YIT wanted to include specific brands into their planning so it was necessary to create new BIM objects for testing. With multiple revisions of similar projects, an extensive own library can be built up. This establishes a competitive advantage across from other construction companies who have to revise the same work every time again.

Classification table

Object	Vedenvälke, Lahti, Finland			
Subject area	Architectural model for block of flats			
XR-Developer	Teatime Research Oy			
XR-Executer	YIT Finland			
Year	2017			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	HTC Vive			
Game engine	No information found			
AEC software	No information found			
Source	(Teatime Research, 2017)			

Table 6. Classification of use case 3.5

3.6 Residential high-rise tower in Espoo (Interior design)

Basics

Similar to the block of flats in Lahti, the residential high-rise tower in Espoo sets a new epoch in the preparation of a building. Marketing strategists can fall back on much more impressive visualizations than before and react much better to individual wishes from customers. The hurdle of buying a flat gets lower with the decrease of risks due to a clear concept with Extended Reality.

Description

In this case, especially the interior design was investigated and the arrangement of the furniture changed. Lamps, sockets and technical equipment were included in the building plans and could be directly changed with the controller of the headset.

Benefits

Customers of the new building were very satisfied with their option on participation. Even if there have been many apartments to sell, the sale was running very well and the safety given that the size of the building was chosen right. Also, the single flats and rooms were confirmed in their size and orientation.

Objectives

The objective was the approval and simplification in the design process of such a big project. A residential tower in this size that is sold to that many different owners gets much easier to handle with the option on visualizing it with Extended Reality.

Distinctions

In further projects, also other parts of the planning could be done with the Digital Twin. It is an attempt for following cases to shift more and more workflows to virtual environments.

Classification table

<table>
<tr><td>Object</td><td colspan="4">Niittyhuippu, Espoo, Finland</td></tr>
<tr><td>Subject area</td><td colspan="4">Interior design for block of flats</td></tr>
<tr><td>XR-Developer</td><td colspan="4">Teatime Research Oy</td></tr>
<tr><td>XR-Executer</td><td colspan="4">SRV</td></tr>
<tr><td>Year</td><td colspan="4">2016</td></tr>
<tr><td>Picture</td><td colspan="4"></td></tr>
<tr><td>Field</td><td colspan="2">Building Construction</td><td colspan="2">Infrastructure</td></tr>
<tr><td rowspan="3">Stage</td><td colspan="2">Concept design</td><td colspan="2">Construction</td></tr>
<tr><td colspan="2">Developed design</td><td colspan="2">Operation</td></tr>
<tr><td colspan="2">Technical design</td><td colspan="2">Dismantling</td></tr>
<tr><td rowspan="2">Addressee</td><td colspan="2">Planner</td><td colspan="2">Worker</td></tr>
<tr><td colspan="2">Seller</td><td colspan="2">Owner</td></tr>
<tr><td rowspan="3">Purpose</td><td colspan="2">Predict user experience</td><td colspan="2">Reduce planning errors</td></tr>
<tr><td colspan="2">Visualize options for voting</td><td colspan="2">Assist in execution</td></tr>
<tr><td colspan="2">Improve marketing</td><td colspan="2">Enhance safety</td></tr>
<tr><td>Showroom</td><td colspan="2">combined</td><td colspan="2">virtual</td></tr>
<tr><td>Role of observer</td><td>Active</td><td>Passive</td><td>Active</td><td>Passive</td></tr>
<tr><td>XR Type</td><td>MR</td><td>AR</td><td>AV</td><td>VR</td></tr>
<tr><td>Equipment</td><td colspan="4">HTC Vive</td></tr>
<tr><td>Game engine</td><td colspan="4">No information found</td></tr>
<tr><td>AEC software</td><td colspan="4">No information found</td></tr>
<tr><td>Source</td><td colspan="4">(Teatime Research, 2016)</td></tr>
</table>

Table 7. Classification of use case 3.6

3.7 Snow castle in Kemi (Structural engineering)

Basics

The snow caste in Kemi is all year round opened but has cold and warm facilities. The cold area comprises 400 m^2, the heated one 3500 m^2. A scenic ice restaurant as well as ice sculptures make the stay of the guests to a special event. For building up this leisure park, the supplier Peikko has used the solution VirtualSite from Sweco. For the structural engineering part, the main program was TEKLA.

Description

The holiday area Kemi castle was designed and executed with the help of Extended Reality in different ways. When having a look at the program TEKLA, structures are visualized very basically in the integrated functions. When using VirtualSite, the possibilities are much more extensive because the participating engineers can collaborate and create content directly in the virtual environment.

Benefits

The VirtualSite solution offers various options for digital workflows. The functions are optimized for realizing difficult projects. Especially complicated content as for example the reinforcement plan can be viewed very understandable and more easily accomplished. Constructions, which would not be depictable in other plans, can be designed in the virtual environment.

Objectives

With the collaboration in structural development, designer and executer on site can work together more closely and profit from each other. Details can be discussed with the tools a long time before they need to be manufactured so that there is the time for changes.

Distinctions

At the moment, the application is made for a part of the whole construction and design process. In future, it can be extended much more so that the whole workflow is linked to the platform as a central unit.

Classification table

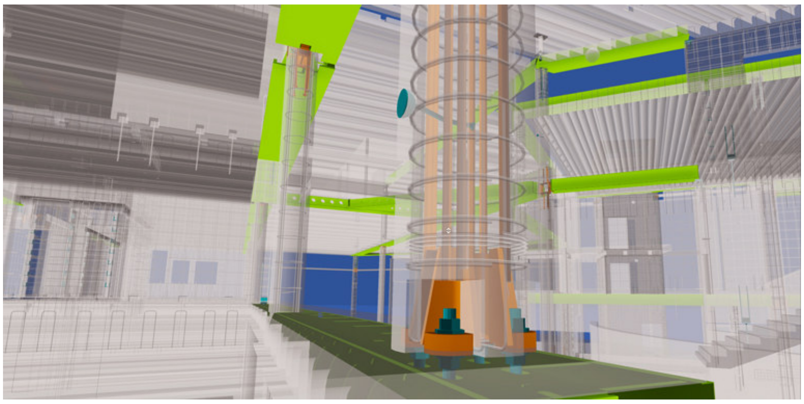
<table>
<tr><td>Object</td><td colspan="4">SnowCastle, Kemi, Finland</td></tr>
<tr><td>Subject area</td><td colspan="4">Structural engineering</td></tr>
<tr><td>XR-Developer</td><td colspan="4">Sweco Finland</td></tr>
<tr><td>XR-Executer</td><td colspan="4">Peikko Group Oy, Lahti (Finland)</td></tr>
<tr><td>Year</td><td colspan="4">2019</td></tr>
<tr><td>Picture</td><td colspan="4"></td></tr>
<tr><td>Field</td><td colspan="2">Building Construction</td><td colspan="2">Infrastructure</td></tr>
<tr><td rowspan="3">Stage</td><td colspan="2">Concept design</td><td colspan="2">Construction</td></tr>
<tr><td colspan="2">Developed design</td><td colspan="2">Operation</td></tr>
<tr><td colspan="2">Technical design</td><td colspan="2">Dismantling</td></tr>
<tr><td rowspan="2">Addressee</td><td colspan="2">Planner</td><td colspan="2">Worker</td></tr>
<tr><td colspan="2">Seller</td><td colspan="2">Owner</td></tr>
<tr><td rowspan="3">Purpose</td><td colspan="2">Predict user experience</td><td colspan="2">Reduce planning errors</td></tr>
<tr><td colspan="2">Visualize options for voting</td><td colspan="2">Assist in execution</td></tr>
<tr><td colspan="2">Improve marketing</td><td colspan="2">Enhance safety</td></tr>
<tr><td>Showroom</td><td colspan="2">combined</td><td colspan="2">virtual</td></tr>
<tr><td>Role of observer</td><td>Active</td><td>Passive</td><td>Active</td><td>Passive</td></tr>
<tr><td>XR Type</td><td>MR</td><td>AR</td><td>AV</td><td>VR</td></tr>
<tr><td>Equipment</td><td colspan="4">No information found</td></tr>
<tr><td>Game engine</td><td colspan="4">VirtualSite (Sweco’s own service)</td></tr>
<tr><td>AEC software</td><td colspan="4">Tekla (BIMsight, Structures)</td></tr>
<tr><td>Source</td><td colspan="4">(Sweco, 2019)</td></tr>
</table>

Table 8. Classification of use case 3.7

3.8 HVAC equipment rooms (MEP design and maintenance)

Basics

The planning of HVAC structures comprises a lot of technical equipment. The execution requires a precise planning because the tolerance is very small. The different parts have to fit very well together, otherwise the function is not suffused.

Description

Kolmeks Oy made an inventory model from existing spaces with a 3D-scan and added new MEP installations. Through that, the collision with old structures can be checked and also a superposition between old and new parts made.

Benefits

For the MEP planning the tools connected to Extended Reality are very useful since the installation is complicated with so many pipes and connectors and a good visualization helps a lot. Furthermore, building in existing spaces is an actual theme that needs a lot of attention because it grows continuously.

Objectives

With the digitalisation of the MEP sector and all the HVAC installations, the work for designer as well as for executer will get much more flawless. Collisions will be recognized even earlier and nested constructions can be thread better.

Distinctions

The recording with 3D-scans can also be very helpful for other planning tasks than only MEP. Existing structures are often very complicated and not so easy to depict. When virtual tools help to dissolve problems, it is a big help. With the link to the classic planning tools that already exist, a good extension is created that allows bring data faster from one program to another.

Classification table

Object	Rental housing located in Kaarina, Finland			
Subject area	MEP design and maintenance			
XR-Developer	CTRL Reality			
XR-Executer	Kolmeks Oy			
Year	2018			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	No information found			
Game engine	No information found			
AEC software	3D Scan			
Source	(CTRL Reality, 2018) (KIRA-digi, 2018)			

Table 9. Classification of use case 3.8

3.9 Highway 41 in Iceland (Infrastructure design)

Basics

Infrastructure projects take place on a big area and hinder many people. In the construction time, temporary constructions are often necessary and need a good preparation. In the past, the planning was not considering the surrounding residents that much into the process. With the virtual models of the infrastructure activities, this will change.

Description

The program Twinmotion is a young tool that comes from the game industry. It tries to make a bridge to construction applications. With a whole highway and the surrounding infrastructure, the integration reaches a new level in the industry. When these elements should be more than only functional, it is a good idea to have also promising tools for the depiction of the planning.

Benefits

Landscapes have not been subject of traditional engineer duties. When common leisure areas are opened, designers are requested to bring a concept and decide about the composition. Nowadays, it is wanted that also other places fit well into the skyline. This makes it necessary to use virtual animation tools also for other infrastructure projects.

Objectives

The correct design of infrastructure is essential for the user since it is loaded very hard and has to last for many years. With the right planning tools, the durability can be increased enormously.

Distinctions

For this highway in Iceland, only the planning was done in a virtual program. When considering also the construction time, a lot of useful applications can be processed there. The traffic animation will help to test different options and decide for the best functioning one. Simulations are the ideal tool to improve infrastructure and relieve bottlenecks.

Classification table

Object	Reykjanesbraut (Highway 41), Iceland			
Subject area	Infrastructure Design			
XR-Developer	EFLA, Iceland			
XR-Executer	EFLA, Iceland			
Year	2019			
Picture				
Field	Building Construction		Infrastructure	
Stage	Concept design		Construction	
	Developed design		Operation	
	Technical design		Dismantling	
Addressee	Planner		Worker	
	Seller		Owner	
Purpose	Predict user experience		Reduce planning errors	
	Visualize options for voting		Assist in execution	
	Improve marketing		Enhance safety	
Showroom	combined		virtual	
Role of observer	Active	Passive	Active	Passive
XR Type	MR	AR	AV	VR
Equipment	No information found			
Game engine	Twinmotion			
AEC software	Autodesk			
Source	(Unreal Engine, 2019b)			

Table 10. Classification of use case 3.9

4 Conclusion

The selected use cases show that the application of Extended Reality is possible very widely in the construction business. Game engines bring life into models and make them dynamic. Various simulations get feasible through the features that have been developed for the film- and game industry already a long time ago. Connector programs provide a bidirectional connection to traditional planning software and help that data flows smooth. PiXYZ, Unity Reflect and Prespective are just a few examples for those applications. With the OpenXR standards basics are laid that bring the communication between different providers to a common language. The result is interoperability between game engines and viewing devices. Digital twins fit perfectly to the development of Extended Reality and are made more lucidly.

In every process connected to the realisation of construction projects, Extended Reality can be helpful. Even if the most spread understanding only considers the visualisation, other improvements are occurring. The digitalisation creates a work space where collaboration and teamwork are made simple. Members of a project can enter a virtual or partly virtual environment together with other participants and discuss important matters in a comprehensible surrounding. The behaviour of objects in planning can be predicted more accurately and the satisfaction with the final product increased. Extended Reality will be the nuts and bones for a modern construction world with a minimal amount of errors and a maximum of effectiveness. A lot of expertise can be stored purified within the software from nowadays.

It does not matter if the project is a private or a public one, the end user can be involved in the development and vote between possible options. It is no wonder, that marketing can be pushed along and more enthusiasm for construction projects is awakened. Workers can be supported in their execution tasks and progress on site brought to a new level. Extended Reality has the potential to bring disputed people together and let them work together through less miscomprehension and the prevention of a lack of communication.

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Appendices

Appendix 1. Participating companies in OpenXR

Figure A1.1. List of Participants in OpenXR (Khronos Group, 2019a)

Appendix 2. Viewing devices

Devices for mainly AV and VR	
	**Remarkable:** ***AV + VR*** • Most advanced technology in the world • Ultra-High resolution • Pro-version with hand-tracking **Versions:** VR-1, VR-2, VR-2 Pro **Source:** https://varjo.com/products/
	**Remarkable:** ***AV + VR (+ AR + MR in future)*** • Best-in industry room scale-tracking • Up to 4 base stations can be combined • Playing area up to 10 x 10 meters **Versions:** Valve Index **Source:** https://www.valvesoftware.com/en/index
	**Remarkable:** ***AV + VR (+ AR + MR in future)*** • Vive Focus is standalone working without wire, computer, base stations and sensors • Widespread distribution • Easy affordable **Versions:** Vive, Vive Pro, Vive Cosmos, Vive Focus **Source:** https://www.vive.com/eu/
	**Remarkable:** ***AV + VR*** • Quest is All-In-One VR • Simple Handling • Increased tracking features **Versions:** Go, Rift, Rift S, Quest **Source:** https://www.oculus.com/?locale=en_EU

Table A2.1. List of devices that support mainly AV and VR

Devices that also support MR	
magic leap 	**Remarkable:** ***MR + AR (+ AV + VR)*** • Unique design and technology • Prescription insert and spatial audio • Superpowered Lightpack **Versions:** Magic Leap One **Source:** https://www.magicleap.com/magic-leap-1
	**Remarkable: MR + AR + AV + VR** • Photorealistic mixed reality • Ultra-low latency • Switching between MR and VR possible **Versions:** XR-1 **Source:** https://varjo.com/products/xr-1/
	**Remarkable: MR + AR + AV + VR** • Eye-based rendering • Built-in spatial sound • Head, Eye, Hand and Motion Tracking **Versions:** Hololens, Hololens 2 **Source:** https://www.microsoft.com/en-us/hololens/hardware

Table A2.2. List of devices that also support MR

Devices that only support AR	
	**Remarkable:** • Ergonomic and modular built-in design • Indoor and Outdoor Use • Hands-Free User-Interface **Versions:** DAQRI Smart glasses **Source:** https://daqri.com/products/smart-glasses/
	**Remarkable:** • Easy to handle development platform • Live video streaming • Seamless integrated CPU **Versions:** Glass Enterprise Edition 2 **Source:** https://www.google.com/glass/tech-specs/
	**Remarkable:** • Very powerful • Safety certified • Linking with drone possible **Versions:** Vuzix Blade Smart glasses, M-Series **Source:** https://www.vuzix.com/products

Table A2.3. List of devices that only support AR

Appendix 3. Operating platforms for XR

Logo	Name	Company
	SteamVR	Valve
	Oculus	Facebook
	Daydream	Google
	Mixed-Reality	Microsoft
	OSVR	Sensics, Razer

Table A3.1. List of operating platforms for XR

Appendix 4. Selection of some appreciable game engines

Game engine	Company	Headquarter
unity	Unity Technologies	United States
UNREAL ENGINE	Epic Games	United States
Twinmotion	Epic Games	United States
lumberyard	Amazon Game Studios	United States
CRYENGINE	Crytek	Germany
VRED	Autodesk	United States
MAYA LT	Autodesk	United States
UNIGINE	UNIGINE Holding	Luxembourg
GODOT	Software Freedom Conservancy (SFC)	United States
PREPAR3D	Lockheed Martin Prepar3D	United States
vuforia engine	PTC	United States

Table A4.1. List of game engines

Appendix 5. Compatibility of the Unity game engine with different viewer

Unity for VR and AR				
Oculus	Google Cardboard	SteamVR	PlaystationVR	GearVR
Windows Mixed Reality	Google Daydream	Apple AR Kit	Google ARCore	Magic Leap

Unity for desktop			
Windows	MAC	Linux/ Steam OS	Universal Windows Platform

Unity for mobile phones			
iOS	Android	Windows Phone	Tizen

Unity for console			
Playstation4	XboxOne	Nintendo Switch	Nintendo 3DS

Unity for web
WebGL

Table A5.1. List of viewing options for Unity (Unity3D, 2019b)

Appendix 6. Import formats supported by PiXYZ

FORMAT	EXTENSIONS	TESSELLATED	BREP	PMI
ACIS	SAT, SAB	🟢	🟢	⚪
AutoCAD 3D	DWG, DXF	⚪	🟢	⚪
Autodesk Alias **(1)**	WIRE	⚪	🟢	⚪
Autodesk FBX	FBX	🟢	🟢	⚪
Autodesk Inventor	IPT, IAM	🟢	🟢	⚪
Autodesk Revit	RVT, RFA	Dev/Beta	⚪	⚪
Autodesk VRED **(2)**	VPB	🟢	🟢	⚪
CATIA V4	MODEL, SESSION	⚪	🟢	🟢
CATIA V5	CATPart, CATProduct, CATShape, CGR	🟢	🟢	🟢
CATIA V5 [3DXML]	3DXML	🟢	🔴	🔴
CATIA V6 [3DXML]	3DXML	🟢	🔴	🟢
Creo - Pro/E	ASM, NEU, PRT, XAS, XPR	⚪	🟢	🟢
COLLADA	DAE	🟢	🟢	⚪
CSB Deltagen **(3)**	CSB	Dev/Beta	Dev/Beta	⚪
glTF	GLTF	🔴	⚪	⚪
IFC **(4)**	IFC	🟢	🔴	⚪
IGES	IGS, IGES	⚪	🟢	⚪
JT	JT	🟢	🟢	🟢
OBJ	OBJ	🟢	⚪	⚪
Parasolid	X_B, X_T, P_T, P_B, XMT, XMT_TXT, XMT_BIN	⚪	🟢	⚪
PDF	PDF	🟢	🟢	🟢
PLM XML	PLMXML	🟢	🟢	⚪
PLY	PLY	🟢	⚪	⚪
Point Cloud	E57, PTS, PTX	Points	⚪	⚪
PRC	PRC	🟢	🟢	🟢
Rhino3D	3DM	🟢	🟢	⚪
SketchUp	SKP	🟢	⚪	⚪
Solid Edge	ASM, PAR, PWD, PSM	🟢	🟢	🔴
SolidWorks	SLDASM, SLDPRT	🟢	🟢	🟢
STEP	STP, STEP, STPZ, STEPZ	🟢	🟢	🟢
StereoLithography (STL)	STL	🟢	⚪	⚪
U3D	U3D	🟢	⚪	⚪
Unigraphics-NX	PRT	🟢	🟢	🟢
USD	USDZ, USDA, USDC	🔴	⚪	⚪
VDA-FS	VDA	🟢	🟢	⚪
VRML	WRL, VRML	🟢	⚪	⚪

🟢 = Supported

⚪ = This concept is not supported by this format

🔴 = Not supported

Dev/Beta = Supported but still under development

Table A6.1. List of import formats in PiXYZ (PiXYZ STUDIO, 2019)

Appendix 7. Export formats supported by PiXYZ

FORMAT	EXTENSIONS	TESSELLATED
Autodesk FBX **(5)**	FBX	🟢
Autodesk VRED **(2)**	VPB	🟢
CATIA V5 [3DXML]	3DXML	🟢
glTF	GLTF	🔴
JT	JT	🟢
OBJ	OBJ	🟢
PDF	PDF	🟢
PRC	PRC	🟢
StereoLithography (STL)	STL	🟢
USD	USDZ, USDA, USDC	🟢

🟢 = Supported

⚪ = This concept is not supported by this format

🔴 = Not supported

Table A7.1. List of export formats in PiXYZ (PiXYZ STUDIO, 2019)