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Master of Science in Civil Engineering

Thesis Report for Master Degree

BIM | Industry 4.0 | VR | OpenBIM

Digital Twin Factory – BIM and IoT for Facility Management with OpenBIM visualizers and Virtual Reality

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"We don't know what we don't know. We don't even know the questions we need to ask in order to find out, but when we learn one tiny little thing, a dim light comes on in a dark hallway, and suddenly a new question appears. We spend decades, centuries, millennia, trying to answer that one question so that another dim light will come on. That's science"

Transcendent Kingdom by Yaa Gyasi

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Abstract

Nowadays, the world has shifted from traditional ways of working to digitalization. Many industries have shifted to digital revolution and have found creative ways to increase the productivity. The building industry is not moving in the direction of digitalization with the same speed as compared to other industries. The aim of this thesis is to address this issue by providing a framework for the development of a smart factory under the umbrella of Digital Twin (DT), industry 4.0.

The main objective is to make an application both for virtual reality and traditional screen-keyboard input for the energy analysis and facility management. The constraints for the application were that it should be scalable and should follow the OpenBIM standards.

This application will help one with understanding the benefits of DT in the construction industry. In addition to that, the benefits of using virtual reality for energy and facility management will also be highlighted. Finally, the benefits of using OpenBIM standards for such an application will be discussed.

This thesis is focused on overcoming the hurdles that one might face in implementing virtual reality in Facilities Management and Energy Management phase of the building with OpenBIM standards. The methodology consists of using an IFC file which can be exported from any IFC compatible BIM authoring software. The geometric data and alpha-numeric data inside the IFC are separated. The alpha-numeric data file is made by converting the IFC to XML while the geometric data file is made by converting IFC file to glTF. Both the XML and glTF are imported inside the game engine "Unity" and are linked together with the help of scripting done in C#.

The methodology proposed in this thesis was used on a real automobile factory located in Turin, Italy.

Keywords: BIM, OpenBIM, VR, IOT, Industry 4.0, Facility Management, Energy Management, Gamification Approach , AEC industry

Acronyms

- **AECO:** Architecture, Engineering, Construction and Operation
- **AR:** Augmented Reality
- **AI:** Artificial Intelligence
- **BIM:** Building Information Modelling
- **bsDD:** BuildingSmart Data Dictionary
- **C#:** Programming language
- **CPS:** Cyber-Physical-System
- **DT:** Digital Twin
- **.dae:** Digital Asset Exchange
- **.fbx:** Film Box
- **. glTF:** Graphic Library Transmission Format
- **GUID:** Globally unique identifier
- **HVAC:** Heating, Ventilation and Air-Conditioning
- **IFC:** International Foundation Class
- **IDM:** Information Delivery Manual
- **IoT:** Internet of Things
- **LOD:** Level of Detail
- **MVD:** Model View Definition
- **RVT:** Revit Project Format
- **SF:** Smart Factory
- **VR:** Virtual Reality
- **VS:** Visual Studio
- **VAR :** Virtual Augmented Reality
- **XML :** Extensible Markup Language

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Thesis Organization

INTRODUCTION

01

The Literature Review has been done and the details of all the papers read have been shown in this part

02

The workflow methodology is defined in this part of the thesis. It discusses the software used and the file types used

03

The final application along with the interoperability test results are shown in this part

04

The Future developments are discussed in this part of the thesis

Introduction

In Recent times, the world has shifted from traditional ways of working to Digitalization. Many industries have shifted to digital revolution and have found creative ways to increase the productivity. The construction industry should not stay behind in this digitalization race and should find innovative ways of introducing state of the art technologies in its day-to-day applications. One of the ways in which the construction industry can move in this direction is with industry 4.0 under the umbrella of digital twin.

A brief history of industrial Revolution reveals that till now there are 4 stages of industrial Revolution .

First industrial Revolution(Industry 1.0) In this Era people shifted from hand production methods to machines with the use of steam or water powered engines.Textile industry was the first to adopt such changes in the manufacturing process [1] .

Second industrial Revolution(Industry 2.0) Electrification was used in this era for the production process.This drastically changed the manfucaturing industry. Increasing electrification allowed for factories to develop the modern production line. It was a period of great economic growth, with an increase in productivity, which also caused a surge in unemployment since many factory workers were replaced by machines [1].

Third industrial Revolution(Industry 3.0) This Era is also known as the "Digital Revolution" [1].The communication advancements took place in this era with the introduction of "Internet".The world was now inteconnected.In addition to the internect, advancements in the manufacturing process were taking place side by side.Supercomputers were developed and were used in the industry [1].

Fouth industrial Revolution(Industry 4.0) Industry 4.0 is revolutionizing the way companies manufacture, improve, and distribute their products. Manufacturers are integrating new technologies, including Internet of Things (IoT), cloud computing and analytics, and AI and machine learning into their production facilities and throughout their operations [2]. These smart factories are equipped with advanced sensors, embedded software and robotics that collect and analyze data and allow for better decision making. Developing smart factories provides an incredible opportunity for the manufacturing industry to enter the fourth industrial revolution. Analyzing the large amounts of big data collected from sensors on the factory floor ensures real-time visibility of manufacturing assets and can provide tools for performing predictive maintenance to minimize equipment downtime [2].
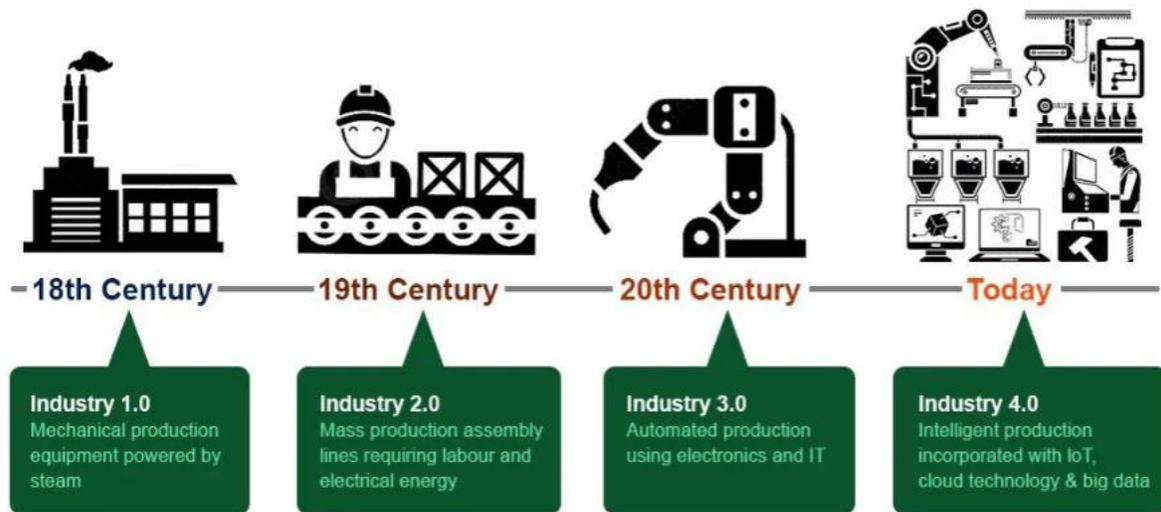
Figure 1-Industrial Revolution

Source : [3]

The aim of this thesis is to define a framework for remote working in AEC industry with the use of VR in a gamified environment using OpenBIM standards. All the technologies used in this thesis are paving the way for the industry 4.0 goal for AEC. The Goal of the thesis is to develop a VR application which can be used on a VR device and can be used for Energy and Facilities management of an asset. The application should be scalable and should be based on OpenBIM philosophy.

Chapter-01 State of Art

1.1 BIM

1.1.1 Definition

There are many different definitions to describe this concept, the ones that are the most descriptive and easy to understand are as follows:

BIM integrates multi-disciplinary data to create detailed digital representations that are managed in an open cloud platform for real-time collaboration. Using BIM gives you greater visibility, better decision-making, more sustainable options, and cost-savings on AEC projects [4].

When we talk about BIM (Building information Modeling) we mean a working method that develops in the context of collaborative culture and integrated practice, and which implies a transformation that involves all the design, construction, and management phases of building processes [5].

BIM is an intelligent model-based process that seeks to achieve objectives such as reducing project costs, increasing productivity and quality, and reducing project lead times [6].

"BIM is a process related to information enrichment of building components. It is a continuous process throughout the project life cycle, whereby building information is utilized and used through stakeholders [7].

BIM is not just limited to 3D modelling of the asset but instead it is a complete process which begins with the preliminary design and continues until the life cycle of the asset
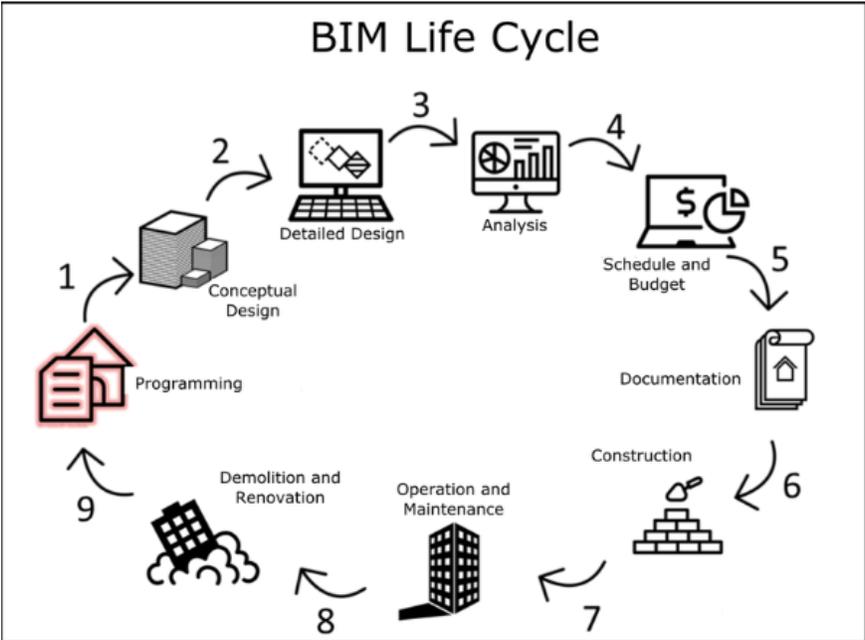
Figure 2-BIM Life Cycle

Source: [8]

1.1.2   OpenBIM and Interoperability

Building information model (BIM) software is widely used in design, construction, operation, and maintenance stages, providing great convenience for construction industry. However, data heterogeneity among different software leads to a series of problems, such as interoperability issues [9]. The development of more complicated construction projects has also created a series of collaboration issues among different stakeholders and software platforms, which has placed higher requirements on the collaboration over the whole lifecycle, including design, construction, operation, and maintenance [9].

OpenBIM provides solutions for these problems by reducing collaborative errors, improving the interoperability between software, and ensuring accuracy of multi-party collaboration, thus improving the efficiency of the whole project [9].

BuildingSMART

BuildingSMART is an open, neutral, and international not-for-profit organization which is committed to creating and adopting open, international standards and solutions for infrastructure and buildings so as to drive the digital transformation of the built asset industry [9]. BuildingSMART standards are the final standards that have been voted by the Standards Committee. The most important standards of the OpenBIM standards are given under the umbrella of BuildingSMART standards. These mainly includes 5 basic standards.

Name	What It Does
IFC Industry Foundation Classes	Transports information or data
IDM Information Delivery Manual	Describes processes
MVD Model View Definitions	Translates processes into technical requirements
BCF BIM Collaboration Format	Change coordination
bsDD buildingSMART Data Dictionary	Defines BIM objects and their attributes

Table 1-OpenBIM Standards

Source: Table taken from [9]

IFC (Industry Foundation Classes)

IFC is a "Data standard" [9].As discussed earlier, BIM is highly dependent on the interoperability of data from different sources. The information present in the BIM model comes from different types of software, modeling programs, structural calculation, MEP, budgeting software, energy behavior analysis, etc. The knowledge of all these tools and the ability to share data and allow the exchange of information and knowledge between them, define the fundamental principle of the BIM methodology.

The data exchange is usually possible by 4 different ways [5]:

1) Direct, proprietary links between specific BIM tools
2) Proprietary file exchange formats, primarily dealing with geometry
3) Public product data model exchange formats
4) XML - based exchange formats

For the purposes of this thesis, we will discuss 2 and 3. A proprietary exchange file format is one developed by a commercial organization for interfacing with that company's application example DXF (data exchange format) by Autodesk. The problem with proprietary exchange file format is that it creates a monopoly for the software house and forces the people to solely use their products if one wishes to achieve interoperability without data loss.

To overcome the above-mentioned problem, public product data model exchange formats come into action. The public level exchange formats involve using an open - standard building model, of which the IFC (Industry Foundation Class) (IAI 2007), or CIS/2 (CIS/2 2007) for steel, are the principal options [5]. In particular, the IFC standard or Industry Foundation Classes, is an open data format developed by Building SMART International. The main objective is to allow the interchange of data contained in a model without the loss of information and to facilitate interoperability within the construction industry, being the format, most used in BIM-based projects.

According to [9] IFC have seen the following maturity levels.
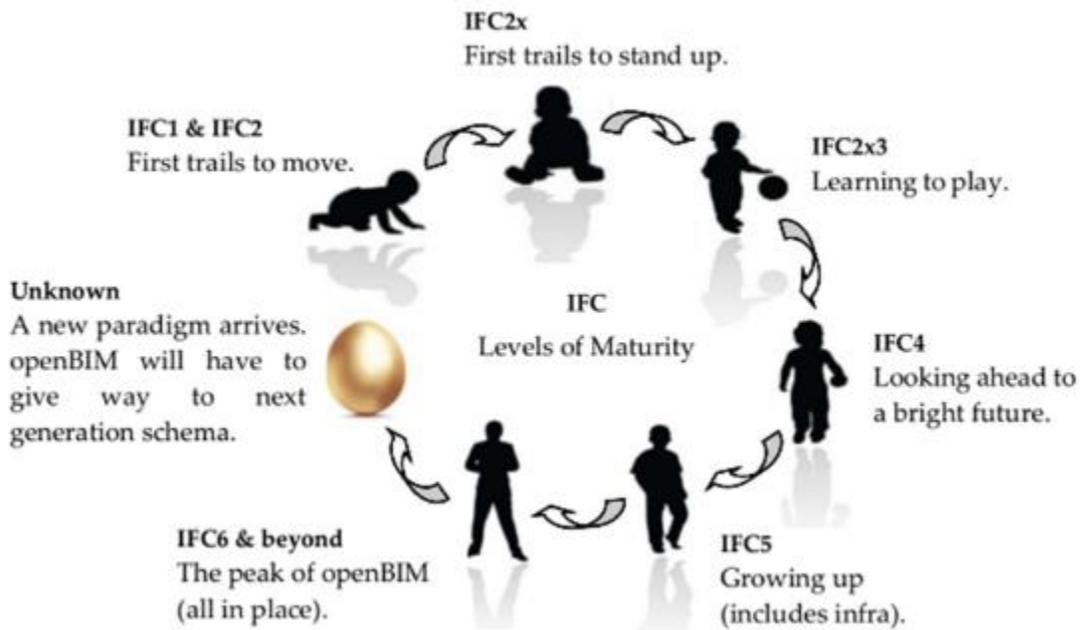

Figure 3- Industry Foundation Classes (IFC) Maturity levels

IDM (Information Delivery Manal)

IDM is a "Process Standard". IDM is a method for capturing and specifying the whole process and information flow during building life cycle [9]. The construction and maintenance of buildings involves many different participants, knowing what information needs to be communicated among them and when it is communicated is important. IDM can facilitate this information communication process by making full use of business process modelling notation (BPMN) and templates for Exchange Requirements [9].

It is important to state that in order to make an information delivery manual operational it has to be supported by software. The main purpose of an information delivery manual is to make sure that the relevant data are communicate in such a way they can be interpreted by the software at the receiving side [10].

MVD (Model View Definition)

MVD is a "Process Translation" standard. The Model View Definition defines a subset of IFC schema that needs to meet one or more exchange requirements in the AEC industry. Together with this subset of IFC schema, a set of implementation instructions and validation rules are issued, and the method of publishing concepts and related rules is mvdXML [9]. The mvdXML is an encoding format, through which MVD can be encoded and allowable values in specific attributes of a specific data type can be defined [9].

An MVD consists of three main components [10]:

1) A set of Concept Templates. These concept templates define additional agreements on how to use the IFC Schema.
2) A set of Exchange Requirements. This is a selection of entities and properties from the IFC Schema that are found suitable for a selection of use-cases.
3) A description on how Software should deal with the data that are exchanged. For example, can the software use the data as a reference, or should the data be mapped to internal objects during import.

BCF (BIM Collaboration Format)

The BIM collaboration format (BCF) is a simplified and open standard XML format used to encode information which enables workflow communication between different BIM software tools [9]. When you exchange BIM data using IFC, you probably also want to communicate about the objects in your model. Doing this over email or using the phone to comment about 'the 3rd column from the right on the 2nd floor' brings risks and unclarities. Therefore the "BIM Collaboration Format" (BCF) was created [10]. The BIM Collaboration Format (BCF) allows different BIM applications to communicate model-based issues with each other by leveraging IFC data that have been previously shared among project collaborators. BCF was created for facilitating open communications and improving IFC-based processes to more readily identify and exchange model-based issues between BIM software tools, bypassing proprietary formats and workflows [10].

bsDD (buildingSMART Data Dictionary)

It is standard library based on IFD (ISO12006-3), that enables collaborative work. The bsDD provides a shared system for identifying and validating the names of objects and their attributes used in building information models, which help to better understand the meaning of general terms, thereby improving the information interoperability during the construction industry [9].

IFD is a terminology library-oriented or ontology-oriented standard, which ensures the accuracy of BIM information exchange and sharing by establishing the mapping relationship between IFC and information representations of different languages and vocabularies, as well as specifying the related conceptual semantics of objects [10].

BuildingSMART Related Other Standards

The buildingSMART related other standards are formed to supplement the openBIM standards. The 2 most famous ones are:

1) Construction operations building information exchange (COBie)

The COBie is an information exchange specification for collecting and delivering information required by facility managers during the life cycle of the buildings. COBie can be viewed in design, construction, maintenance software, and simple spreadsheets, and this versatility enables COBie to be used in all projects regardless of project size and technical complexity [11].

2) LandXML

LandXML schema includes surveying, road design, and digital terrain model (DTM), which is capable of capturing, validating and displaying civil engineering and survey measurement data [9].

1.1.3 LOD

Level of Development Specification (LOD) is a reference that allows professionals in the architecture and construction sector (AEC) to define and express the content and reliability of BIM in the different phases of the design with a high level of clarity [12]. The LOD they have the task of precisely defining the level of depth of information of various kinds that are contained within the model. In BIM methodology we mostly tend to over design, by overdesign we mean by modelling in much more detail than what is required for the task. To discuss the details of the models' different regulations have been created for different countries. We will discuss a few of them below.
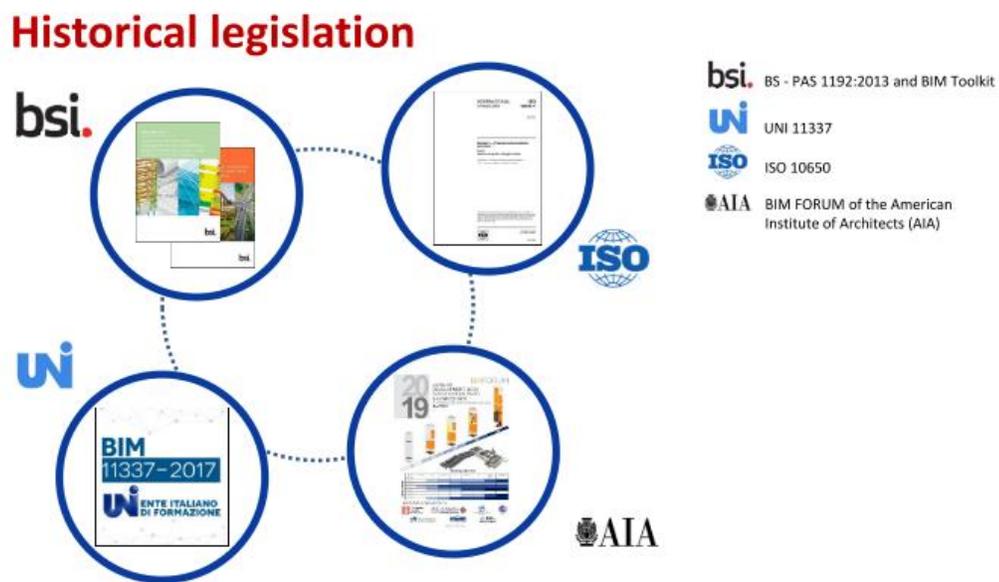
Figure 4-Historical Legislation

The relationship between LOD and the element type is described in mainly 2 of the codes UNI 11337 of 2017 and AIA (American Institute of Architects) respectively.

In Italian code UNI 11337 which was introduced in 2017, introduces the concept of LOD and defines it as the "level of development of the object", defining its scale ranging from A to G. It is divided into LOG (level of development of objects regarding geometric properties) and LOI (level of development of the information). The LOD scale is as follows:

Figure 5-LOD Based on UNI 11337

- LOD A - symbolic object
- LOD B - generic object
- LOD C - defined object
- LOD D - detailed object
- LOD E - specific object
- LOD F - object executed
- LOD G - object updated

A more of less same approach is followed by the AIA. The AIA (American Institute of Architects), which defines the LOD as the "Level of Development" of the quantity and quality of data. Instead of A-G it is from 100-500 with 100 being the lowest and 500 equals to LOD G in the UNI 11337.
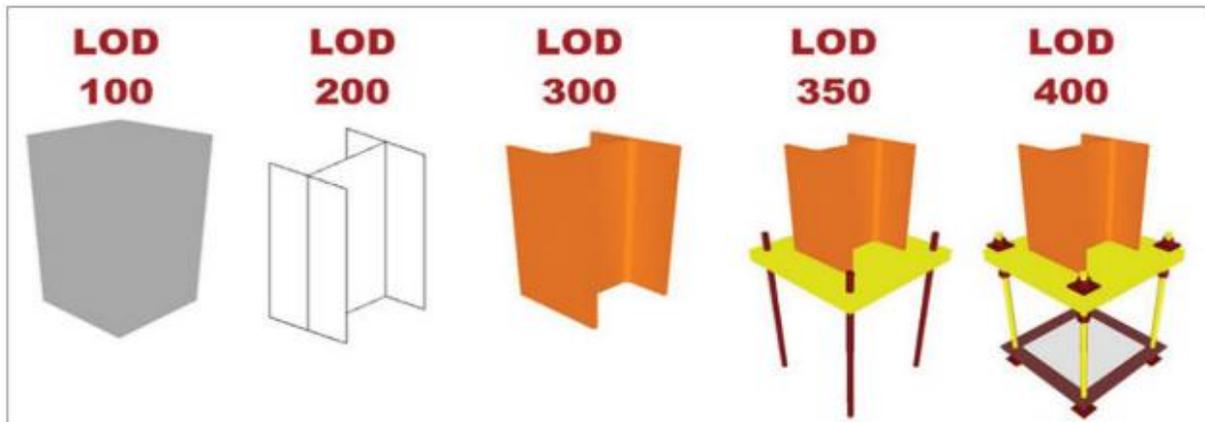
Figure 6-LOD Based on AIA

- LOD 100 (Representation of an element with a symbol or shape)

- LOD 200 (Represented shape occupies a space in the position of the real object)

- LOD 300 (The element has a greater level of detail, and has some parameters that define it at an informative level)

- LOD 350 (The graphical representation of the object becomes more reliable)

- LOD 400 (Increasing the details in LOD 350 for much better reliability on the model)

- LOD 500(This can be called as "As-built model")

1.1.4   Level of information need -ISO 19650:

To solve the problem of overdesign a new concept called "Level of information need" was introduced in ISO 19650. By introducing this new term ISO-19650 abandons the terms "Level of development" and "Level of definition" [13]. The ISO requires that the "Level of information need" be defined **for each** *information deliverable* .ISO 19650 refers to as "wastes" for all the additional information which might not be required for a particular deliverable [13].Even after the release of this regulation there still are some problems such as what metrices should be used to pre-define the "Level of information need " for each deliverable . This discussion is beyond the scope of this thesis thus we will not go into much detail.

1.1.5   BIM Dimensions

The dimensions of the BIM are used to outline the "potential" that the computerization of the project allows. In fact, it is possible to extrapolate, combine and analyze data concerning aspects that go beyond traditional architectural modeling [14].We will first discuss the dimensions which have been incorporated in Italian regulations and then we will discuss about some future potential dimensions of BIM.

According to UNI 11337-2017 there are 7 Dimension of BIM (2D-7D).

Figure 7-BIM Dimensions

- **2D** As the name indicates it is 2D which means the number of axes is 2 namely X and Y with no 3D data inside.

- **3D** The model is based on 3 axes and in addition to the graphical 3d information we also of alphanumeric information regarding the elements in the model.

- **4D** Time schedule is attached with the 3D model making it much easier to visualize the schedule. With the help of visualizing the schedule, we can find the coordination errors in the time schedule which were not possible before.

- **5D** Cost component is added in addition to the time schedule. This helps us in better construction Management keeping both the costs and time under observation.

- **6D** FM (facility Management) allows us to optimize the management and maintenance of the building object throughout its life cycle. It provides information about all the components of the asset regarding its maintenance.

- **7D** Energy Analysis is added in this dimension. This allows us to know the performance of the Asset in terms of energy consumption. Assessments using different materials and changing occupants' behaviors can be performed.

In addition to the previously described dimensions, there are few more dimensions under discussion but not yet incorporated in the regulations [14].
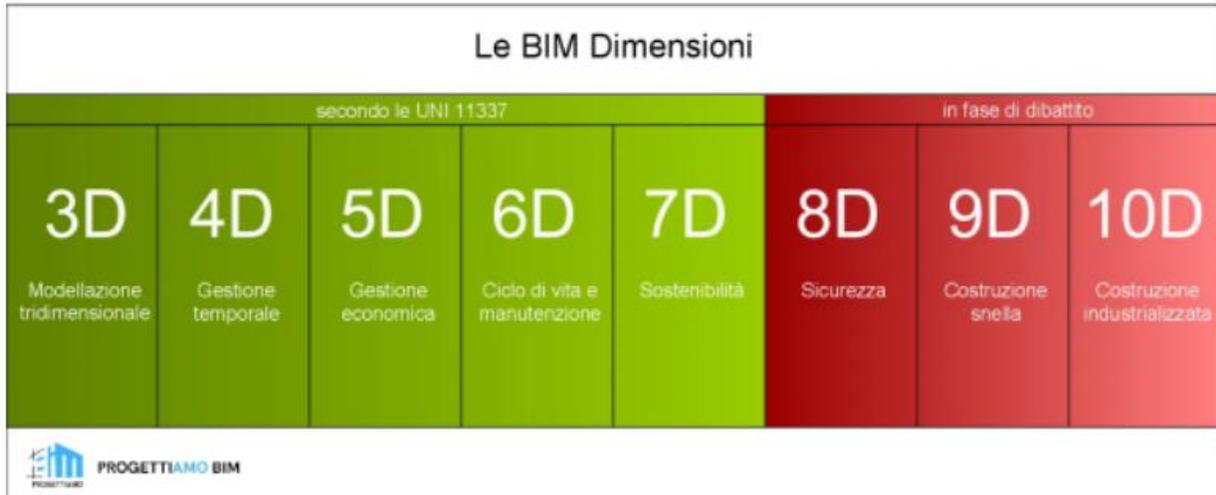
Figure 8-BIM Dimension under discussion

- **8D** Safety is under discussion to be the 8th dimension. This allows us to know all safety hazards before the construction phase of the project. Different AR/VR tools can be used to simulate the construction phase and to know about the potential risks.

- **9D** Lean construction can possibly be the 9th dimension. This allows us to simulate the entire supply chain and helps us to reduce the repeated activities which might not add value to the project but causes time and effort.

- **10D** Industrialized construction is supposed to be the 10th dimension in the BIM philosophy. With this we will be able to achieve full BIM potential from the start to the end of the lifecycle of the asset.

1.2 IOT

The term IoT was first coined by Kevin Ashton in 1999 with reference to the supply chain management [15]

IoT is the acronym for the Internet of Things, literally "Internet of Things", there is no single definition available for the Internet of Things that is acceptable to the global community of users. The best definition of the Internet of Things is: "An open and complete network of intelligent objects that have the ability to self-organize, share information, data and resources, react and act in the face of situations and changes in the environment" [16].

Recent trends show researchers huge interests towards the amalgam of various technologies such as integration of sensors and embedded systems with cyber-physical systems (CPS), device-to-device communications (D2D) and 5G wireless systems with IoT as a center [17].

Therefore, IoT refers to the ''things or devices and sensors'' that are smart, uniquely addressable based on their communication protocols, and are adaptable and autonomous with inherent security [17].

There are 3 main components of the IOT architecture [17].

1) Hardware: Sensory nodes comes in this part of the IOT architecture
2) Middleware: Data storage comes under the umbrella of Middleware
3) Presentation layer: Data visualization for the end user comes under this part.

1.2.1 IOT Applications:

Figure 9-IOT Applications

Source: [10]

As is evident from the figure-09 above that we have numerous applications of IOT in the world today. In fact, we are taking benefit IOT in our daily lives without even realizing it. We will discuss a few out of the many available applications of IOT in this thesis.

Smart Health: There are many components to the concept of Smart health, wearables is one of them. It allows the patient to give updates regarding his/her health in real-time to their personal doctors outside the doors of the hospital. The concept of the smart gym allows the end-user to monitor his exercise schedule regularly [17].Other applications like digital diaries are there which keeps a track of personal data and updates on Google calendar [18].

Smart Transport: The use of IOT for transportation is often used now a days. Concepts like augmented maps, autonomous car, mobile ticketing, and passenger counting in transportation/logistics domain are a few examples [17]. In addition to that, the concept of IoT enabled Robot taxi, which is underway as a futuristic application [17].

Smart Homes: Smart Homes are mainly aimed at consumers to control IoT home automation devices, such as remote home temperature monitoring, home automation devices [19].This concept when applies to buildings they become Smart buildings.

Smart Cities: With the introduction of technology and IOT in almost all aspects of our lives it has been made possible to automatize the dynamics of Governance, Environment, Mobility, and people. These in a nutshell are the basic building blocks of a city. Thus, cities are becoming smarter and smarter.

Smart Factories: A smart factory is a factory that provides flexible and adaptive manufacturing processes capable of solving the problems that arise on a manufacturing plant with dynamic and rapidly changing boundary conditions in a world of increasing complexity [20].This means that with the use of IOT the factories will move in the direction of full automation , which will reduce the cost and increase the quality of production. As the data is in real time thus real time error predictions can be done and a proactive problem approach can be implemented.

1.2.2   IOT and BIM:

Linking real-time data streams from the rapidly expanding set of IoT sensor networks to BIM models provides numerous applications that enable projects to be constantly fixed and monitored in a short time. Today, real-time data is a prerequisite in any industry to embrace digitization as it helps to effectively manage work and material [21]. The integration of information may provide value despite existing barriers and considerations upon combining the managerial building information with the live data [22].IOT devices gives us information with the help of sensors but to view then and to make sense of that information it is recommended to integrate them with BIM. BIM upon integrating data, can organize and prepare them under certain usable format. As an example, a laser scanning cloud provides good information, but it lacks semantic information or geometrical context which makes BIM searching for external sources such as building specification and construction materials [22].

1.3 Digital Twin (DT)

The term Digital Twin was coined by "Michael Grives" in his article *"Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management"* [23].

According to [23],DT is mainly composed of 3 distinct parts:

a) Physical Part in the Real world
b) Virtual Part in the Virtual space
c) Data connection that ties the physical and virtual parts together
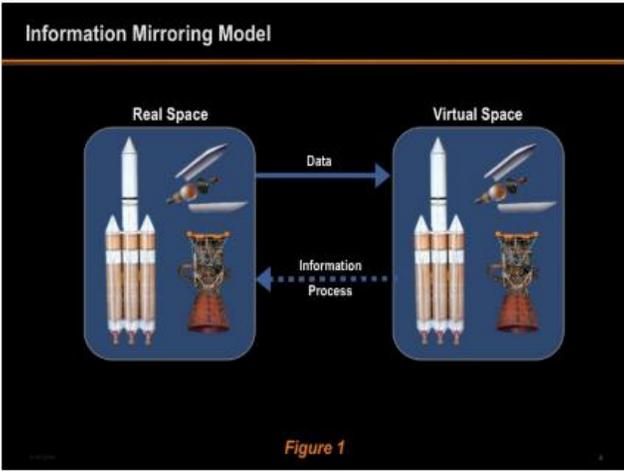
Figure 10-DT Schematic by Michael Grives

BIM itself can generally only provide static data of the built environment and cannot update real-time information in the models automatically without additional data sources [24]. With the help of smart devices, visualization and analysis of real-time environmental data become available in BIM models, and automated update of BIM models based on real-time building status was achieved. For example, appropriate integration of BIM and IoT technologies can help with the real-time monitoring of the construction process and building indoor environment status [25].

In order to have an in-depth knowledge of DT we will take the research of "Min Deng's" paper [26] as reference.
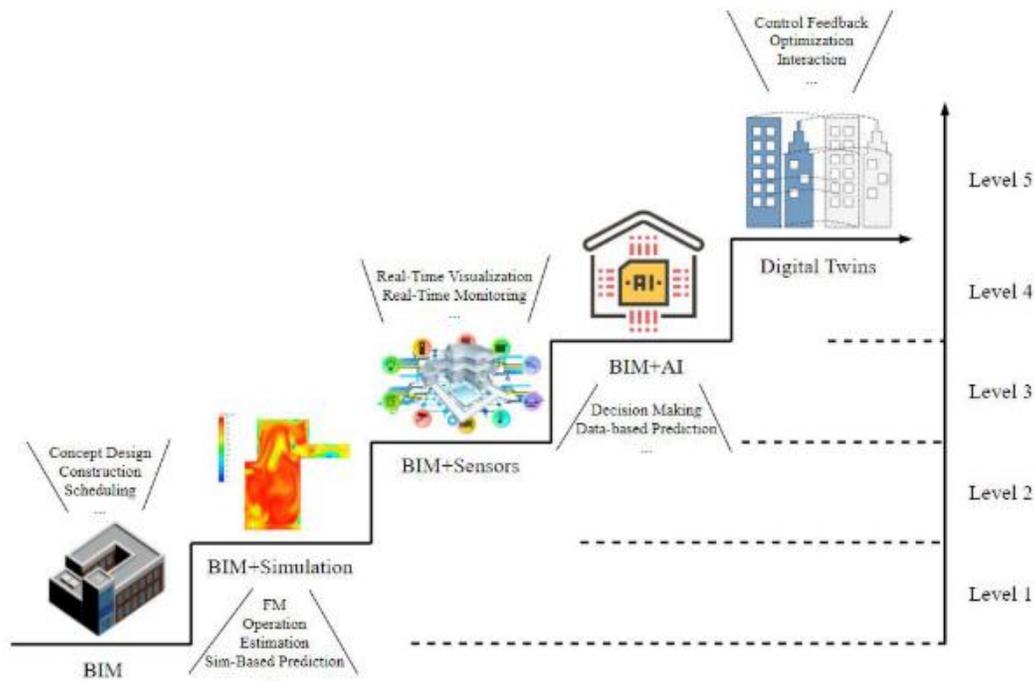
Figure 11- Evolution of BIM to Digital Twins in the Built Environment

Source: [20]

The paper discusses digital twin's history, its current state and what the author suggests about an ideal DT of the future. Levels have been defined to categorize the evolution of BIM to DT based on its data enrichment and functionalities. The five levels include Level 1 – BIM, Level 2 – BIM-supported simulations, Level 3 – BIM integrated with IoT, Level 4 – BIM integrated with artificial intelligence (AI) techniques for predictions, and Level 5 – ideal Digital Twins [26]

Level-01(Static BIM): In Level 1 use BIM as a static 3D visualization tool to provide required information to help with traditional ways of building envelope design, drawing modification, construction scheduling, cost estimation, and other functions. The application of BIM in this level aims to provide a better information sharing strategy between different stakeholders across the building life cycle [26].

Level-02(BIM-Simulations): In addition to relying solely on static BIM models for traditional conceptual design and facility management based on 3D walkthroughs, this level starts to incorporate different analyses and simulations with BIM models. Rather than being used as a visualization tool, BIM models in this level are used as data sources for conducting further analysis of construction processes or building performance. Therefore, rather than treating BIM as a static 3D visualization tool, studies in this section further integrate the project information stored in BIM with different data analysis and simulations [26]. Simulations like "Construction Process, Energy performance and Thermal Environment Evaluation can be performed. In addition to major research domains related to construction, energy performance, and thermal environment, some other areas such as embodied carbon, lighting, and acoustics have also been studied occasionally [26].

Level-03 (BIM with IOT integration): This level start to connect digital building models with real-time sensing data for building environment monitoring and management. After incorporating different smart IoT sensors, real-time building environment data can be easily obtained and visualized in 3D digital models, which can be helpful for in-time decision-making or strategy changing during any phases of the building life cycle [26].Its application includes but not limited to "Construction Process Monitoring, Energy Performance Management, Indoor Environment Monitoring, indoor thermal comfort, Space Management and Hazards Monitoring"

Level-04 (BIM and IoT integration Associated with Real-Time Predictions): This level has further enhanced the building environment monitoring and management by incorporating algorithms for real-time predictions based on models developed using data collected from smart sensors. With appropriate decision-making strategies based on real-time prediction, more accurate and reliable strategies can be obtained automatically or semi-automatically by the building manager to achieve more efficient building operation and facility [26].

Integration of BIM, IoT, and the real-time prediction was investigated to help with the construction process of the buildings. [27] proposed a framework to allow automated simulation of construction projects. Unity game engine was utilized to integrate the data from BIM and real-world images, through the ML algorithms, the system could update the 3D virtual view of the construction site, thus providing an advanced decision-making tool for different stockholders of the project [26].

[28] proposed a data driven framework for the FM of the indoor system. The developed approach applied ANN and support vector machine (SVM) to predict the future conditions of the MEP components based on the condition monitoring of the equipment, thus help with the scheduling of the maintenance tasks.

[29]developed a framework to forecast the life-cycle-cost (LCC) of the building facilities. The study concluded the feasibility of using machine learning techniques to predict the LCC of facilities based on the data from current systems

Level-05 (Ideal DT of the Future): Digital Twins at this level include not only real-time visualization and prediction to support decision making, but also support automatic feedback and control of the built environment. In addition to the capabilities supported in Levels 1-4, the built environment is enabled with an intelligent feedback control system that allows it to automatically take actions based on the optimized results and control strategies. This can be typically achieved by exploiting related enabling technologies such as artificial intelligence (AI) and ML algorithms. In such Digital Twins, the virtual and real-world built environments could interact with each other seamlessly [26].

The capabilities of an ideal DT can be summarized as follows:

- Visualization of real-time data
- Predictions are based on the real-time data received from the visualization phase.
- Automatic feedback with optimized management is done by the asset itself based on the data received from the previous phases.
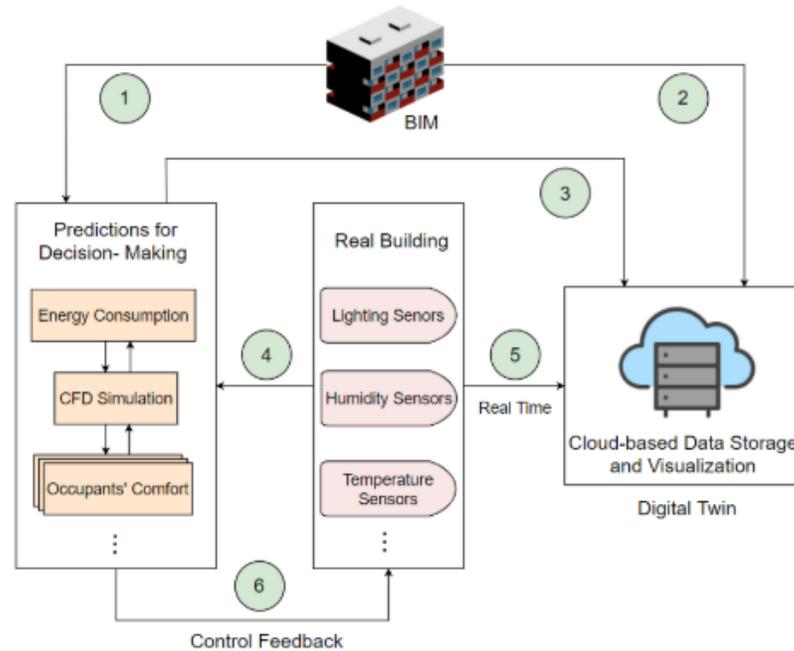
① *BIM model for supporting simulations and predictions*
② *BIM model visualization on cloud*
③ *Visualization of simulation/prediction results on cloud*
④ *Real-time indoor sensing data to support simulations and predictions*
⑤ *Real-time sensing data visualization on cloud*
⑥ *Simulation/prediction results feedback to support automatic building system control*

Figure 12- Ideal DT of the future

Source: [20]

Digital Twin (DT) Benefits:

According to [23] there are 3 main advantages of using DT.

1) Better Conceptualization:

Instead of looking at reports and excel sheets of factory performance and then conceptualizing the performance of the factory based on those numbers, digital twin simulations allow us to see the progress of the physical asset as it is operating

2) Improvements in Comparison:

With the digital twin model, we can view the ideal characteristic, the tolerance corridor around that ideal measurement, and our actual trend line to determine for a range of characteristics whether we are where we want to be. Tolerance corridors are used to check the conditions. With the help of color coding in the DT we can check whether we are under the tolerance limits, or we can go above it. Based on the colors shown in the DT we can adjust the future strategy to bring the conditions inside the tolerance corridor.

3) Increased Collaborations

The digital twin model allows a shared conceptualization that can be visualized in the same way by an unlimited amount of individuals and by individuals who do not need to share the same location [23].

With the help of DT, we can compare the performance of a factory with other factories around the world as well. Sharing the DT with other experts around the world can help us identify the problems that might be developing and eventually may cause major problems in the future.

1.4 VAR Virtual Augmented Reality

1.4.1 History of VR/AR

The concept of virtual reality, while it seems so well established in the 21st century, has actually been around for several decades, starting in the 1930s.However, it wasn't until the 1960s that the world's first computer-generated overlays were produced [30]. The idea of this technology was to make people communicate with each other despite being kilometers away through a virtually generated environment [31]. Years later, during the 1970s and 1980s, the concept of augmented reality finally emerged in the field of independent research.

Fuchs and Bishop in 1992 gave a concept of Virtual Reality they define virtual reality as interactive real-time graphics with 3D models, combined with visualization technologies that provide the user with an immersion. in the model world and direct manipulation [30].With these researches companies like Nintendo launched their Virtual boy console but due to lack of software support and difficulties in its use , soon it was discontinued [31].

In 2007, Google introduced an innovative immersive system called Street View that gives users a panoramic view of streets, building interiors, roads, avenues and rural areas [32].Products like oculus Rift came to the markets as well This device featured a never-before seen 90 degree view, which sparked and increased interest in VR.

In 2016, the growth of VR comes to the fore, where more than 230 companies including names like Amazon, Apple, Facebook, Google, Microsoft, Sony, Samsung and many more are working on VR-based projects [32].

In 2018 , Half dome was created which drastically changed the field of view from previously 90 degree to a staggering 140 degrees [32].
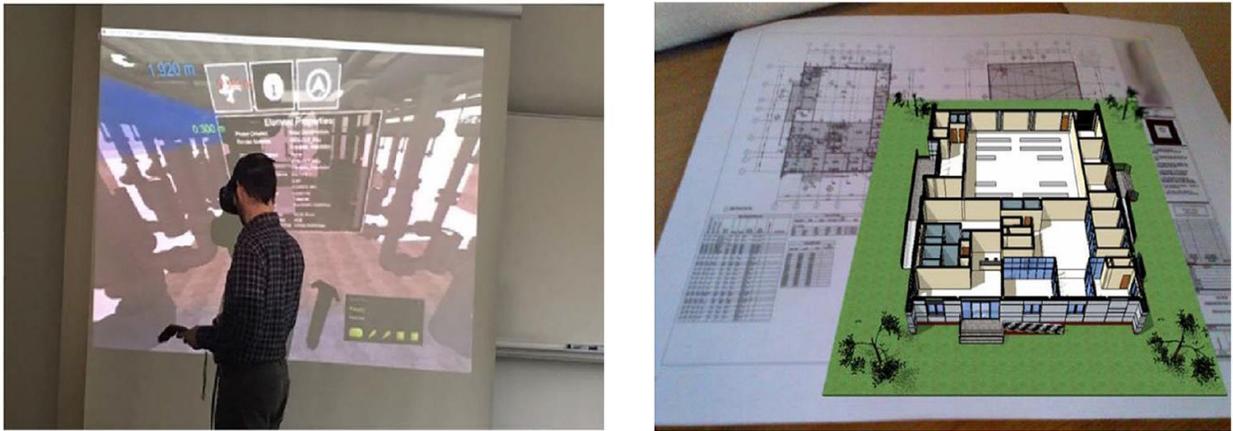
Figure 13-VAR Applications

Source : [33]

1.4.2   VR/AR in AEC

According to [33], the use of VR/AR In the AEC industry can be divided in the following categories :

1) Design Phase
2) Construction Phase
3) Facility Management (FM)

These categories were defined after doing a research on the already present literature on VR/AR in the AEC industry. The author collected and applied his methodology on the papers from 2010-2022.The results of the research are shown in the table below.

Number of articles covering AEC phases and technologies annually from 2010 to 2020.

Year	AEC Phase						Technology	
***	Design	Design/Construction	Construction	Construction/FM	FM	All	AR	VR
2010	1	1	8	1	3	0	2	8
2011	2	0	14	2	3	0	7	11
2012	4	0	22	0	6	2	18	12
2013	5	1	39	1	8	4	26	17
2014	2	0	19	2	9	0	18	8
2015	6	2	23	0	4	0	19	15
2016	7	3	22	0	4	1	13	15
2017	20	3	29	0	7	5	25	23
2018	16	1	47	2	10	2	31	42
2019	16	6	62	2	17	1	43	46
2020	3	1	5	0	4	0	7	5
Total	82	19	290	13	75	15	209	202

Table 2-Number of Articles covering AEC phases

VAR Devices in AEC industry

Device category	3D Keyboard Mouse Screen (KMS)	VR CAVE		VR Standalone HMD		VR Tethered HMD	
Subcategory Commercial examples	Not immersive	Powerwall	CAVE	Low cost	All-in-one	Outside in	Inside out
Price	++	+++	++++	+	++	++	++
Interaction	+++	+	++	–	++	+++	+++
Tracking	N/E	Outside in	Outside in	IMU	Inside out	Outside in	Inside out
Portability	+++	+	–	+++	+++	+	++
Configuration Setup	Instantaneous	Start projectors (5–10 min)	Start projectors (2 min)	Instantaneous	Room setup (5 min)	Install tracking camera + Room setup (15–30 min)	Room setup (5 min)
Requires external computing power	Is itself a computer	1 PC	Cluster of PCs	No	No	1 PC	1 PC
Geometry optimization needed	No optimization needed	Optimization needed	No optimization needed	Optimization needed very much	Optimization needed	No optimization needed	No optimization needed
Usage	Virtual visit, simulations, virtual meetups, pseudo-3D interaction in scene, text commentary	Virtual visit, simulations, virtual meetups, 3D interaction in scene, multi-user experience	Virtual visit, simulations, virtual meetups, 3D interaction in scene, multi-user experience	Virtual visit, simulations	Virtual visit, simulations, virtual meetups, 3D interaction in scene	Virtual visit, simulations, virtual meetups, 3D interaction in scene	Virtual visit, simulations, virtual meetups, 3D interaction in scene

Table 3-VR Devices Currently Available

Source : [33]

- **3D KMS (Keyboard Mouse Screen)** It is Desktop based VR in which keyboard mouse is used as input devices while the screen is used as an output. It can be considered as a traditional way of communication [33]. 3D KMS devices allow users to interact with the 3D environment without a dedicated device. Although the 3D interactions are limited, 3D KMS devices are useful for writing textual feedback which is more difficult to do with HMD controllers [33].

- **VR CAVE** It is large screen projected and offers an immersive environment with a wide range of views and multi-users collaboration possibilities. One of such devices is referred to as a "Powerwall". It gives an immersive multi-screen cube in which it is easy to experience VR alone or in groups [33]. VR CAVE devices are applicable for multi-user meetings and are often used for design review

- **VR Standalone** Headsets with a processor and a storage unit. These are also called all-in one headset such as Google Daydream, Samsung Gear VR or Oculus Go. It can also refer to a headset which gives the possibility of mounting and smart phone can be used which gives it processing power and storage one of such devices is Google cardboard [33].

- **VR tethered HMD** These are modern VR devices that are wired to a computer. Popular VR HMDs include the HTC Vive Cosmos, Oculus Rift, Samsung Gear VR, and the

PlayStation VR [33]. The scalability of using such devices is high. VR tethered HMD devices allow 3D interactions and do not need optimized 3D models because rendering is performed by a powerful GPU card. Therefore, these devices are mainly used to review designs or in construction management because they require importing regularly the most recent BIM model which is computationally intensive when used in VR [33].

AR overlays 3D Virtual contents onto the real-world objects. The user sees the real world, but the additional information is provided with AR. Virtual objects provide relevant and contextualized information.

The simplest and quickest way to use the AR is with a marker-based system. This uses real world patterns or any visual markers.
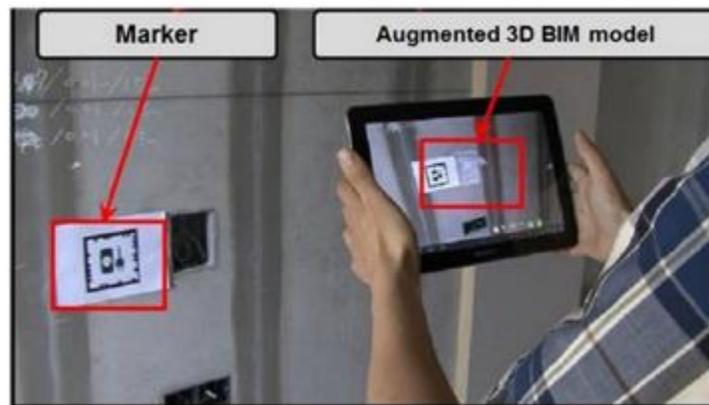
Figure 14-Marker Based AR

Source: [33]

AR based on the marker-based systems were not proved much effective on the construction sites due to the additional efforts of keeping the markers well position in those environments. To solve this problem, a new method SLAM (simultaneous localization and mapping) was introduced. This kind of tracking does not look for a known object in the real scene but builds an internal 3D representation of the scene and places virtual objects accordingly. Modern AR engines like Google ARCore or Apple ARKit, (released in 2017) and Microsoft HoloLens released in 2016 use AR SLAM-based systems [33].

Device category	AR mobile handheld	AR mobile smart glasses		AR fixed
Subcategory	Smartphone or Tablet	Optical See-Through (OST)	Optical Glance	A camera and pc screen
Commercial examples				
Price	++	+++	++	+++
Interaction	++	+	+	–
Tracking	Marker-based and SLAM-based	Marker-based and SLAM-based	Marker-based and SLAM-based	Mainly Marker-based
Portability	++	+++	+++	–
Needs external computing power	no	no	Embedded small PC unit	Is a PC
Application optimization needed	Optimization needed	String optimization needed	String optimization needed	No optimization needed
Usage	Superimpositions on top of physical world, simulations, 3D projections on markers	Superimposition on top of physical world, simulations, 3D projections on markers	Superimposition in front of user view, 3D projections on markers	Superimposition on top of PC screen

Table 4-AR devices in the Market

1.4.3   Uses of VR/AR in AEC Industry Today

The top activities for which VR/AR is being used in the AEC industry are as follows [33]:

1. Design
2. Construction Management
3. Facilities Management
4. Simulations
5. Quality Control and logistics

Some other activities were also identified for which AR/VR can be used but either it is too complicated, or its full potential can't be utilized [33].

1. On-site operations
2. Safety and Risk Prevention
3. Cost Management

1.5 Gamification Approach used in the AEC

One of the Gamification approaches in the AEC industry was presented by [34].There research was mainly based on Gamification approach for FM.

Typical problems in facility management are overheated offices, big energy loss due to the opened windows with enabled heating at the same time, improper lighting of the working area and others [34]. To tackle the problem mentioned, they proposed a novel approach in which the employees of a facility record the states of building elements by playing a competitive mobile game. Traditionally, external sensors are used to automatically collect information about the building usage. In contrast to that, their methodology utilizes personal mobile phones of employees as sensors to identify objects of interest and report their state.

The idea behind this novel approach is that it is harder to install sensors and IOT devices in existing buildings. BIM Model was created from Point cloud. For each element under study QR codes were created. The idea behind QR code is that FM employees will scan the code and update the status of the element in the smartphone application. To make this game (smartphone application) more exciting, point collection, competition with other employees and advanced challenges were added in the game.

Figure 15-QR Code for Element Identification

Every object type can have its own states. For example, the heater can have the values from 1 to 6 and the window can have the states open, partially open and closed [34]. To visualize the collected building information, we developed a web application which utilizes WebGL. As the data is coupled with BIM representation of the building, we can visualize it in 3D. The visualization shows color coded values on the 3D BIM model directly to the facility manager [34].
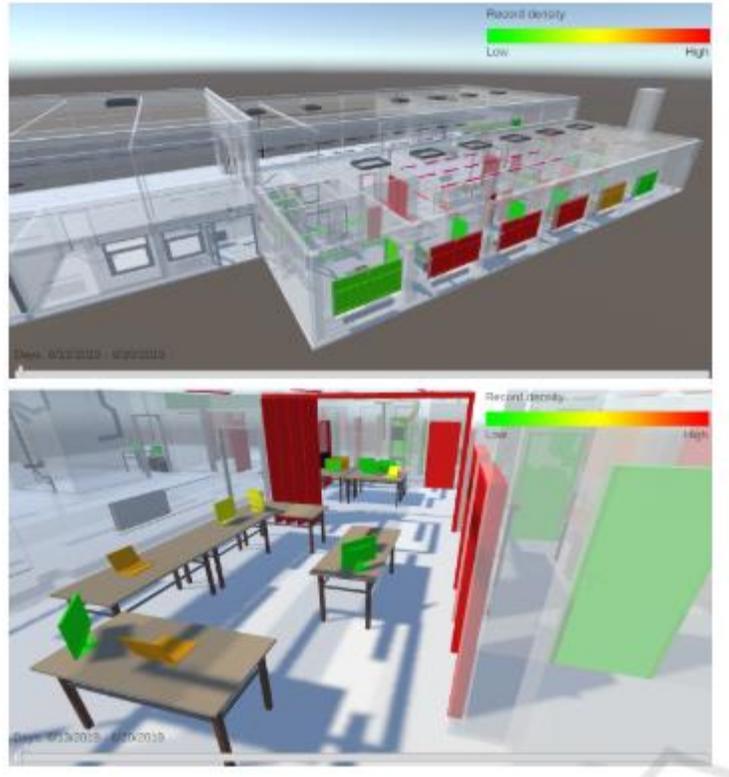
Figure 16-Web Application View

This novel approach had many limitations.one of the biggest limitation is the Motivation of workers. What will happen if people are not any more motivated to update the status daily. Also, this approach requires many readings of the same element to be reliable.

Another paper that discusses the Gaming approach in AEC is given by [35].The authors have studied gaming approach in the context of Training. According to [35], gaming is an approach that applies technology to provide an almost real experience with interactive field training and supporting the theory of learning by doing with real case scenario. Different game like genres such as simulation game, role-playing, action game, strategy game etc. were studied. The findings of the study show that serious game is a suitable genre to be adopted as an approach in hazard identification training for the construction industry.

Serious game "is all about leveraging the power of computer games to captive and engage end-users for a specific purpose, such as to develop new knowledge and skills" [36].

Serious games have the capability to achieve specific learning objectives by combining the gameplay, simulation and learning theory. Serious games also offer a flexible approach that enables hands-on, active learning in a safe environment simulated to mimic a real-life situation at the workplace [35]. It is anticipated that the development of such a blended training module will be of great significance to safety training among construction workers in handling occupational hazards [35].

The limitation to this approach of training is that construction projects are unique, and each project have their own set of hazards. This means that the game must be modified each time for every project.

Another study which we will discuss in this thesis deals with the use of Gaming approach for Education purposes for architects and engineers. According to [37] traditional architectural education is based 2D and 3D visualizations. The authors propose BIM with VR in a gaming environment can not only increase the interest of the students but also creates a learning platform beyond boarders. The COVID-19 pandemic proved education's over-reliance on classroom to be inadequate and adaptation to future demands is overdue [37].
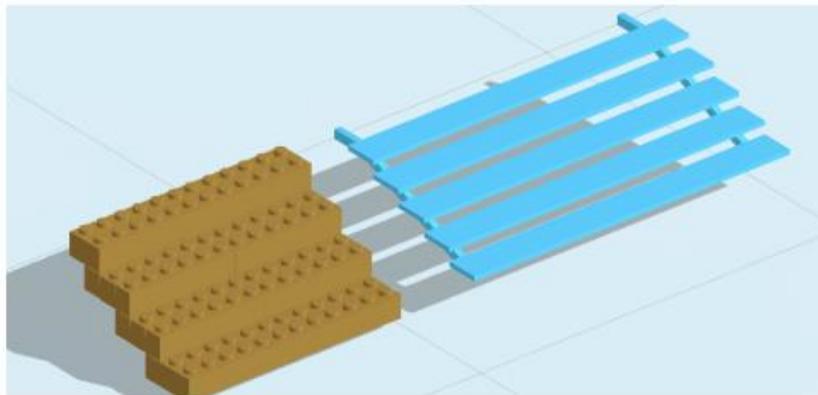

**Figure 17-Level 01 and Level 02 for Stair Elements**
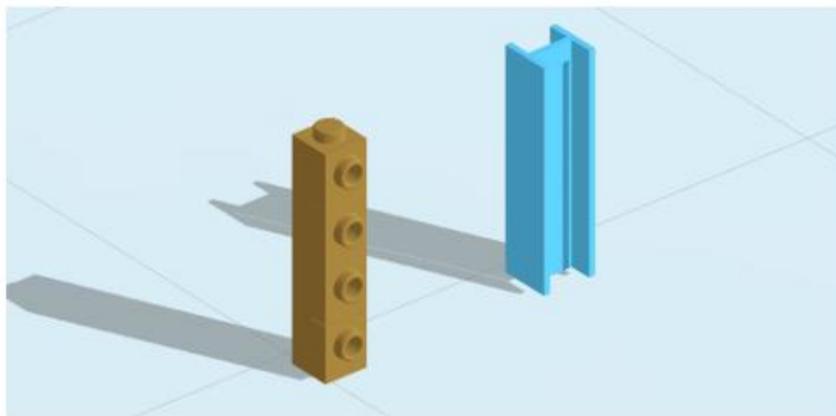
Figure 18- Level 01 and Level 02 for Column Elements
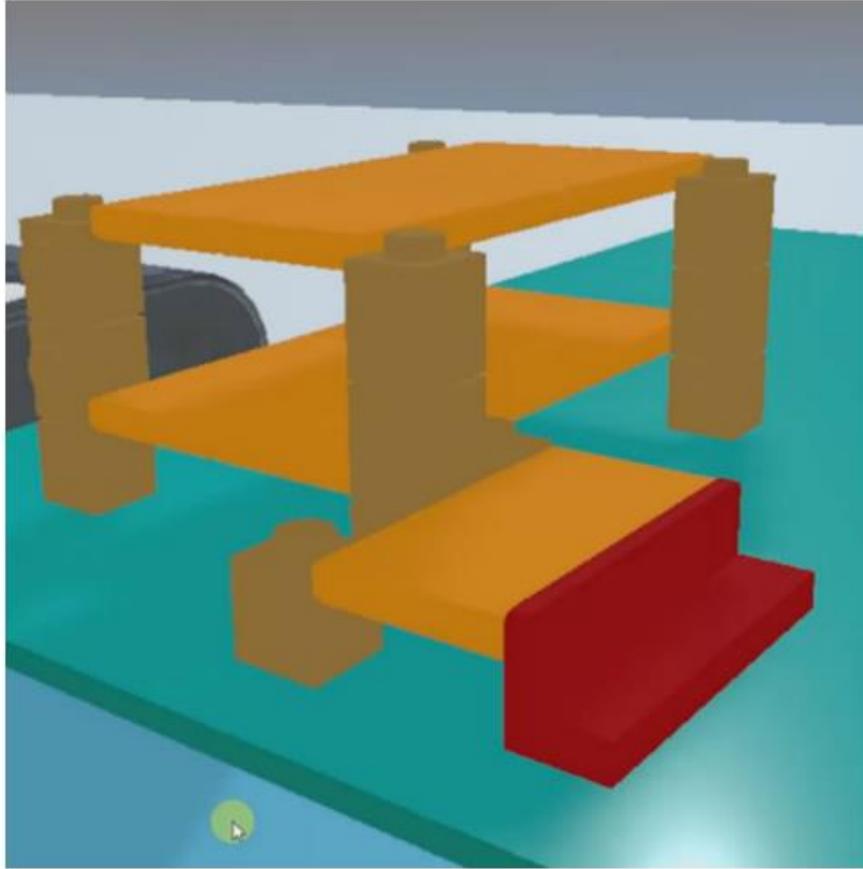
**Figure 19-Completed Level 01**
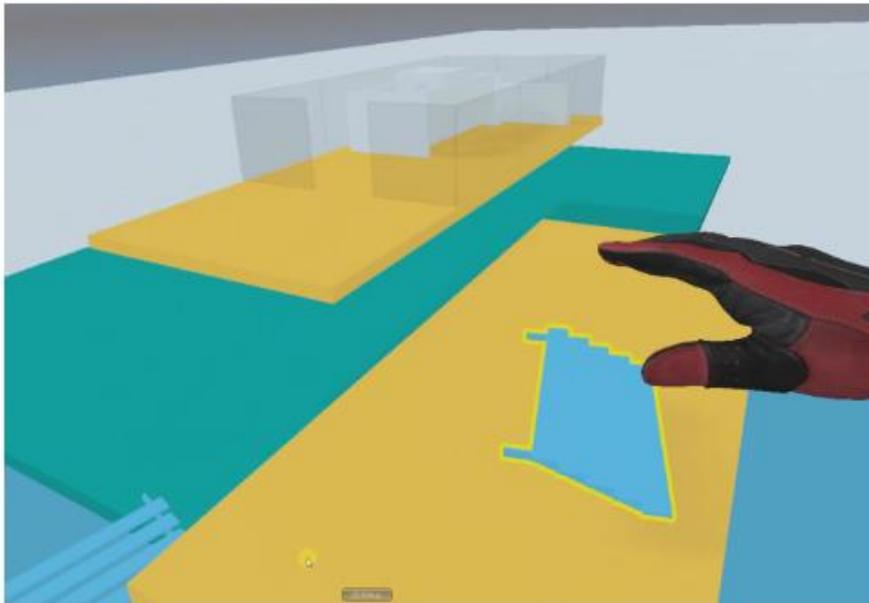
Figure 20- Level 02 in Progress

Level-01 is based on Basic LOD (200) and is represented with the simple geometry of LEGO. After the player completed level-01 he must play level-02 where the LOD (300) is there, and the geometry is much complex. Players also indicated increased depth of understanding with the voice/video narration during the exploration stage.

VR along with this gaming approach can used as a teaching medium which requires no classrooms. In addition to that, people who don't have any previous knowledge of architecture can also use this method of learning beyond reading technical drawings which can be a tiresome task for both architectural and non-architectural students.

Gamification approach can also be used for monitoring the construction progress .According to [38] In large-scale construction projects, the process of monitoring the implementation of every single part of buildings and reflecting them on the BIM models can become highly labor intensive and error-prone, due to the vast amount of data produced in the form of schedules, reports and photo logs. This paper [38] presents a framework and a proof-of-concept prototype for on-demand automated simulation of construction projects, integrating some cutting edge IT solutions, namely image processing, machine learning, BIM and Virtual Reality.
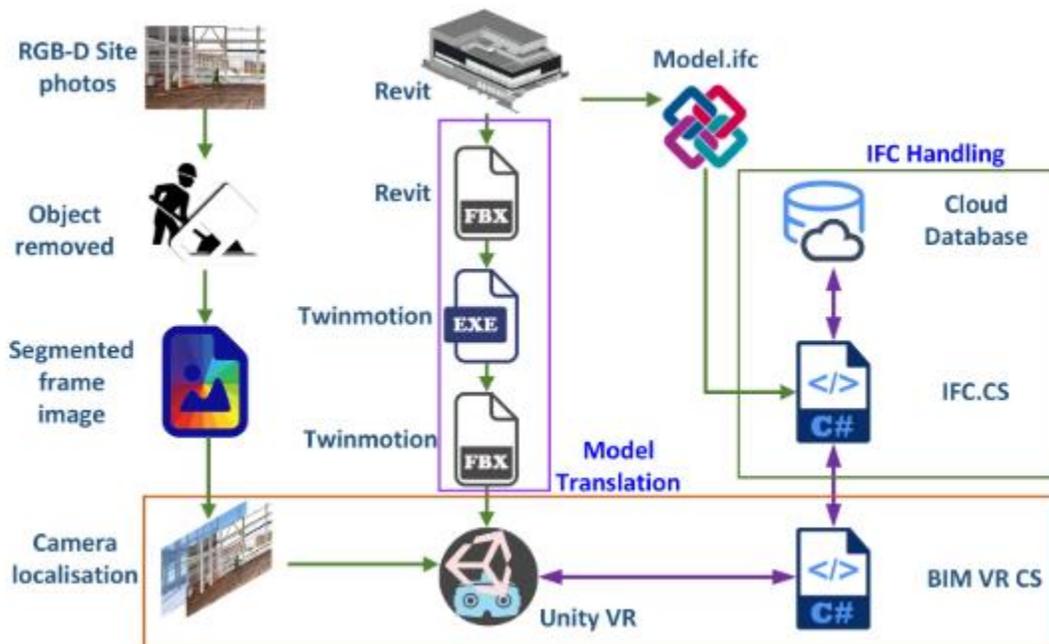
Figure 21- Flow chart of Achieving Progress monitoring with VR

The above image shows the flow chart of the prototype, based around the principles of remote construction project monitoring, it takes advantage of ML and image processing in removing unwanted objects, recognizing and extracting main building characteristics, and overlaying these on the corresponding as-planned nD components. VR technologies, including Unity and HTC Vive, provided a virtual environment to allow better user interaction with these elements [38].

It was concluded that the proposed platform could help construction companies to follow the progress of their work and diagnose any discrepancy without interrupting the on-site operations. This remote managing tool can also save a great deal of time and provide a more accurate comparison of constructed parts with the as-planned BIM mode [38]. As this approach uses VR it is easy to visualize the progress monitoring in an immersive environment. In addition to that, future planning can also be performed using VR which will give us a better understanding of the clashing that might happen.

Chapter-02 Methodology

2.2 Case Study ("Stellantis")

"Stellantis" is a multinational automotive manufacturing corporation formed in 2021 on the basis of a 50-50 cross-border merger between the Italian-American conglomerate Fiat Chrysler Automobiles and the French PSA Group. The company is headquartered in Amsterdam [39].The principal activity of Stellantis is the design, development, manufacture, and sale of automobiles bearing its 14 brands. At the time of the merger, Stellantis had approximately 300,000 employees, a presence in more than 130 countries with manufacturing facilities in 30 countries [40].In the past, it was the largest Italian industrial complex. It is the oldest automobile factory in Europe and is still partially in operation today. It occupies an area of 2,000,000 m². Today around 18,000 employees work in the area and in 2012 tabout 41,600 cars were produced. Currently it produces the Maserati Levante luxury SUV, Maserati Ghibli sport sedan and Maserati Quattroporte luxury sedan.In the more than 80 years since inauguration, over 35 types of cars and 28.7 million vehicles have been produced at the Mirafiori plant [41].The case study focused on the Fiat Mirafiori industrial complex, one of the largest plants in the City of Turin.
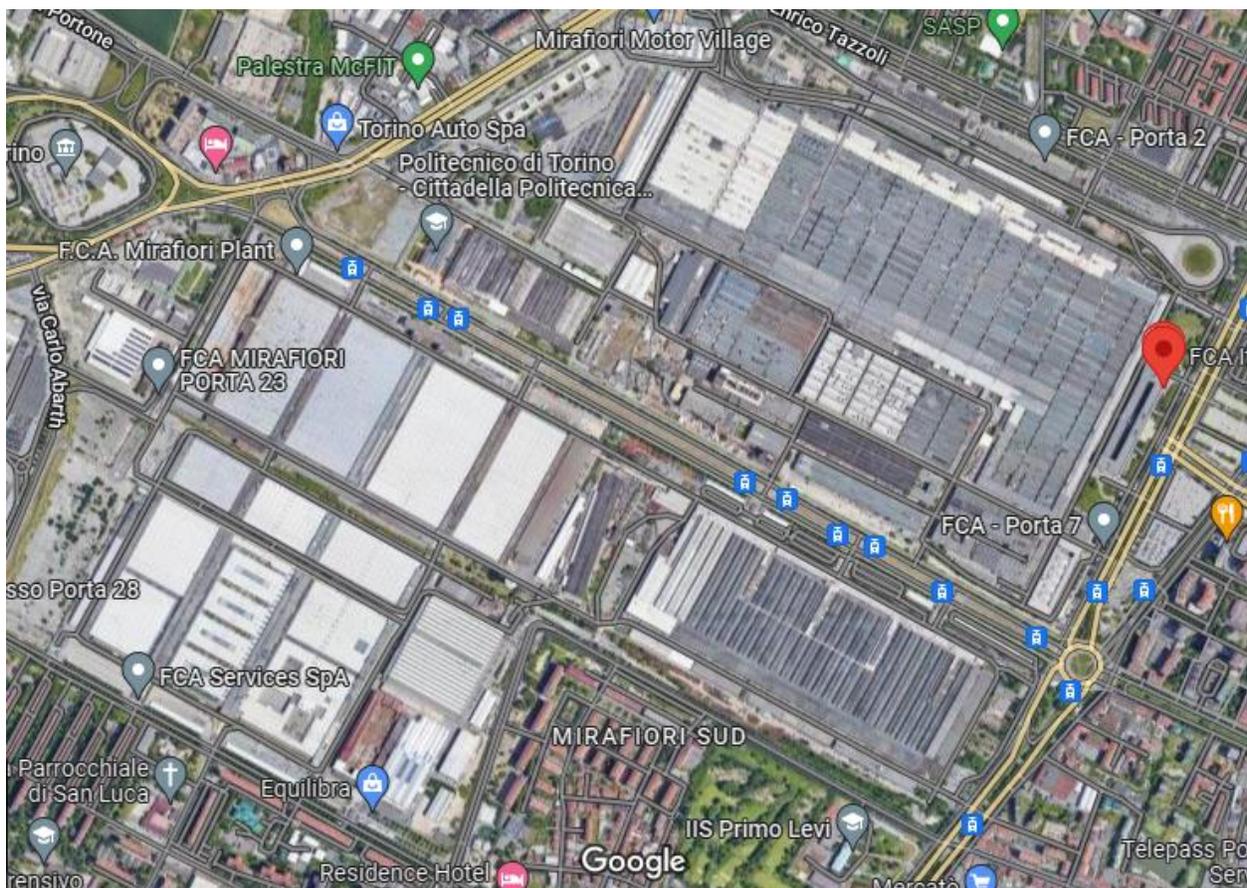

Figure 22- Google Maps view of the Area

## 2.3 Workflow for the Application Development
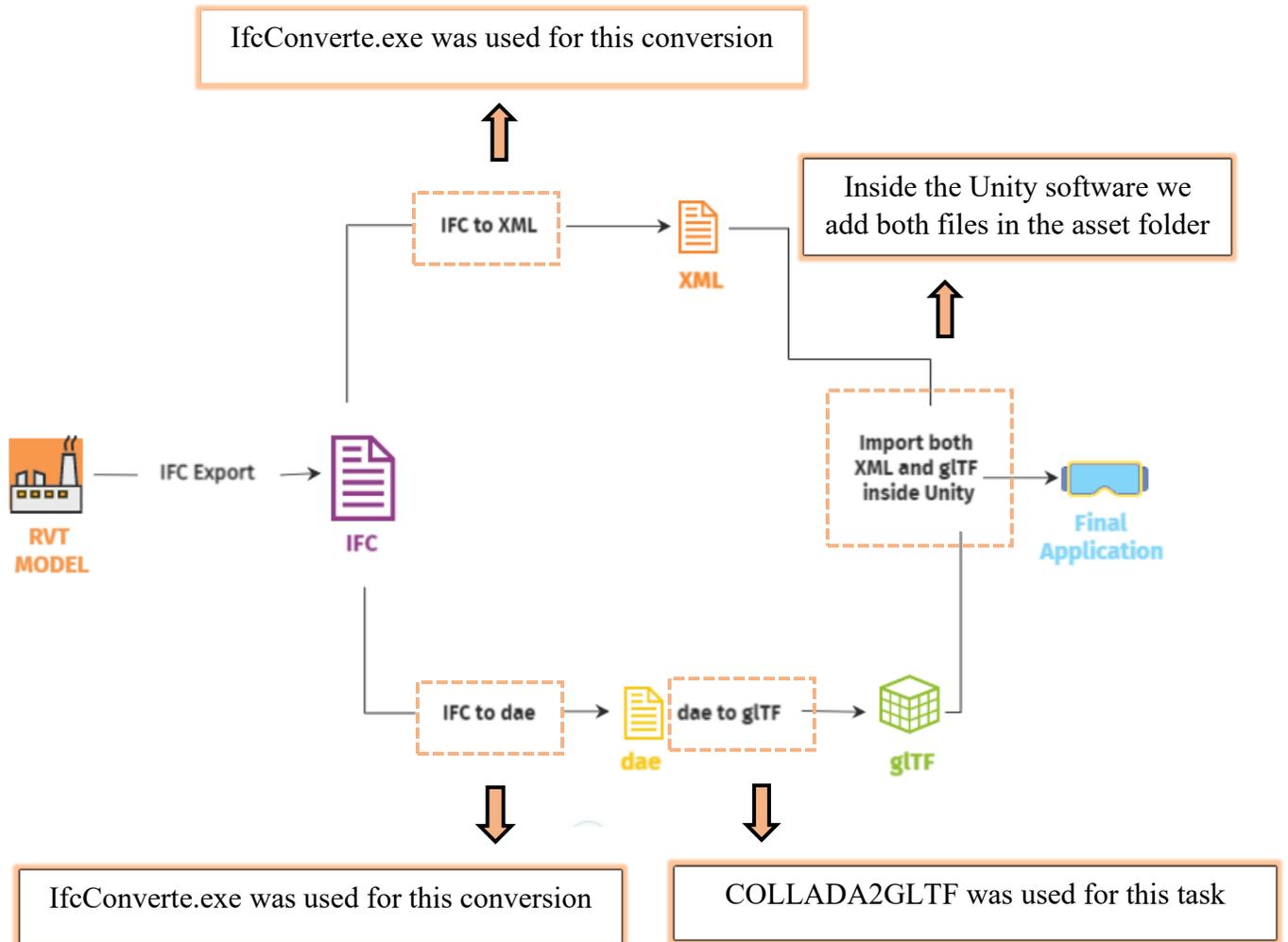
**Figure 23- Back-End workflow of the Application**
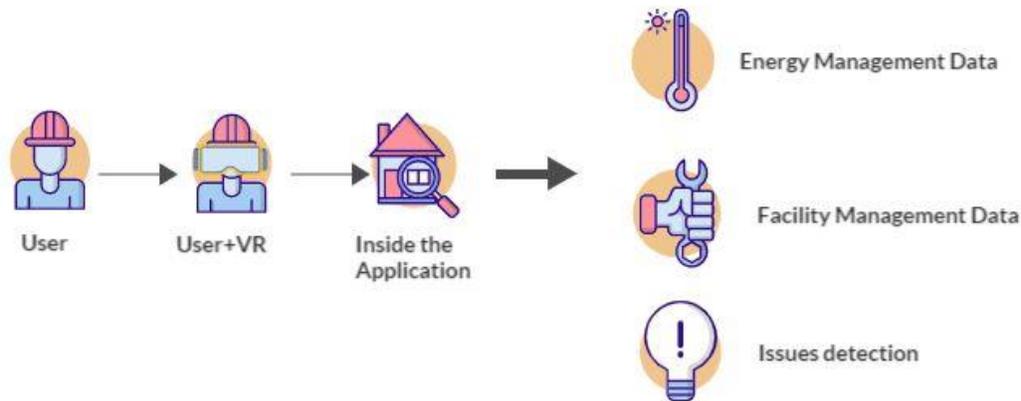
Figure 24- User end/Front end workflow of the Application

The figure 23 indicates the workflow followed for the application development. As this thesis is focused on OpenBIM usage, we tried to follow the OpenBIM protocols. BIM model of the factory was made with the use of Autodesk Revit 2020.As our focus is on OpenBIM any BIM authoring software can be used which exports IFC. Our model was then exported into IFC file format. The alpha numeric data and the geometric data of the model were separately imported inside the UNITY game engine. For alphanumeric data IFC was converted into XML file with the use of "IfcConverte.exe" IfcOpenShell. For geometric data of the model, the IFC file was converted into ".dae file" first and then converted into "glTF" format with the use of "COLLADA2GLTF" siccity.

Both XML and glTF were imported inside Unity With the help of the application developed inside Unity it was made possible to use VR for AEC application with a gamified approach.

For referencing the alpha-numeric data with the correct geometric data inside Unity , GUIDs played a very important role.

GUID or UUID:

According to [10] "The IFC specification uses a unique identifier for object instances that follows the universal unique identifier standard UUID with its implementation as a globally unique identifier GUID. The generated GUID is compressed for exchange purpose following a published compression function. The compressed GUID is called "IFC-GUID".

Standard GUIDs are a series of hexadecimal numbers from 0-6 along with letters from A-F. It's 32 digits long and arranged in an 8-4-4-4-12 series. (393e7c63-4848-4a44-8d8e-3bf8595a15f7) BuildingSmart uses another approach for the IFC's GUIDs to conserve disk space. According to [10]

"IFC-GUID Base-64 character encoding mapping:

(0123456789) =10 characters

"ABCDEFGHIJKLMNOPQRSTUVWXYZ"= 26 characters

"abcdefghijklmnopqrstuvwxyz"= 26 characters

"_$"= 2 characters

Total= 64 characters are used to make a 22 digit string length of GUID.

The resulting IFC-GUID is a fixed 22 character length string. Software implementations will need to use an algorithm that converts standard GUIDs to and from this encoding for compliance with the IFC specifications"
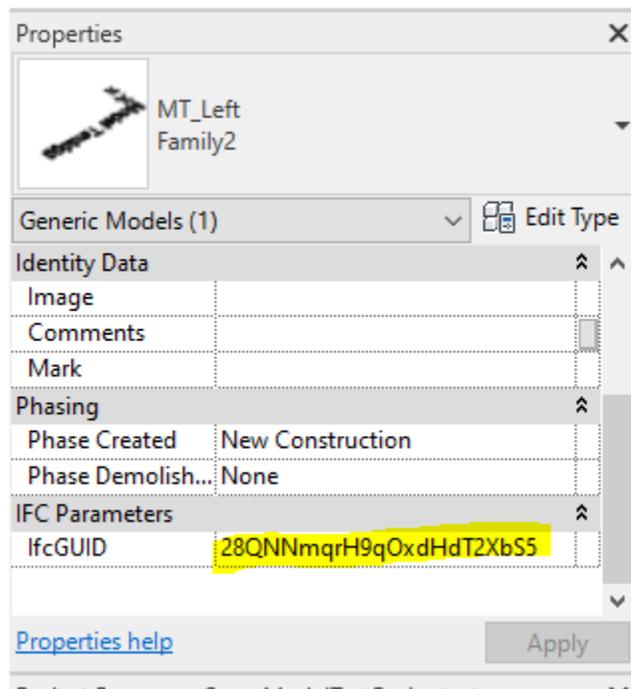
Figure 25-IFC GUID Example

Source: [42]

Benefits of GUIDs in BIM Projects:

1) Well structured BIM data is achieved

2) As object maintains its GUID, Changes to objects in different models' versions can be tracked.

3) Every object has a unique GUID thus each object can easily be managed if required.

4) Different property set can be assigned under a single GUID this can be seen in the XML converted file.

2.3.1 Overview of the Technologies Used

BIM Authoring Software

Autodesk Revit 2020 was used for the developed BIM model of the FCA factory. The model made were Architectural, electrical, and mechanical model. These 3 models can be combined to form a federated model. Which then can be used for the required purposes which in our case were Facility Management and Energy Analysis.


Figure 26-Architectural Model of the FCA Factory

Required LOD

The figures shown below indicates the objectives to be achieved in the first box on the left, in the middle box the model use scenarios are discussed and on the right side the LOD required to achieve this objective is indicated.
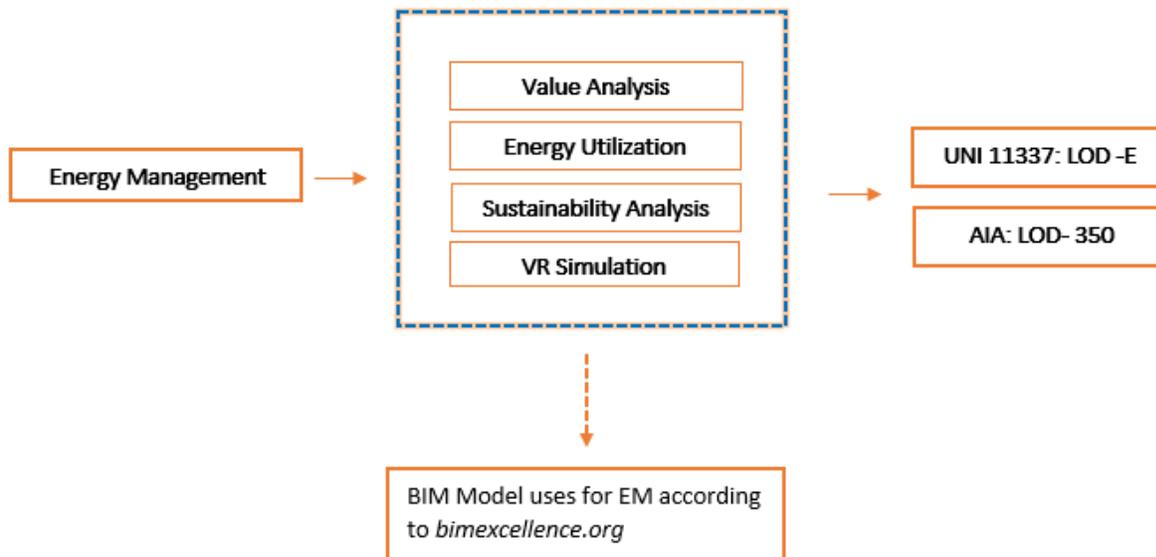

Figure 27-LOD Along with Model use for EM
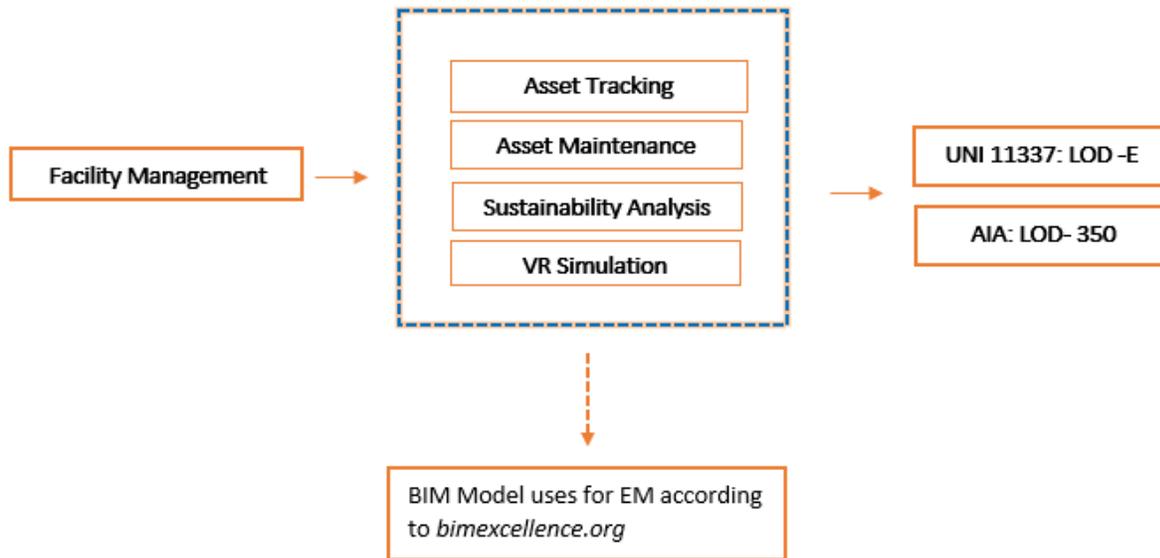
Figure 28-LOD Along with Model use for FM

Game Engine

Unity is a multi-platform game engine developed by the Unity technologies. Initially at launch in 2005 it was an exclusive game engine for apple MacOS [43]. This game engine has gradually increased its support for desktop, console, and virtual reality platforms. As of September 2019, 52% of the top 1,000 mobile games were powered by Unity, as well as 60% of all AR/VR content, according to the company. Unity game players are in **195 countries** -- which is literally every single country on the planet [44].As is indicated by [44] around 60% of VR/AR applications are being made of this engine thus this was one of the reasons for selecting UNITY as our game engine for this Thesis. The other reason was that it is completely free. With many programmers using UNITY as their main game application development platform its community is getting bigger and bigger each day. This vast community helps others in their applications which is another reason for its popularity.
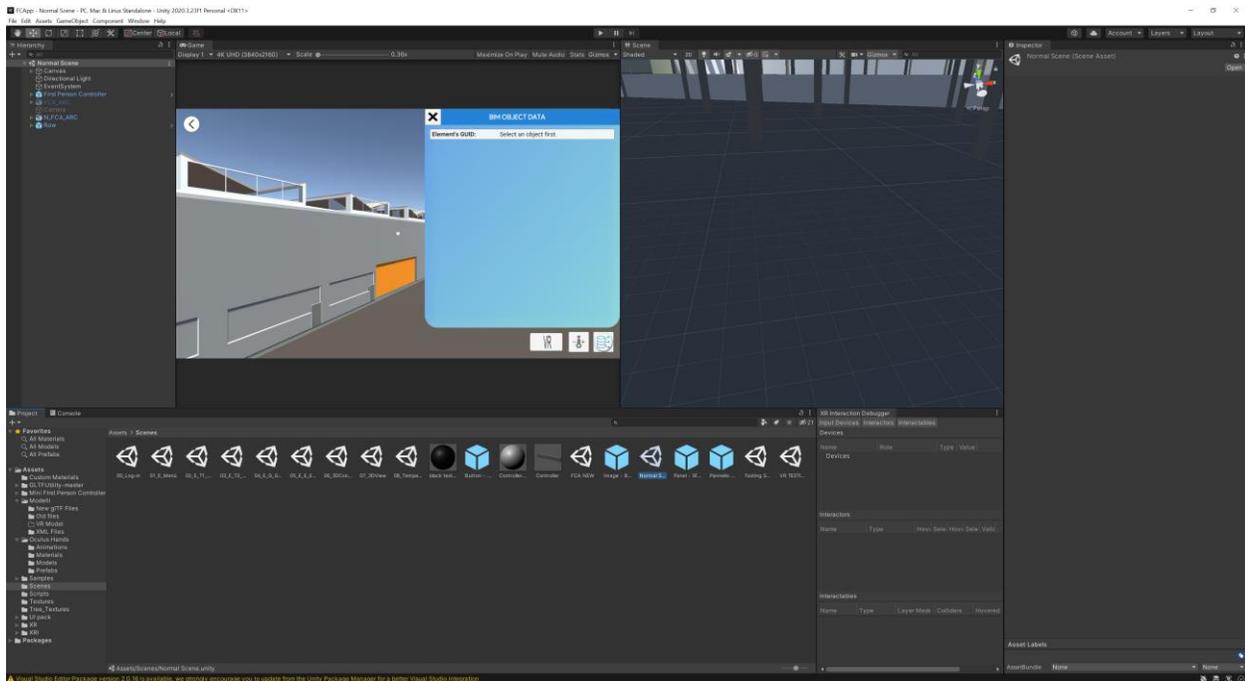
Figure 29-Unity Game engine "Standard Application Scene "
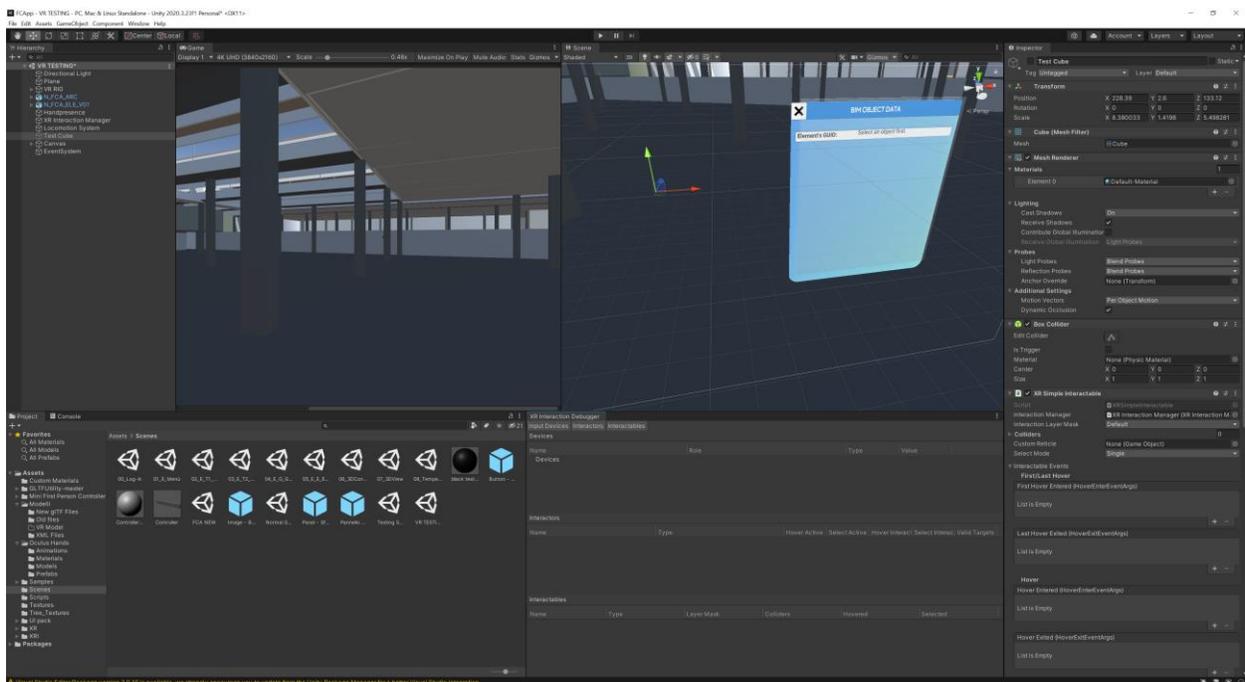
Figure 30- Unity Game engine "VR Application Scene "

The steps involved in unity are creating a scene by the setting the main camera position and then importing the XML and glTF inside the assets folder. A canvas is created as a gameobject with the desired buttons and area for the results to be displayed. Different C# scripts are created for different functions. The first script registers the click and store is as a variable. The second script takes that

variable and search for the same GUID inside the XML file and looks for the property set values. The final script transforms the canvas to display the desired output values on the screen. A few smaller scripts are also created for the better use of the canvas.

For the VR scene, first new packages have to be installed inside Unity namely "XR Plug-in Management" and " XR interaction ToolKit".With the help of these packages we are able to set the oculus devices inputs inside our application.
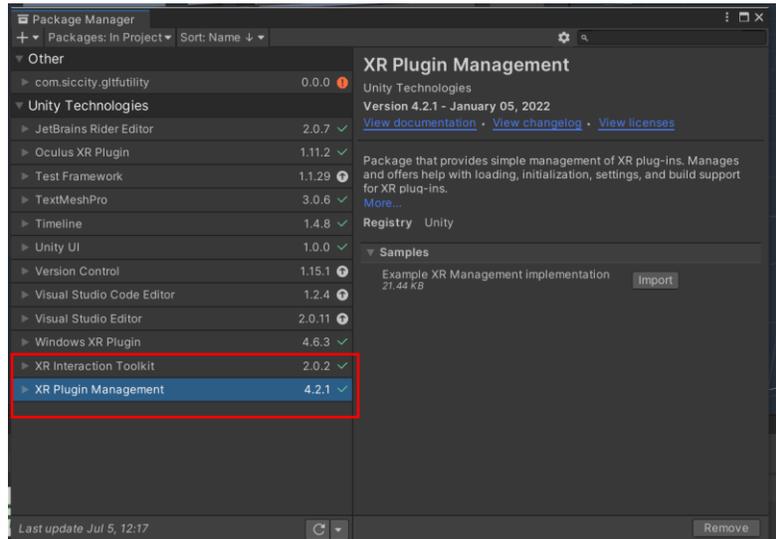
Figure 31-Package Manager for Unity Game engine

For the camera and controllers to be set in the scene "XR origin (Action-Based)" game object under XR the is selected. Script called "input action Manager" is added.
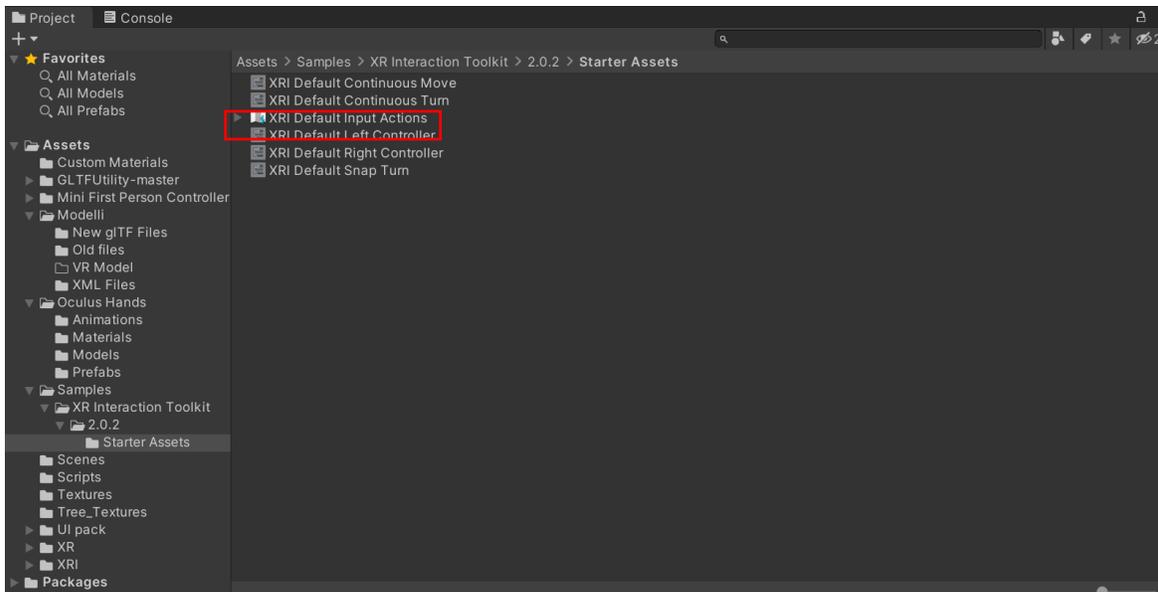
Figure 32-Starter Assets inside XR Toolkit
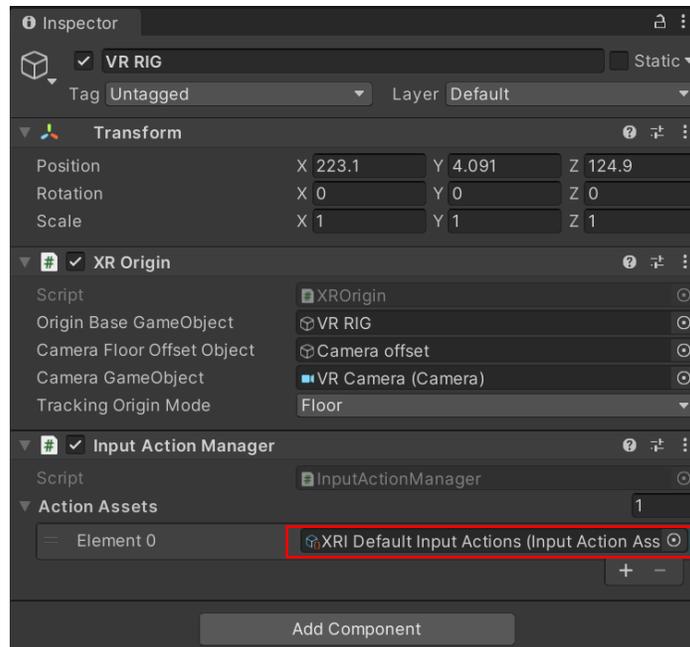
Figure 33-XR Origin Game object

Now inside the "XR origin "renamed as VR Rig in our case we have 2 ray interactors namely "Right_Ray interactor" and "Left_Ray interactor" respectively. We have to assign new components to the left and right interactor and delete the already assigned component named "XR Controller (Action-based)". The new scripts are already present inside the sample folder of the "XR interaction Toolkit" previously downloaded. This will save us from manually setting up the controllers. As all the functions have already been assigned in these scripts.
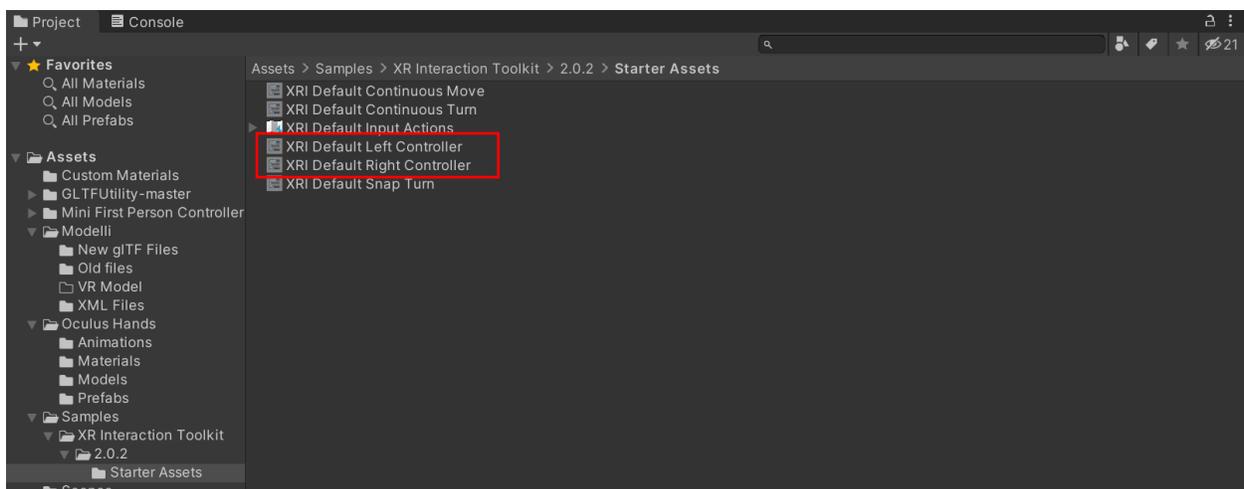
Figure 34- Starter Assets for Controllers

For movement inside the VR environment we have to create a game object called "Locomotion system" under XR. To assign the left and right controller for movement we have to assign components called "Continuous Move Provider" and "Continuous Turn Provider".
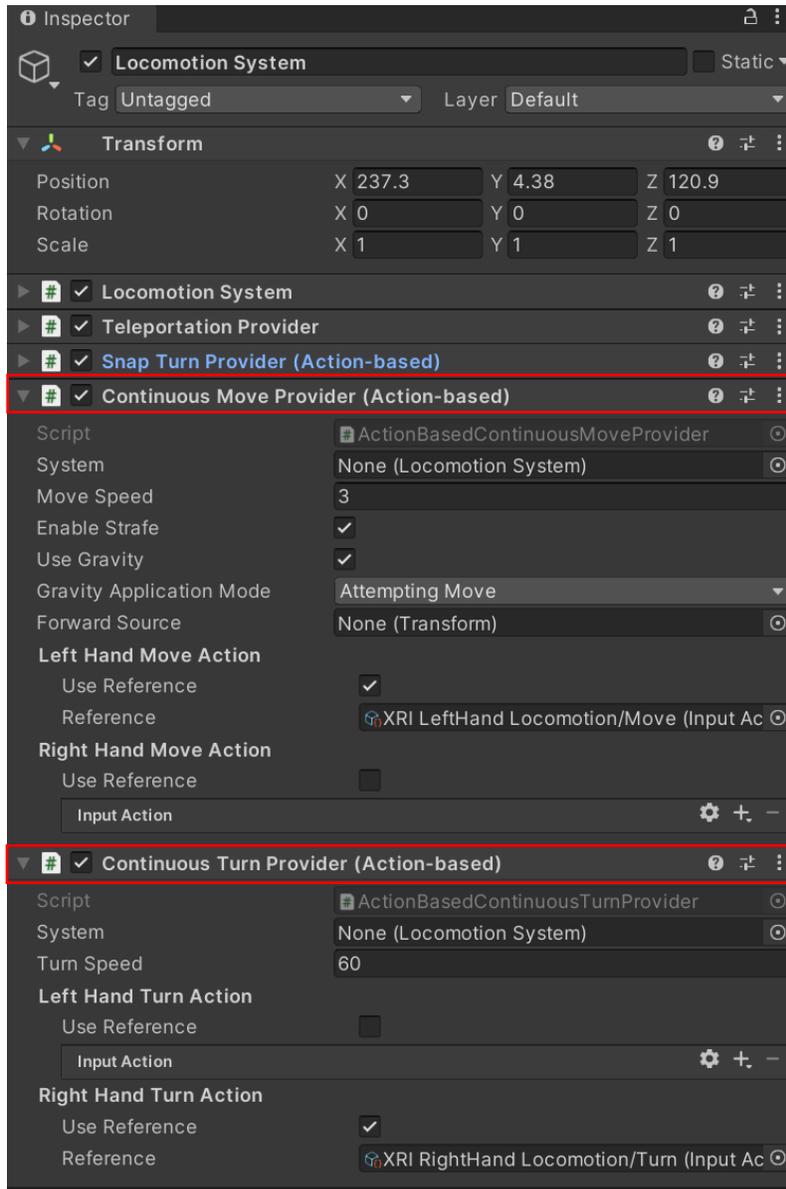
Figure 35-Locomotive Game object

For making a game object intractable with the rays coming out of the controller we have to assign 2 main components to that game object namely "Mesh collider" and "XR Simple intractable "respectively.
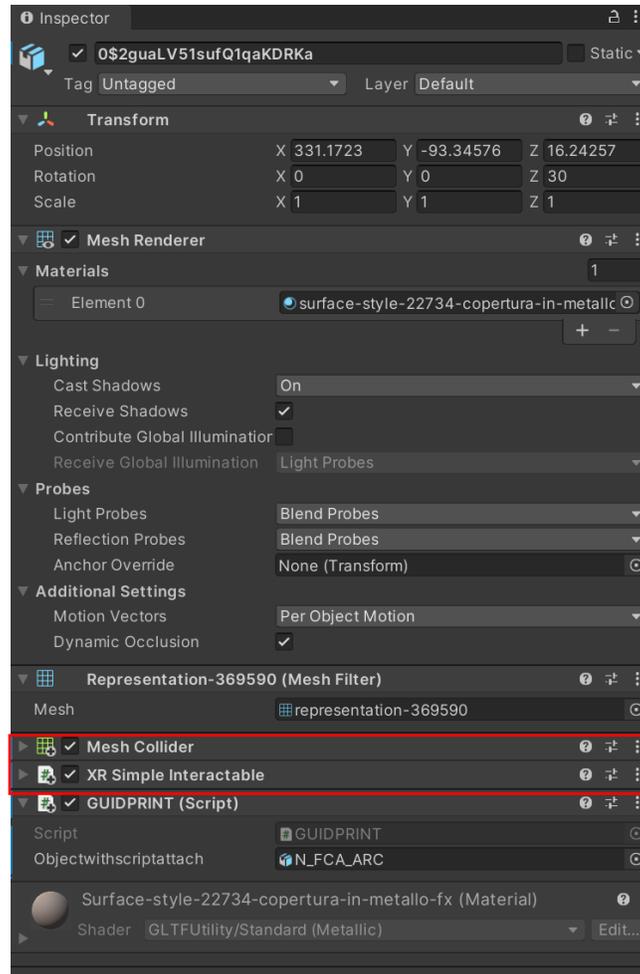
Figure 36-Mesh Collider and XR interactable

After assigning the interactors and intractable, we must perform the same steps which we made while making the standard screen-keyboard input application but with a modified script for registering the press of the controller button instead of a mouse click. The logic remains the same which is the click which now in this case is the controller "button press" will store a GUID and a script will check the properties inside the XML file. In the VR we want the canvas to move with us and not stay at one position this was done by changing the parent of the "Panel" from canvas to the "Left controller". This allows us to move the panel with the left controller

IDE (Integrated Development Environment)

For scripting inside UNITY, C# was used as the language while the IDE (integrated development Environment) which was used was Visual Studio. Visual studio is and IDE developed by Microsoft [39]. Computer programs, websites, webapps, web services and mobile applications can be developed using Visual studio. Visual Studio supports 36 different programming languages and allows the code editor and debugger to support (to varying degrees) nearly any programming language, provided a language-specific service exists. Built-in languages include C, C++, C++/CLI, VisualBasic.NET, C#, F#, JavaScript, TypeScript, XML, XSLT, HT ML, and CSS [39].
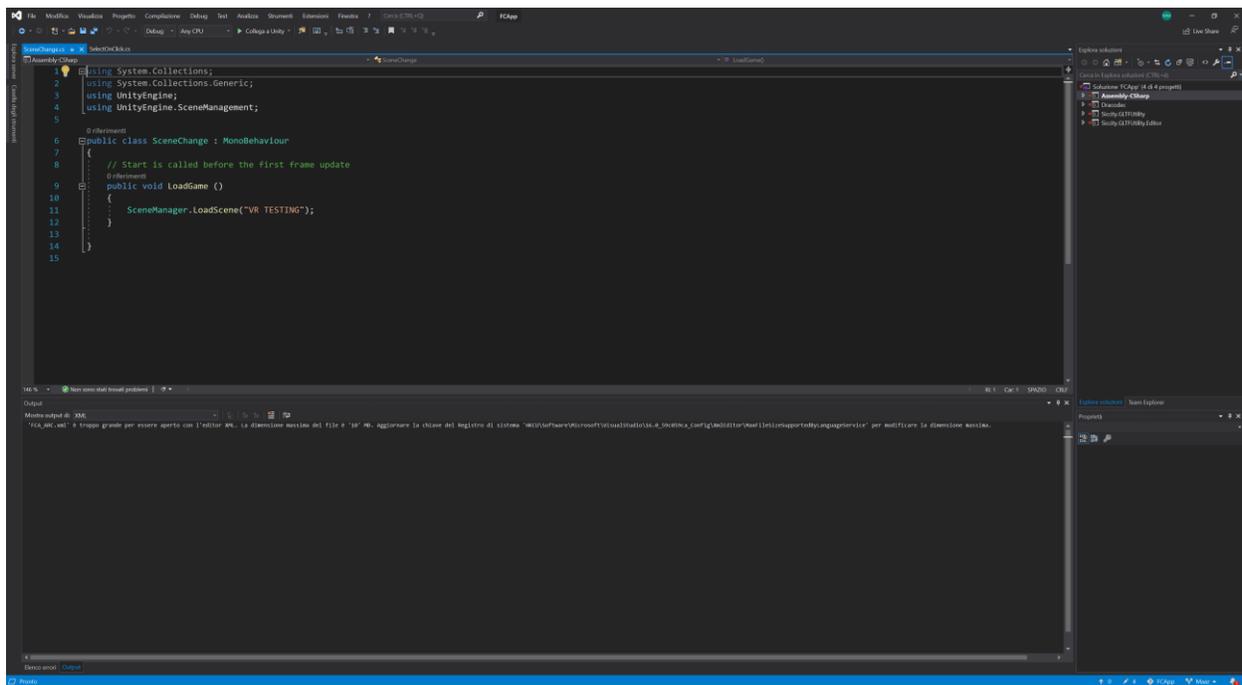
Figure 37-Sample Script inside VS

VR Device:

Oculus Rift S was used for the VR application development. The Rift S has a 1,280[35] ×1,440 LCD @ 80 Hz [39]. The Rift S tracks the position of itself and its controllers in 3D space using a system known as Oculus Insight, which uses the 5 cameras on the HMD to track points in the environment and infrared LEDs on the controllers, information from accelerometers in both the HMD and controllers, and computer vision to predict what path the HMD and controllers are most likely to take [43].

The SDK of oculus is already integrated inside the most popular game engines like Unity 5, Unreal engine 4.0. The Rift is an open platform, and thus developers do not need any approval or verification to develop, distribute, or sell content for it, and do not have to pay any licensing fees. The SDK, however, cannot be modified or reused for other purposes or hardware without permission [43].

Figure 38-Oculus Rift S

2.3.2 Overview of the File types

 XML

XML (Extensible Markup Language) is a markup language like HTML, but without predefined tags to use. Instead, you define your own tags designed specifically for your needs. This is a powerful way to store data in a format that can be stored, searched, and shared [45]. Markup is the process of using codes called tags (or sometimes tokens) to define the structure, visual appearance and, in the case of XML, the meaning of any data [46].The portability feature of XML is reason which makes it a popular technology for data exchange. We can store the data in a while structured form and retrieve the desired results from it with any other device irrespective of the hardware and operating system differences [46]. XML allows you to create any tags needed to describe the data and data structure thus this was the reason we converted our IFC metadata into XML.
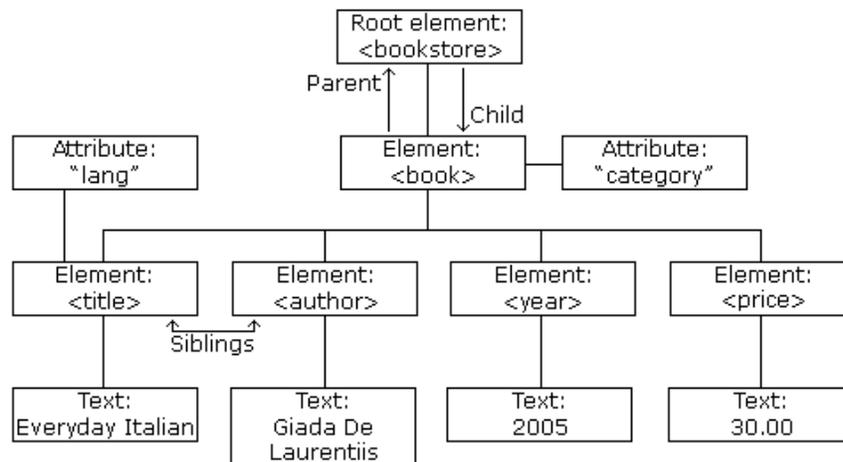
Figure 39-Simple XML Structure

Source: [47]

```xml
<?xml version="1.0" encoding="UTF-8"?>
<bookstore>
  <book category="cooking">
    <title lang="en">Everyday Italian</title>
    <author>Giada De Laurentiis</author>
    <year>2005</year>
    <price>30.00</price>
  </book>
</bookstore>
```

Figure 40-XML Document based on above structure

Figure 41-XML file of FCA Architectural Model

glTF

glTF™ is a royalty-free specification for the efficient transmission and loading of 3D scenes and models by engines and applications. glTF minimizes the size of 3D assets, and the runtime processing needed to unpack and use them. glTF defines an extensible, publishing format that streamlines authoring workflows and interactive services by enabling the interoperable use of 3D content across the industry [48].According to [49] it is an open standard made by khronos Group. The purpose is to streamline the heavy 3D files imports in different game engines and making the whole process much smoother. In fact, its creators have described it as the "JPEG of 3D.

Chapter-03 Results

3.1 Level of DT Achieved

This thesis was focused on the static data present in the digital twin, but this can be improved with the addition of dynamic near-real time or real-time data. With our digital twin, we can see the energy related components inside the factory in VR. This will help us in understanding the current sustainability state of the factory and will help us in improving the factory in terms of energy consumption. For the facility management, the user can view all the data inside the VR and can decide the facility management operations. Future planning for the facility management operations can be devised by using this application which means that the physical asset can be modified according to the planning done in the DT.

According to Min Deng's paper, we have achieved a Level-02 DT but with the addition of VR. This can be increased to Level-03 by connecting the dynamic data from the sensors inside the game engine Unity, unfortunately, this was not done in thesis due to time limitations.

3.2 Interoperability

The table shown below shows the interoperability results along with the pros and cons of specific exchange format.

Purpose	Operation	Exchange Format	Benefit	Issues	Score
BIM Data Export	RVT ⬇ IFC	IFC 2X3	1. Full integration 2. No plug-in required 3. OpenBIM standard 4.No Programing Skill required	Knowledge of IFC is required	(green)
VR Visualization alphanumeric data	XML ⬇ Unity	XML	1. No programing skill is required. 2. Alpha-numeric data is well organized 3.No plug-in Required	No issues were observed .XML data can easily be added inside the asset folder inside unity.	(yellow)
VR Visualization Geomatric data	dae ⬇ Unity	dae	1.Based on XML thus easy to Read 2.Free and open source format	1.Material were not properly assigned from the IFC file 2.Considered unpredictable and buggy	(orange)
VR Visualization Geomatric data	FBX ⬇ Unity	FBX	1.No loss of information between compatible applications	1.Larger file size which makes the application heavy 2.Scaling issues been observed in Unity 3.Owned by Autodesk not open source	(red)
VR Visualization Geomatric data	glTF ⬇ Unity	glTF	1.Royalty free format 2.No programming Skills 3.More consistent and Reliable file format	1.Plug-in is required	(yellow)

Table 5-Interoperability Matrix

To understand the scoring system, we have to refer to the table shown below which indicates the meaning of each color.
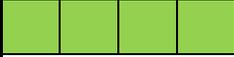
Score	Explanation
🟩🟩🟩🟩	1.No data loss 2.Follows OpenBIM philosophy 3.No plug-in Required for import 4.No programming Skills Required
🟨🟨🟨	1.No data loss 2.Follows OpenBIM philosophy 3.No Programming Skills
🟧🟧	1.No Programming Skills 2. Not much data lost
🟥	1.No Programming Skills *Doesn't follow the OpenBIM philosophy*

Table 6-Score Explanation

3.3 Reliability of the Results

The Reliability of the final application developed depends on the accuracy of the IFC file. This means that if we have a very reliable IFC file the results obtained from our application will be reliable and vice versa. Our application is reading the XML file along with its glTF counterpart. This makes it possible to view the property sets of any element on which the user clicks or interact with the Ray depending on the setup (VR input or mouse-keyboard) .

3.4 Benefits of Using the VR version of the Application

The following are the reasons for using the VR version on the application over the Normal (Keyboard-mouse input) version.

1) Full immersion:

With the use of VR, the communication with the model elements is increased by increasing the senses involved. Hardware peripherals, VR experiences will include tactile and other sensory information to further emulate physical reality

2) Better Collaboration

Teams can use the VR and each applicant can have their own avatar in the application. This will allow us to better understand the asset and will eventually help us in reaching the best solution with the help of others.

3) Cost savings

VR will also improve the training of operators, as training can be carried out in virtual environments that perfectly reproduce real conditions, with simulated failures and risky situations. This is especially important when we consider prevention of occupational hazards. This drastically reduces paid hours of training time and days off for training on real sites or conferences

4) Better Safety Inspection

Manual inspections might miss crucial points but with VR experts can clearly take into consideration every minute detail in the factory. As it is VR, and it is fully immersive it will feel like playing a game rather than doing a tedious task on the PC screen.

5) Less Distractions

When the application is used with the VR feature the user is less disturbed with its surrounding environment, this helps the user to focus on the problem much more than what would have been possible with a traditional screen mouse input approach.

Chapter-04 Conclusion and Future developments

4.1 Final Application
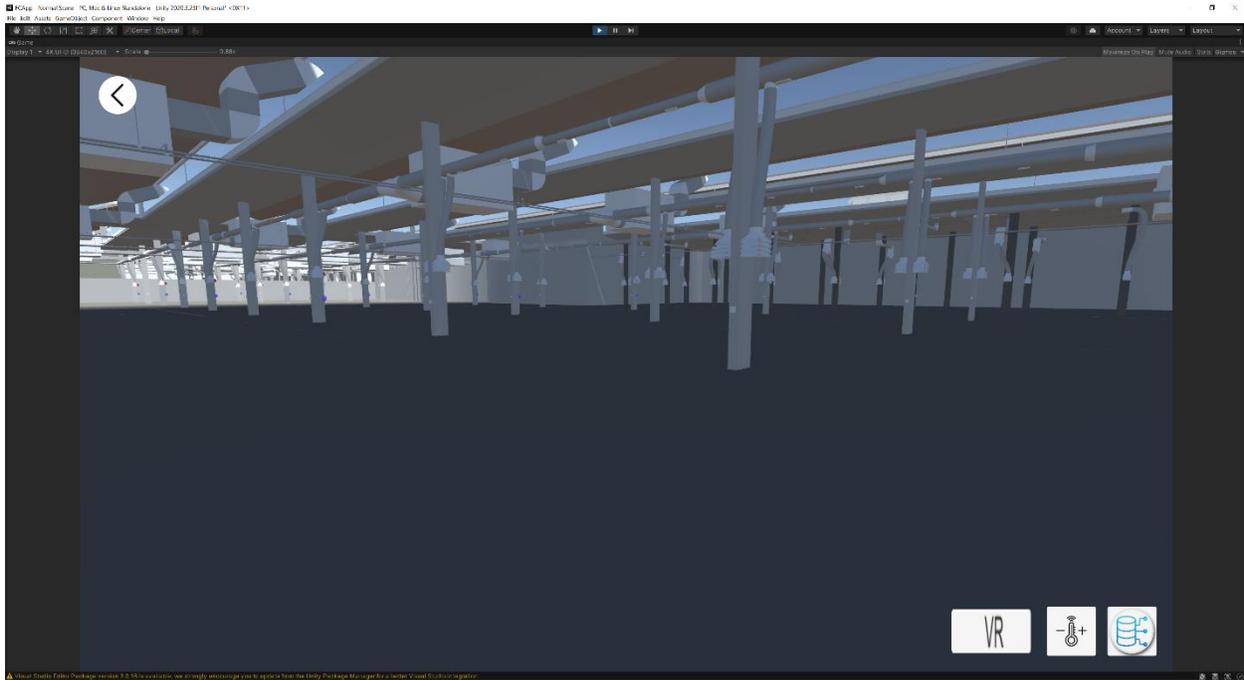

Figure 42-Standard Application Scene
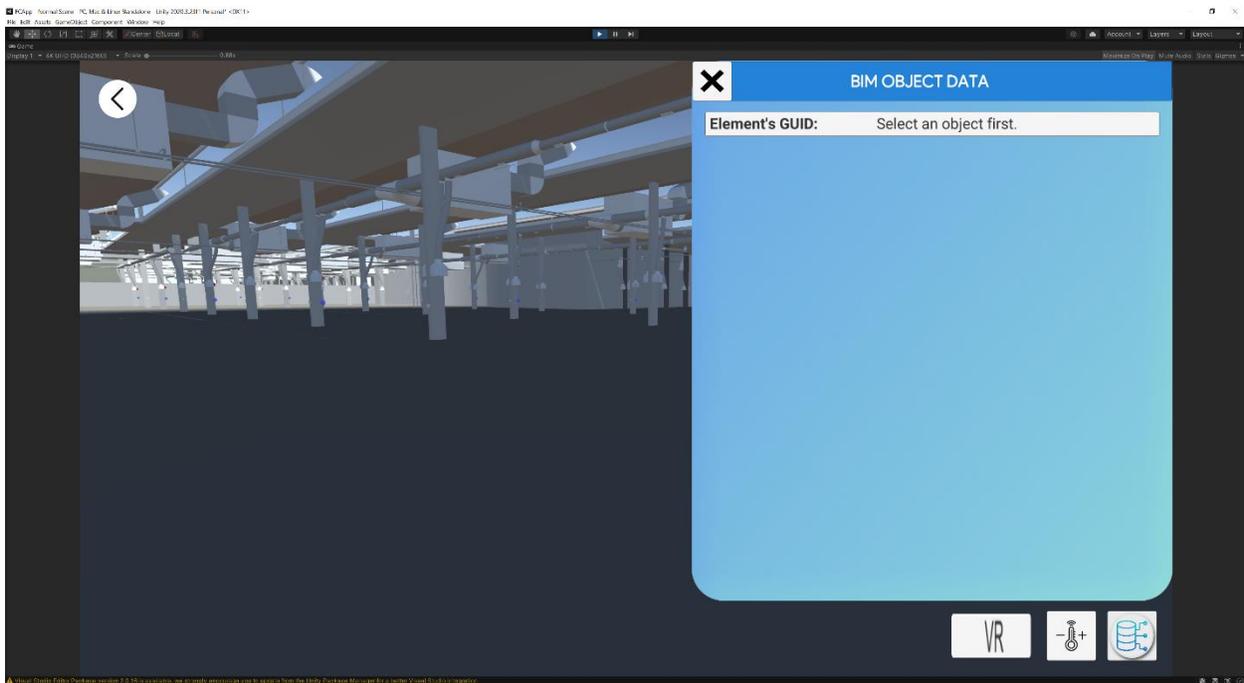
**Figure 43-Standard Application with BIM Panel**
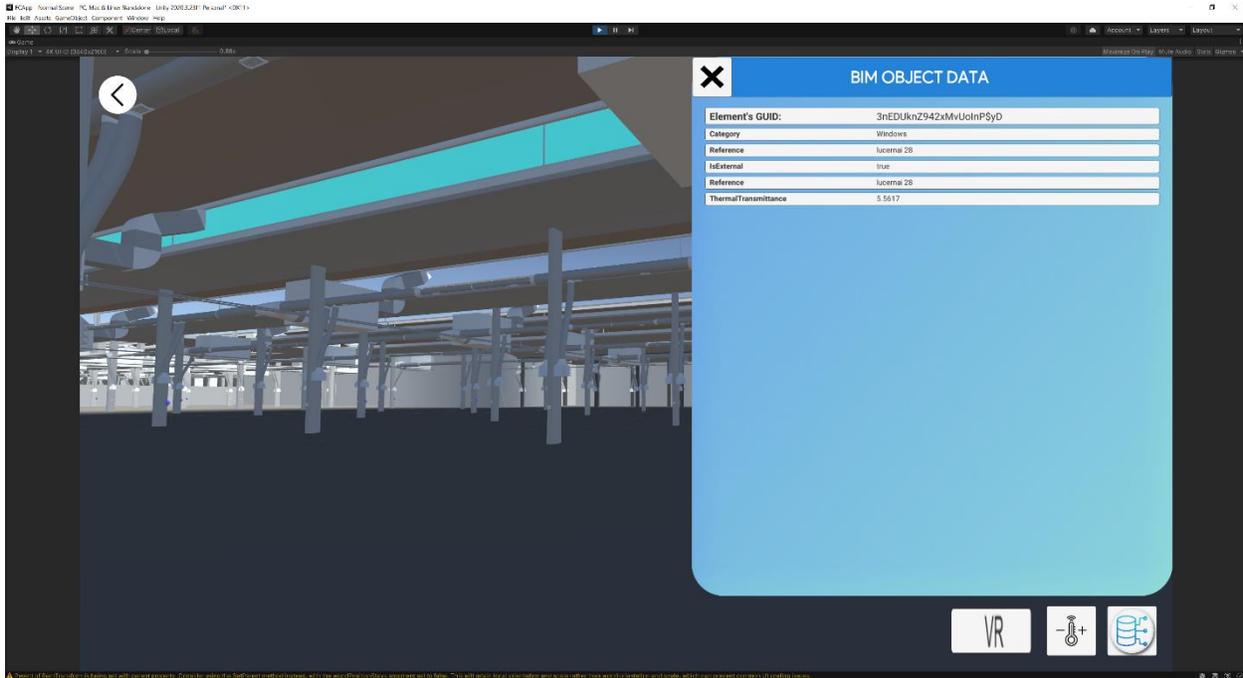
**Figure 44-Standard Application with Detail of windows shown**
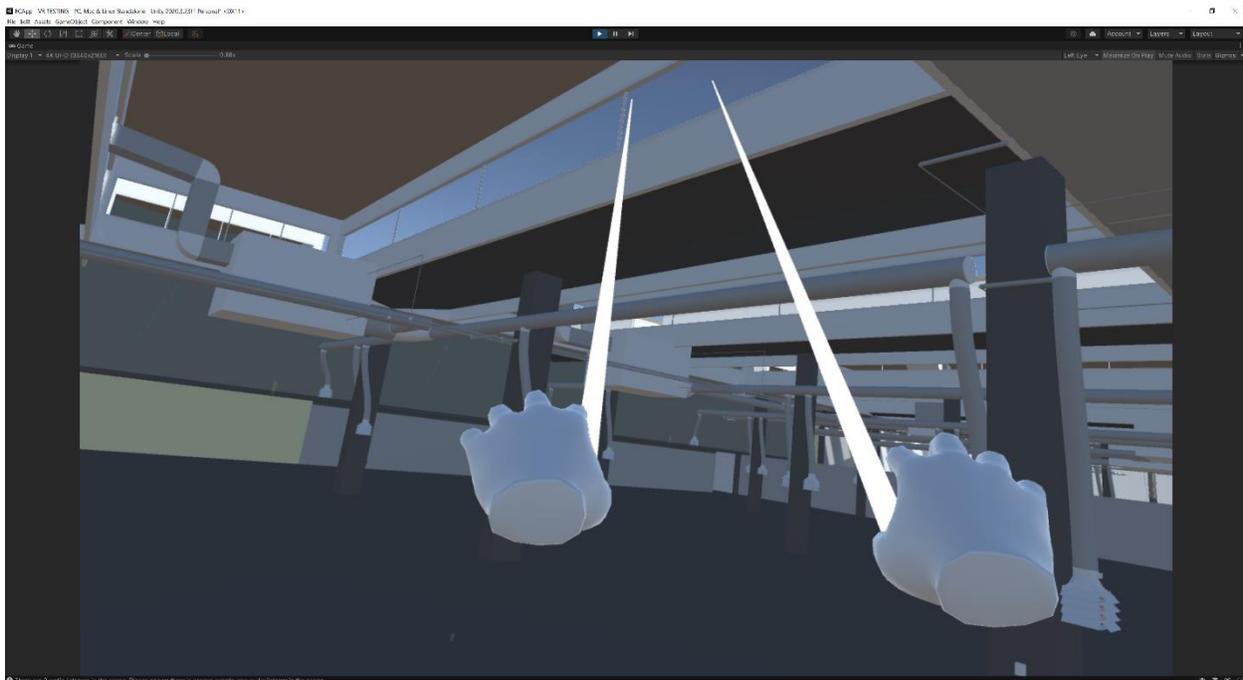

Figure 45-VR Application scene
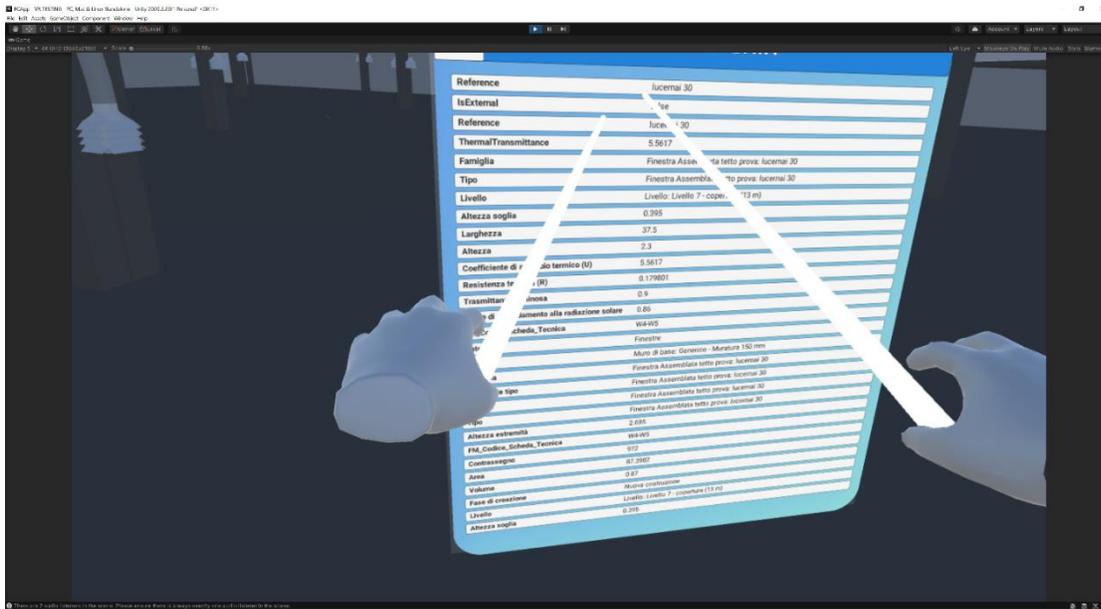
Figure 46-VR Application with Panel
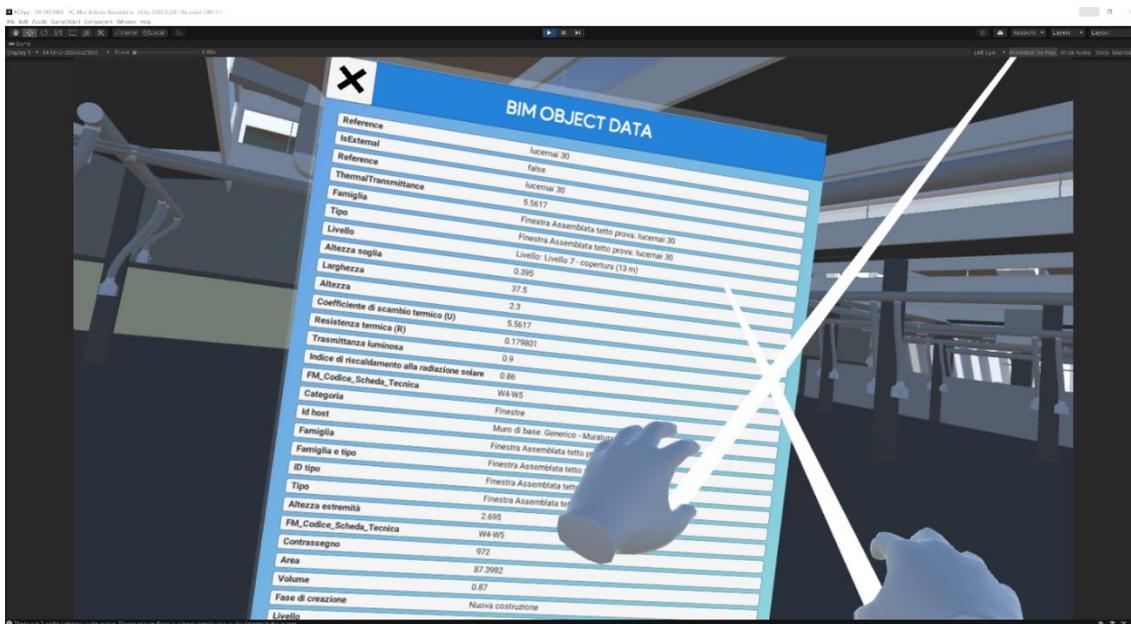
Figure 47-Movement of Panel with the Left hand controller

4.2 Scalability and Future developments of the Application

This application was made using one element of the factory i.e., windows and sensors inside the factory. As the focus was energy analysis and facility management. The energy data can be seen in VR in our application. For facility management the manufacture's data, the last maintenance log and the future required maintenance data can be seen.

Scalability with respect to the number of Elements:

The application can be scaled with respect to the number of elements. This means that if we want to know the information regarding other structural or nonstructural elements it can easily be done in VR environment.

Scalability with respect to the Properties and Property sets:

The application can be scaled for more properties. In our case we were focused on the Energy related properties, but it can be scaled for more properties depending on the use. If the focus is on facility management, then properties like Manufacturer's data, last maintenance date, Scheduled maintenance dates can be viewed. A tutorial video can be added on a particular element for better understanding of its maintenance, and this can also help in training of new facility management employees.

Scalability with respect to Number of Models:

Different IFC files can be present on an IFC server. We can select the desired file and get the required information in the VR application. It is useful because big organizations have many assets and to be able to use all the IFC files in the application it is necessary to for them to be uploaded in an IFC server.

Scalability with respect to console and operating systems:

We have used UNITY game engine for the application development. This game engine can build applications for various platforms thus this means that with application developed only once, the application can easily be modified for other platforms. As indicated on unity's website *"Create once, deploy across 25+ leading platforms and technologies to reach the largest possible audience."* [50]

Figure 48-Types of Platforms supported by UNITY

Source : [51]

Scalability with respect to type of Asset:

Scalability regarding the asset type is also possible. This means that the application can be used if we have other types of assets for example Hospitals, Schools and even for assets other than buildings example roads, bridges, tunnels, and dams.

Scalability because of IFC format:

As we have built the application based on IFC file format this has given us the freedom to use any modeling software that exports in IFC. Using a single type of modeling software is not a compulsion anymore. According to buildingSMART [10], there are more than 356 software by various software houses that supports IFC. The buildingSMART International Standards Implementation Database was last modified at 2022-04-11 19:54:11 by Jeffrey Ouellette [10].

Addition of Real-time Sensor Support

Due to time limitations of the thesis the real-time or near real-time sensors data was not included in the application. This can be done in the future with the implementation of BIM server. This will help us to increase the level of digital twin from 2 to 3. With the help of real-time sensors data inside the VR, we can better visualize the asset's condition through its digital twin's condition. Color coding based on certain tolerance brackets can be set. This means that whenever we have a sensor showing a reading outside the set tolerance it will change its color inside the application.

Addition of HVAC controls:

HVAC (heating, ventilation, and air-cooling) controls can be set in the future inside the application. Whenever, the energy manager observes some abnormality in the energy reading he/she can adjust the HVAC according to the energy plans previously set. This will help experts from around the globe to control the energy related parameters of the real asset through its DT.

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