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Sistema di supporto in realtà aumentata basato sul BIM per il facility management

BIM based augmented reality support system for facility management

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Summary

ABSTRACT

Il tema centrale del lavoro di tesi è la ricerca relativa alla costruzione di un “Sistema di supporto in realtà aumentata basato sul BIM per il facility management” ovvero un sistema informativo, capace di migliorare l’efficienza e l’efficacia di tutte quelle operazioni che avvengono nel post costruzione di un edificio e che sono paradossalmente poco elaborate confrontate alla progettazione e realizzazione dell’opera, seppure esse vengano protratte per più tempo, e sono molto più impattanti in termini economici.

Per poter trattare in maniera più chiara tali aspetti è necessario conoscere le tematiche relative al tema centrale, ovvero il Facility Management, il BIM e la Realtà Aumentata. Per questo proprio come è avvenuto l’approccio al lavoro di tesi, è stato necessario partire dalla ricerca documentale e informativa relativamente a queste tematiche, che sono riassunte al capitolo due.

Al capitolo tre vengono invece descritte le tecnologie in maniera più tecnica che poi sono state strumento della ricerca in campo, si parlerà dunque dei vari software e hardware utilizzati e le loro capacità.

Successivamente sono descritte le operazioni effettuate al fine di validare o meno il lavoro di ricerca, capitolo quattro, mentre al capitolo cinque sono esposti i risultati delle operazioni precedentemente descritte.

Infine nel capitolo sei vengono esposte le conclusioni relative allo studio che dimostra che tecnologie come il BIM e la Realtà Aumentata sono già ad uno stadio di maturazione tale per essere sperimentate sul campo, e che questo lavoro di tesi basato su studi in itinere non fornisce solo risposte ma vuole porre l’attenzione su queste tematiche che purtroppo ancora oggi sono relegate solo ad una trattazione accademica.

1. INTRODUCTION

It is indisputable that in recent years we are increasingly immersed in technology, how it is used daily without the general public noticing its presence and how it has become a fundamental part, let's think of Google Maps that allows us to find the best way, but above all it offers us the overview of traffic in real time, we also think of the many video games such as Pokémon Go which through augmented reality and the camera of a smartphone allows us to see imaginary creatures in the real world.

These and many other examples have a common thread, which is that technology is becoming more affordable for everyone, and that relatively cheap hardware is bringing it into our lives.

And where are we in the construction field? And in the management of real estate assets?

Without going into the merits, construction is one of the least developed sectors regarding digitization mainly for two reasons:

- 98% of companies are SMEs and have objective difficulties in implementing new technologies.[1]
- Construction is a sector not very used to changes, and the owners have an advanced average age and therefore not very sensitive to these issues.

This leads to the main problem, that is, huge economic resources are wasted every year due to obsolete systems, which start from design but are mainly connected to maintenance operations.

But small steps towards the digitization of the sector (at least as regards the design) are being made, an impulse in Italy in this direction was given by the Ministerial Decree

[1] Istat January 2019

560/2017 which will lead to the obligation to use BIM methodologies by 2025 for all public procurement. This will certainly lead to a radical change in the sector, projecting (at least in the public sector) the construction sector into industry 4.0.

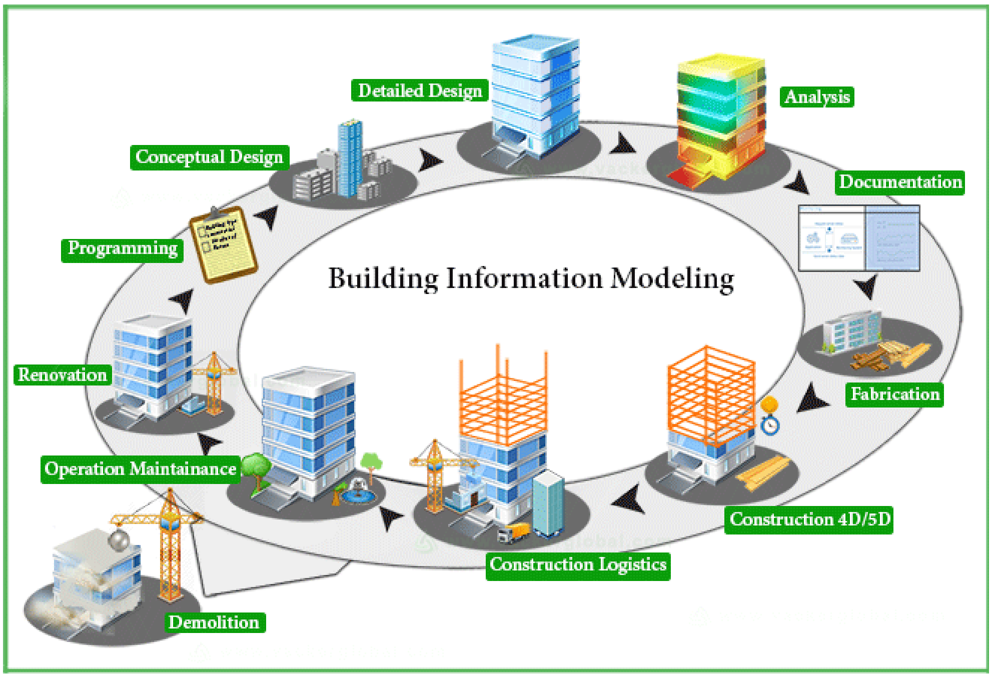

Figure 1-1 Building Information Modeling (InGenio)

The idea of the thesis therefore arises from these issues (BIM, Industry 4.0) and focuses on Facility Management, and with an eye to new technologies.

To inspire the research activity relating to this work is the following image (Fig.1-2)

Is it therefore possible to use technologies such as Mixed Reality and Augmented Reality in the field of AEC / FM (Architecture, Engineering, Construction Facility Management) processes?

So, is it possible to imagine the creation of information systems capable of managing and improving all those maintenance and management processes that normally take place in an analogue and manual way?

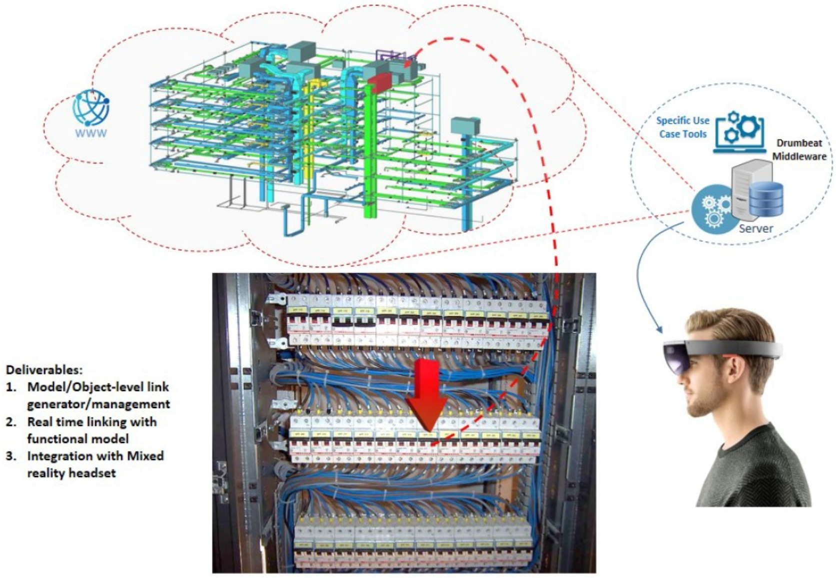

Figure 1-2 Mixed Reality assisted Facility Systems Maintenance (PRIN 2018)

A positive answer to these questions could have a significant impact, especially if you think of large infrastructures, complex plants, or networks of buildings scattered throughout the territory that still present significant critical issues today, given the amount of information and heterogeneity of the personnel involved in these operations.

The main objective of this thesis is to try to answer these questions and test as much as possible the creation of the aforementioned information system.

We therefore started from a documentary and informative research of all the connected topics that are summarized in chapter 2, then in order to be able to think concretely on the topic we hypothesized a possible maintenance workflow, and how it can be modified by abbreviating or improving it through the use of Mixed Reality.

After which we have chosen to reason on a hypothetical real case, they lower the reasoning to such a scale to be able to carry out the experimentation. It was chosen due to the restrictions given by the pandemic in progress to work on the network plant of the DICEA department of the Monte Dago pole of the UNIVPM, and reasoning starting from the end, or in the event of a malfunction in one of the rooms of the department, how does the maintenance and resolution of the problem take place? And how can the use of technology improve this process?

The aim of this work of thesis is to verify the feasibility of creating an information system supported by augmented reality for facility management operations.

It goes without saying that the objective goes beyond the classic themes of building engineering and architecture, but projects itself into the implementation of cutting-edge principles and technologies still under development and research, which places this work as a temporary point of arrival. which will be significantly affected by the development of the IT sector.

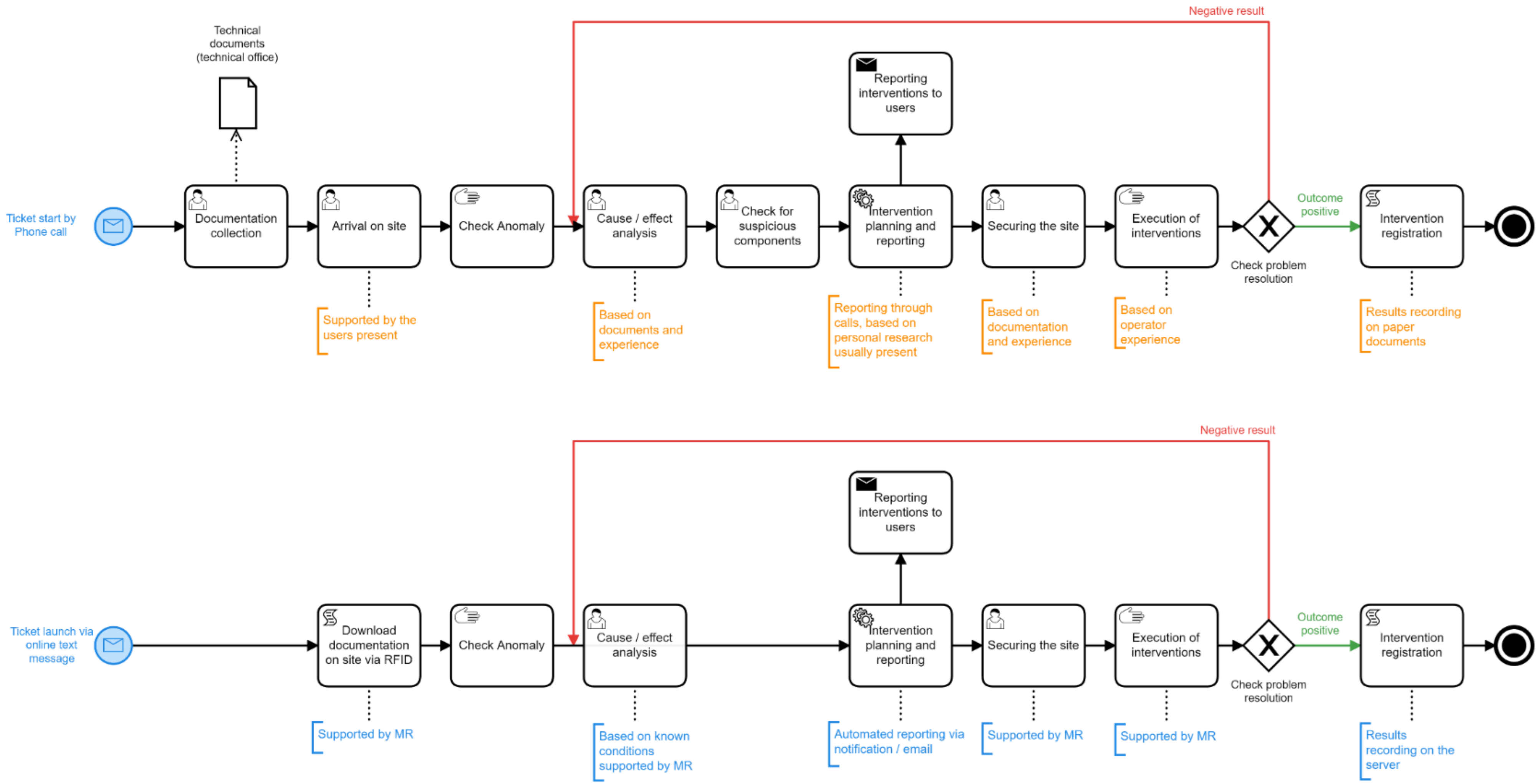

Figure 1-3 Hypothetical operating schemes, in BPMN format in the first there is the traditional way of operating in the second the way supported by MR

2. LITTERATURE REVIEW

In this section the topics of study and documentary research carried out as an introduction to the thesis topic will be exposed. All the salient information will be exposed, but each of these topics require hundreds of pages each in order to be considered exhaustive in every single aspect.

2.1. FACILITY MANAGEMENT

The building sector is constantly growing and requires more and more specifications; Today is it evident that the continuous control of the quality ratio, technical solutions e price in the process of a work, from its realization, to maintenance, functionality and end of the work itself.

IFMA Italy, the Italian non-profit association directly descendant of the International Facility Management Association, founded in the United States in 1980, defines the facility Management such as:

- A profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology
- Integration of processes within an organisation to maintain and develop the agreed services which support and improve the effectiveness of its primary activities[2]

In other words, Facility Management is the design, implementation and control process through which the facilities (i.e. the buildings and services necessary to support and facilitate the company's business) are identified, specified, found and provided for the purpose. to provide and maintain those levels of service capable of satisfying business needs, creating a quality work environment with the lowest possible cost. Facility Management is therefore an integrated approach which, through the design, planning and

[2] UNI EN 15221 – 1:2007

provision of support services to the company's main activity, aims to increase the effectiveness of the organization and make it capable of adapting easily and quickly to changes. of the market.

The three main aspects that characterize the Facility Management discipline are strategic, analytical and managerial-operational:

- The **strategic aspect** concerns every decision relating to the management and procurement policy of services, the distribution of resources to be used to support corporate objectives (budget preparation and management, cost allocation, etc.), choice of supplier, etc.
- The **analytical aspect** relates to understanding the needs of Internal Customers relating to services, monitoring management results and efficiency in providing the service, identifying new techniques and technologies that support the corporate business. It is therefore a fundamental aspect to ensure that Facility Management effectively contributes to the achievement of the company's objectives.
- The **managerial-operational** aspect concerns the management and coordination of all services as a whole (not individual services) and includes the definition of systems and procedures and the implementation and re-engineering of delivery processes.

In summary, the FM integrates the management principles:

- Financial and economic of a company.
- Architecture and engineering.
- Of the behavioural sciences.

This is an integrated approach Facility Management starts from the premise of implementing and developing standards and I processes to support the company's primary activities, with the aim of making the organization and management able to adapt to new needs, to the modernization of the sector, improving its effectiveness. In the role of guarantor of the quality of real estate structures, facility management stands becoming increasingly important, ensuring continuity, reliability, operation and the optimal usability of the work.

2.1.1. History of Facility Management

In the early 1980s, the discipline of Facility Management was born in the United States. For the North American economy, it is a very difficult period, the market was rapidly ed radically modified its characteristics and the companies had paid for it consequences. We can talk about the domino effect, geographic barriers became less rigid as regards the circulation of goods, a very differentiated offer emerges that brings more freedom in the offer and greater possibility of choice, the consumer's need changes considerably, evolving significantly. The relationship between customer and supplier is completely different, they begin to ask customized products and services, but the US firms that had standardized the production are found unable to respond to the new needs of the market.
Consumers are choosing more and more carefully and with awareness based on the offer that is qualitatively more convenient, on the best quality / price ratio and not more only on the lowest price.
The phenomenon spreads to all sectors of production, including the construction sector and, parallel to the finished product is accompanied by the "service" component, with the inevitable consequence of the increase in competitiveness.

Following what has been analysed above, the need for a transformation becomes clear radical, it is a question of rethinking the organization of the company to make it competitive on the market. The concentration of resources on the company's main business is the consequence the request for greater speed and effectiveness in the decisions to be made in relation to the efficiency of the company itself. In the 1990s, the process of organizational adjustment of companies invests heavily all company functions 2. The goal is to transform the fundamental concepts of management by having for goal is to increase the performance and effectiveness of the company.

The emphasis and interest shift in a concrete way to flexible solutions and model's collaborative organization. These models are based on the articulation of responsibilities and on different roles of professionals and decentralization. In particular, it can be asserted that the organizational and strategic evolution of the companies of 1990s is based in particular on the following point:

- the processes are based on mainly engineering solutions;
- the activities are considered integrated functions;
- the role of the information systems of the network architectures and the databases make them accessible company data to all interested parties.

It inevitably follows a strong review of the real estate assets, in particular on their use, their management and how income is made, these problems are warned by all companies. This has prompted companies to tackle the problem of property management for both maintenance and for the definition and optimization of the main services related to the spaces and business activities.

The development of Facility Management, in particular in the construction sector is therefore a consequence:

- of the new need for spaces or buildings that are increasingly flexible and variable to meet the needs of the activities that take place there;
- the variability of the activities themselves over time;
- the strong need for quality spaces. The intelligent and dynamic building is born, equipped with traditional and innovative systems;
- to create spaces / buildings that can be easily transformed to adapt when necessary or appropriate;
- the quality must be verified and have costs that can be planned and evaluated with certainty.

In summary, the value of service activities and the birth of quality-built spaces, with the consequent need to manage these activities and spaces, have been identified as basic elements to overcome the crisis of the 80s and were subsequently implemented in the 90s, resulting in the birth of the Facility Management discipline and the role of the Facility Manager.

2.1.2. “Facility” and real estate assets

Classification of “Facility”

The term "facility" indicates both the property where the work takes place, and all of them service activities. Facility is therefore both the container of work and services that make the activity itself possible. It can therefore be argued that the sector in which the methodology in question is applied is that of the strategic management of properties and services and in particular of all those activities that support the company.
IFMA Italia has classified the "Facility" into three macro areas of services: to the building, to the space and to the people[3]:

- **Building services**: includes all the activities aimed at maintaining the property and all its facilities and structures. The ultimate goal of these services is to ensure continuity of operation of the building intended as a "box" within which the company carries out its business, in compliance with the regulations on hygiene of the environments of work, safety and rational use of energy.
- **Space services**: the goal in this case is to ensure that the workspace is a useful support for the company, facilitating the processes of value creation, of communication, socialization and knowledge creation and circulation. How is easy to imagine, therefore, this group of services presents a high level of complexity from the point of view of the organization.
- **Services to people**: very large macro-area that includes elements such as the catering, document management, reception, environmental hygiene, safety, etc. In

[3] http://www.ifma.it/index.php

practice, it is a set of activities that aim to increase productivity, the well-being and loyalty of those who work for the company.

- “Auditing” of buildings- real estate assets

In particular, with regard to the construction sector, Facility Management assumes the role and the responsibility of "auditing" (in the language of management, corporate function that carries out control duties on a specific sector of production o of the administration) of buildings-real estate assets.

The auditing or "control" of a building consists of:

1. in the identification, analysis and definition of problems;
2. in the definition of organizational, contractual, economic and technological strategies aimed at obtaining improvements and / or adjustments to their management skills real estate, in particular:
    a. methods and tools that can be used in property management;
    b. criteria and tools for managing relationships with service providers;
    c. organizational changes;
    d. methodological settings and tools for budget planning and control costs and activities.

The "control" of the building is almost always structured in three phases of work:

1. **Data collection**: is carried out through ad hoc interviews with company managers and the manager of the structure in charge of management. The interviews are based on a questionnaire divided into specific sections. In this phase, accounting, contractual, organizational and technical.
2. **Processing of the collected data and definition of problems and critical points of the organization**: the results of the analysis and processing of the collected data will form a map articulated of the factors that hinder it on an economic, organizational and technical level innovative development of the management process.

3. **Design of possible solutions**: has the purpose of proposing hypotheses and "feasibility" projects for the improvement of activities management of real estate assets, starting from the specific reality of the structure in examination. The "feasibility" must be structured according to an order of priority such as:
    a. ease in implementing the change proposal;
    b. economic importance of the achievable results.

The "auditing" activity is carried out by consulting firms, professionals and structures universities that have carried out research and training programs as part of the Facilties Management and who are able to offer research and consulting services. Building auditing allows you to acquire a vast and multifaceted information base that constitutes the indispensable premise for identifying valid alternative solutions on the plan organizational-managerial and technological.

2.2. INDUSTRY 4.0

Small and medium-sized enterprises (SMEs) are the backbone of the EU economy: they represent 99.8% of EU companies, almost 60 % of GDP (total value added) and almost 70 % of the total available workforce. This data is of fundamental importance in order to understand the impact that industry 4.0 innovation can have in this sector.
In order to be able to implement these concepts there is a need to continue with the research, to be able to overcome all the difficulties related to the application in SMEs of the construction sector.

But before continuing, let's describe the principles of industry 4.0

2.2.1. The principles and the history of the industry 4.0

Industry 4.0 (Ger. Industrie 4.0) is the concept relating to the idea of "industrial revolution", whose main objective is the integration of production processes with the information technologies and techniques. It combines production methods with information and communications technology. It assumes that products can be manufactured based on the individual needs of customers, for example sneakers that come with a tailor-made sole and a design selected by the customer, or a customised individually designed piece of furniture. Industry 4.0 makes it possible to produce items that are unique in excellent quality and at a price equal to that of mass-produced goods. Smart, digitally connected systems and production processes serve as the technical basis for this concept. Industry 4.0 also defines the entire life cycle of a product: from idea to development, manufacturing, use and maintenance – and ending on recycling of the product [2]. For better understanding this idea the development of the Industry 4.0 concept was shown in the Figure 2-1

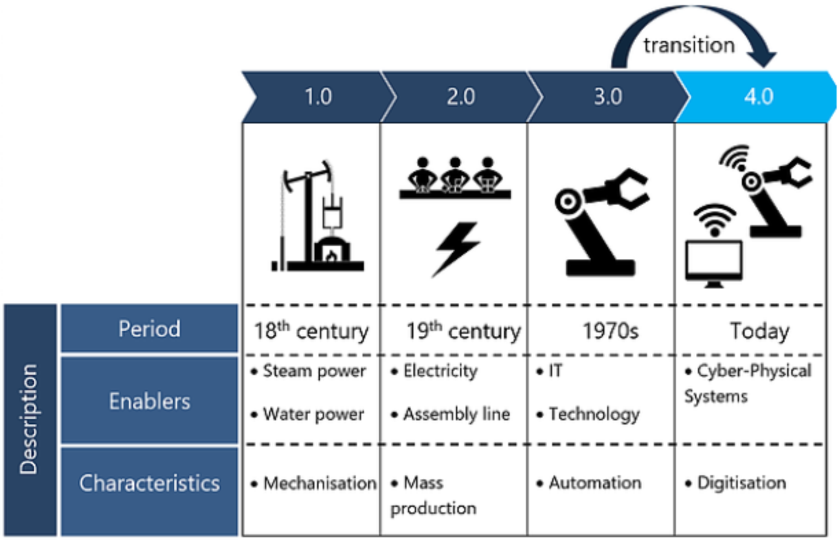

Figure 2-1 Industry 4.0 concept development

Historical data confirms that the first industrial revolution was connected with steam machine invention which enabled significant level of mechanisation compared to the previous industry level. 2nd industrial revolution was related to the beginning of the mass production in 19th century with electricity usage and assembly line creation. 3rd industrial revolution was connected with inventing Information Technology and introducing technology into the production as well as the use of automation in processes. 4.0 level can be described as usage of cyber physical systems (CPS) connected with the digitalization and the Internet of Things (IoT) concept. Development time of the industry 1.0 was vast, as it took ages to invent steam powered machines. Between 1.0 and 2.0 version there were approximately 100 years. Level 3.0 was introduced after 70 years and now discussion is on 4.0 concept after 30 - 40 years form the last revolution. It has to be noted that in the short time an introduction of 5.0 version of this can be expected.

Industry 4.0 was initially developed by the German government to create a coherent policy framework to maintain Germany's industrial competitiveness on the global market. Related terms used internationally include Internet of Things, Internet of Services, Industrial

Internet, Advanced Manufacturing and Smart Factory. The main features of Industry 4.0 are[4]:

- Interoperability: cyber-physical systems (work-piece carriers, assembly stations and products) allow humans and smart factories to connect and communicate with each other.
- Virtualisation: a virtual copy of the Smart Factory is created by linking sensor data with virtual plant models and simulation models.
- Decentralisation: ability of cyber-physical systems to make decisions of their own and to produce locally thanks to technologies such as 3d printing.
- Real-Time Capability: the capability to collect and analyse data and provide the derived insights immediately.
- Service Orientation: Production must be customer-oriented. People and smart objects/devices must be able to connect efficiently through the Internet of Services to create products based on the customer's specifications.
- Modularity: flexible adaptation of smart factories to changing requirements by replacing or expanding individual modules.

[4] Directorate General For Internal Policies Policy Department A: Economic and scientific policy Industry 4.0, IP/A/ITRE/2015-02 PE 570.007, pp. 20-21, 2016.

2.2.2. Advantage of Industry 4.0

The benefits of industry 4.0 include improved productivity and efficiency, better flexibility and increased profitability. Also improves the costumers experience.
While Smart Factory technologies are interesting and exciting, the benefits of Industry 4.0 should always be at the centre of any discussion. After all, any investment in technology, improved manufacturing processes or advanced systems should provide a return. With Industry 4.0, the ROI opportunities are significant due to the benefits offered by technologies. This includes technologies that improve automation, machine-to-machine communication, on-site manufacturing and decision making.

2.2.3. Integration of industry 4.0 in to the construction field

When we talk about new capital goods with a view to Transition 4.0 we mainly talk about the industrial sector, for the simple reason that it is the context for which everything reported in the budget laws referring to digitalization and technological innovation is applicable. However, with the introduction of the most recent methods of design, construction and management of buildings we can say that slowly these principles are starting to be applied also to the construction sector.

The node of contact between industry 4.0 and the construction field is Building Information Modeling (BIM) which in Italy is becoming mandatory for public works thanks to the Ministerial Decree 560/2017.

In practice, the construction and infrastructure sector already report many examples of application of the advanced technological and digital world, not only abroad but also in Italy. These are not only Hi-Tech systems used for management and tracking, but also monitoring systems and “twin models”, as well as 3D printers of such size that they can even build an entire building.

The first of all is the work carried out by Autostrade per l'Italia, more precisely by the group company called Autostrade Tech together with IBM and Fincantieri NexTech who presented an innovative monitoring platform supported by different technologies and disciplines such as drones, IoT, Intelligence. Artificial based on 3D BIM information modeling. This will allow the inspectors who will have to check the health of the infrastructures to have data that are always updated and available, especially in real-time and at the time of on-site verification.

It is a real digital archive that represents the state of the work, creating a form of three-dimensional digital twin, constantly updated thanks to laser scan surveys carried out with drones, instrumental monitoring through Industrial IoT sensors, which will also allow the parameters related to the structural engineering of the infrastructure, and the construction of algorithms for evaluating behaviour in operation as well as during maintenance.

To complete the picture of available data, dynamic weighing tools will also be included which will allow real-time verification of compliance with the authorized weight limits for Exceptional Transits and the passage of heavy vehicles.

Another example is what has been achieved for the management of the Castelfranco Veneto hospital. Also, in this case the term "digital twin" is used, where reference is mainly made to the creation of an information model for building and plant assets in order to optimize processes in the health sector. The physical characteristics of the assets are reproduced inside the Digital-Twin in support of both static and dynamic information. Also, in this case, in a similar way to the previous example, a platform was created where the basis is an integrated BIM model of the graphics received in the final phase of construction.

This cloud-based platform reports and displays all the sensors installed in the building, thus returning all the data that can be consulted when necessary. Also, within it, it is also possible to open a ticket for the maintenance of the various rooms and equipment, for the immediate application of what is Facility Management.

These cases are proof of the possibility of integrating the principles of industry 4.0 into construction, continuous experimentation and research will expand these applications, also bringing a sector as ancient and complex as that of construction to an ever-greater technological innovation, in order to be more efficient and with less waste in economic and environmental terms.

2.3. BUILDING INFORMATION MODELING

Those who are not from the field certainly do not yet know the meaning of this word, while many others who are insiders have certainly heard of it but do not know how to explain it perfectly, unfortunately there are still few who are experts and know perfectly what BIM means.

Before explaining it let's take a step back.

Building Information Modeling (BIM) has become established as invaluable process enabler for modern architecture, engineering, and construction (AEC). With BIM technology, one or more accurate virtual models of a building are constructed digitally. They support all the phases of design, allowing better analysis and control than manual processes. When completed, these computer models contain precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realized, operated, and maintained.

BIM also has many of the functions needed to model the life cycle of a building, providing the foundation for a new design and construction skills and changes in roles and relationships between a project team.

When adopted well, BIM facilitates a more integrated design and construction process that results in better-quality buildings at lower cost and reduced project duration. BIM can also support improved facility management (FM) and future modifications to the building.

In order to fully understand the changes that BIM has introduced, it is necessary to describe the paper-based design and construction methods and the predominant business models traditionally used by the construction industry. It then describes various problems associated with these practices, outlines what BIM is, and explains how it differs from 2D and 3D computer-aided design (CAD). Ill briefly describe the kinds of problems that BIM can solve and the new business models that it enables. I will also describe the most significant problem when using new technologies, which even if in use for decades is still evolving.

Traditionally, the facility delivery process has been fragmented and dependent on communication using 2D drawings. Errors and omissions in paper documents often cause unanticipated field costs, delays, and eventual lawsuits between the various parties in a project team. These problems cause friction, financial expense, and delays. Efforts to address such problems have included alternative organizational structures such as the design-build method; the use of real-time technology, such as project website for sharing plans and documents; and the implementation of 3D CAD tools. Though these methods have improved the timely exchange of information, but they have done little to reduce the severity and frequency of conflicts caused by the use of paper documents or their electronic equivalents.

One of the most common problems associated with 2D-based communication during the design phase is the considerable time and expense required to generate critical assessment information about a proposed design, including cost estimates, energy-use analysis, structural details and so forth. These analyses are normally done last, when it is already too late to make important changes to the design. Because these iterative improvements do not happen during the design phase, value engineering must then be undertaken to address inconsistencies, which often results in compromises to the original design.
Regardless of the contractual approach, certain statistics are common to nearly all large-scale projects ($10 M or more), including the number of people involved and the amount of information generated. The following data was compiled by Maged Abdelsayed of Tardif, Murray & Associates, a construction company located in Quebec, Canada (Hendrickson, 2003):

- Number of participants (companies): 420 (including all suppliers and sub-sub-contractors)
- Number of participants (individuals): 850

- Number of different types of documents generated: 50
- Number of pages of documents: 56,000
- Number of bankers' boxes to hold project documents: 25
- Number of 4-drawer filing cabinets: 6
- Number of 20-inch diameter, 20-year old, 50-feet-high, trees used to generate this volume of paper: 6
- Equivalent number of megabytes of electronic data to hold this volume of paper (scanned): 3,000 MB

It is not easy to manage an effort involving such a large number of people and documents, regardless of the contractual approach taken. Figure 2-1 illustrates the typical members of a project team and their various organizational boundaries.

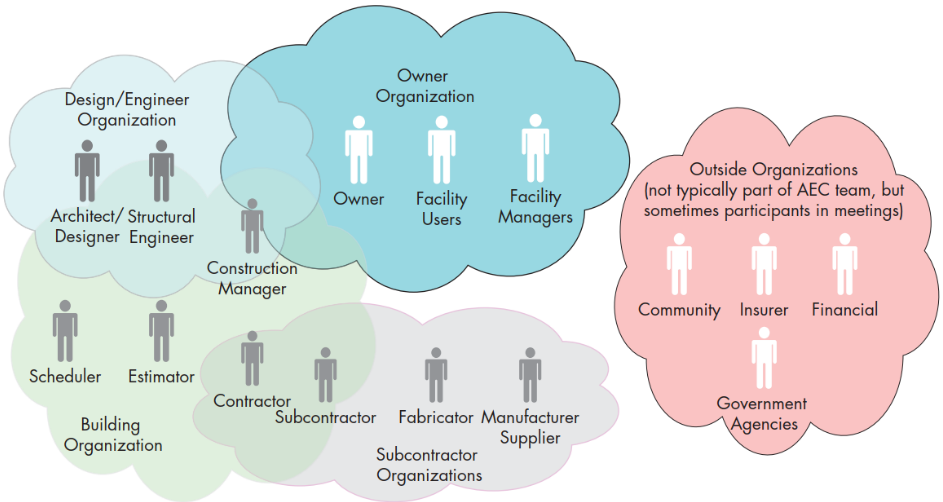

Figure2-2 Conceptual diagram representing an AEC project team and the typical organizational boundaries.

2.3.1. Traditional approach design

The traditional design approach contributes unnecessarily to errors and waste. In support of these theses I will illustrate the studies of Center for Integrated Facility Engineering (CIFE) at Stanford University (Teicholz, 2001); and the impact of poor information flow and redundancy is illustrated by the National Institute of Standards and Technology (NIST) (Gallaher et al. 2004).

- CIFE study of construction industry labor productivity

Extra costs associated with traditional design and construction practices have been documented through various research studies.

Paul Teicholz first called attention to the significant difference in productivity between construction and nonfarm industries in a widely publicized discussion paper published in 2001. More recently compiled data, shown in Figure x–x, shows that the trend of increasingly weaker construction productivity when compared with manufacturing has continued, but it also shows the gap between off-site and on-site construction activities. It is clear that fabrication off-site is more productive than construction on-site. The productivity index values were calculated by dividing constant value-added dollars by numbers of employees.

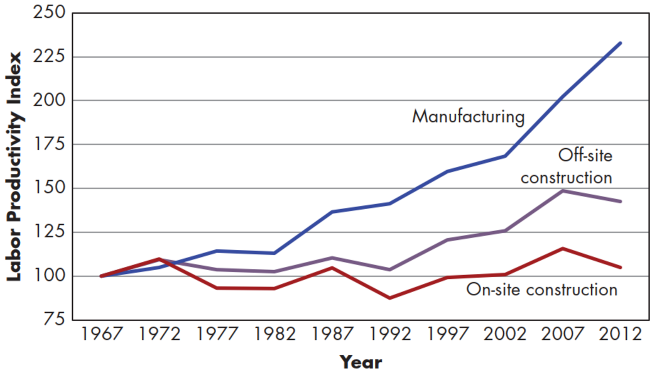

Figure 2-3 Indices of labor productivity for manufacturing, off-site construction trades, and on-site construction trades, 1976-2015

Of course, many material and technological improvement have been made to buildings in the last four decades. The results are perhaps better than they appear, because quality has increased substantially and off-site prefabrication is becoming a bigger factor. Contractors have made greater use of off-site components that take advantage of factory conditions and specialized equipment. Clearly this has allowed for higher quality and lower cost production of components, as compared to on-site work.

It is clear that efficiencies achieved in the manufacturing industry through automation, the use of information systems, better supply chain management, and improved collaboration tools, have not yet been achieved in field construction. Possible reasons for this include:

- Sixty-five percent of construction firms consist of fewer than five people, making it difficult for them to invest in new technology.
- The real inflation-adjusted wages and the benefit packages of construction workers have stagnated over this time period. Union participation has declined, and the use of immigrant workers has increased, discouraging the need for labor saving innovations. While innovations have been introduced, such as nail guns, larger and more effective earthmoving equipment, and better cranes, the productivity

improvements associated with them have not been sufficient to change overall field labor productivity.

- Additions, alterations, or reconstruction work represents about 29 percent and maintenance and repair represents about 16 percent of construction volume. It is more difficult to use capital-intensive methods for these kinds of work.
- The adoption of new and improved business practices within both design and construction has been noticeably slow and limited primarily to larger firms. In addition, the introduction of new technologies has been fragmented. Often, it remains necessary to revert to paper or 2D CAD drawings so that all members of a project team are able to communicate with one another and to keep the pool of potential contractors and subcontractors bidding on a project sufficiently large. Almost all local authorities still require paper submittals for construction permit reviews. For these reasons, paper use maintains a strong grip on the industry.

Another possible cause for the construction industry's stagnant productivity is that on-site construction has not benefited significantly from automation.

This study, albeit linked to the US market and a few years ago, is exhaustive and comparable to the Italian construction sector. Paradoxically, in Italy the points indicated as possible causes of lost productivity compared to industry are even more marked.

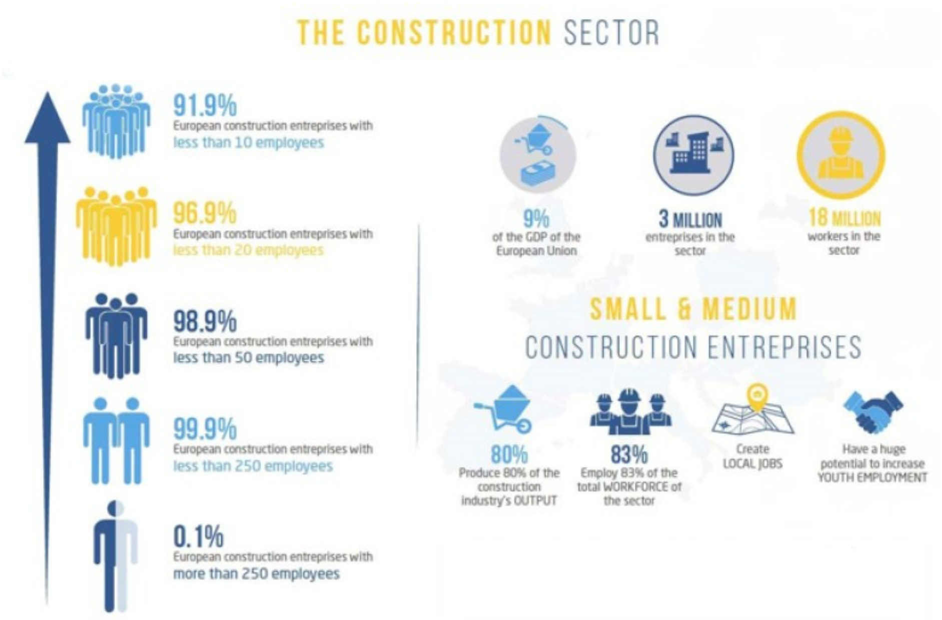

Figure 2-4 PRIN 2018

- NIST Study of cost of construction industry inefficiency

The National Institute of Standards and Technology (NIST) performed a study of the additional cost incurred by building owners as a result of inadequate interoperability (Gallaher et al., 2004). In the construction industry, incompatibility between systems often prevents members of the project team from sharing information rapidly and accurately; it is the cause of numerous problems, including added costs.

The results showed that inefficient interoperability accounted for an increase in construction costs by $6.12 per square foot for new construction and an increase in $0.23 per square foot for operations and maintenance (O&M), resulting in a total added cost of $15.8 billion.

In the NIST study, the cost of inadequate interoperability was calculated by comparing current business activities and costs with hypothetical scenarios in which there was seamless information flow and no redundant data entry. NIST determined that the following costs resulted from inadequate interoperability:

- Avoidance (redundant computer systems, inefficient business process management, redundant IT support staffing)
- Mitigation (manual re-entry of data, request for information management)
- Delay (costs for idle employees and other resources)

Stakeholder Group	Planning, Engineering, Design Phase	Construction Phase	O&M Phase	Total Added Cost
Architects and Engineers	$1,007.2	$147.0	$15.7	$1,169.8
General Contractors	$485.9	$1,265.3	$50.4	$1,801.6
Special Contractors and Suppliers	$442.4	$1,762.2		$2,204.6
Owners and Operators	$722.8	$898.0	$9,027.2	$10,648.0
Total	**$2,658.3**	**$4,072.4**	**$9,093.3**	**$15,824.0**
Applicable sf in 2002	1.1 billion	1.1 billion	39 billion	n/a
Added cost/sf	**$2.42/sf**	**$3.70/sf**	**$0.23**	**n/a**

Table 2-5 Additional costs of inadequate interoperability in the construction industry, 2002 (in $M) "NIST study (Gallaher et al., 2004)"

Of these costs, roughly 68 percent ($10.6 billion) were incurred by building owners and operators. These estimates are speculative, due to the impossibility of providing accurate data. They are, however, significant and worthy of serious consideration and effort to reduce or avoid them as much as possible. Widespread adoption of BIM and the use of a comprehensive digital model throughout the lifecycle of a building would be a step in the right direction to eliminate such costs resulting from the inadequate interoperability of data.

2.3.2. BIM: New tools and new processes

For our purpose, we define BIM as a modeling technology and associated set of processes to produce, communicate, and analyse building models. BIM is the acronym of "Building Information Modeling," reflecting and emphasizing the process aspects, and not of "Building Information Model." The objects of BIM processes are building models, or BIM models.

This kind of models are characterized by:

- Building components that are represented with digital representations (objects) that carry computable graphic and data attributes that identify them to software applications, as well as parametric rules that allow them to be manipulated.
- Components that include data that describe how they behave, as needed for analyses and work processes, such as quantity take off, specification, and energy analysis.
- Consistent and nonredundant data such that changes to component data are represented in all views of the component and the assemblies of which it is a part.

Another way to characterize BIM is to define a progression of levels of maturity of application of information technology in construction that expresses the degree of collaboration in the process as well as the levels of sophistication of use of the individual tools. In this view BIM is seen as a series of distinct stages in a journey that began with computer-aided drawing and is taking the industry into the digital age. Since the UK Government BIM Task Group adopted the concept of "BIM Levels," the following chart and the four levels it defines (Level 0 to Level 3) have become a widely adopted definition of the criteria for a project to be deemed BIM-compliant. In Figure x–x, BS standards numbers refer to British Standards Institution and the description of each level is their definition (BS, 2017).

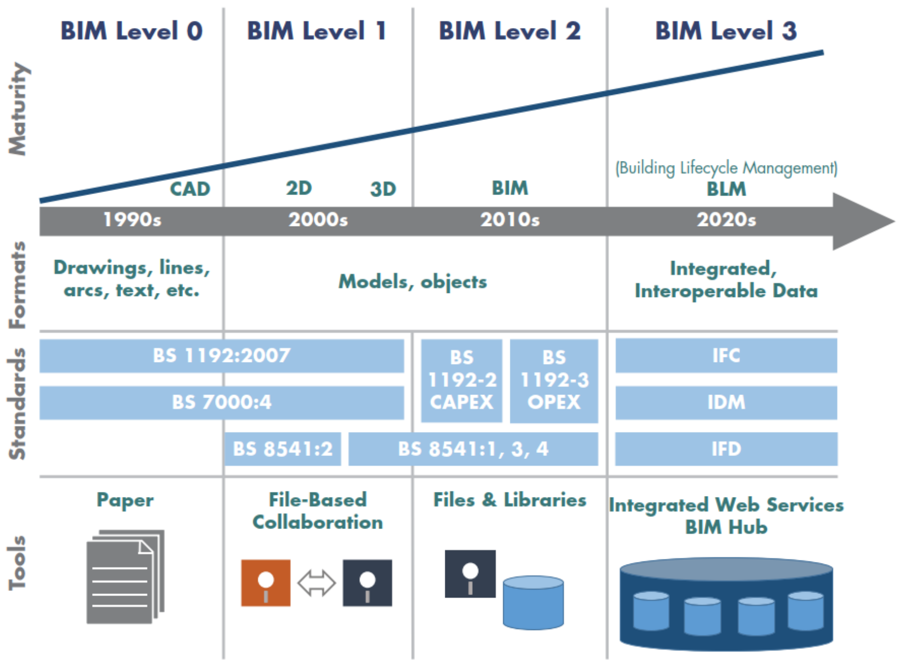

Figure 2-6, The BIM maturity model by Mark Bew and Mervyn Richards

Level 0 BIM

This level is defined as unmanaged CAD. This is likely to be 2D, with information being shared by traditional paper drawings or in some instances, digitally via PDF, essentially separate sources of information covering basic asset information. The majority of the industry is already well ahead of this now.

Level 1 BIM

This is the level at which many companies are currently operating. This typically comprises a mixture of 3D CAD for concept work, and 2D for drafting of statutory approval documentation and Production Information. CAD standards are managed to BS 1192:2007, and electronic sharing of data is carried out from a common data environment (CDE), often managed by the contractor. Models are not shared between project team members.

Level 2 BIM

This is distinguished by collaborative working—all parties use their own 3D models, but they are not working on a single, shared model. The collaboration comes in the form of how the information is exchanged between different parties—and is the crucial aspect of this level. Design information is shared through a common file format, which enables any organization to combine that data with their own in order to make a federated BIM model, and to carry out interrogative checks on it. Hence any CAD software that each party uses must be capable of exporting to a common file format such as IFC (Industry Foundation Class) or COBie (Construction Operations Building Information Exchange). This is the method of working that has been set as a minimum target by the UK government for all work on public-sector work, by 2016.

Level 3 BIM

This level represents full collaboration between all disciplines by means of using a single, shared project model that is held in a centralized repository (normally an object database in cloud storage). All parties can access and modify that same model, and the benefit is that it removes the final layer of risk for conflicting information. This is known as “Open BIM.”

From “What is BIM and why do you need it?”, TMD Studio, London and Prague, Jan Gasparek and Ondrej Chudy.

2.3.3. What are the advantages of BIM, which problems it faces

BIM is at the heart of the ways in which the building design and construction process can respond to the increasing pressures for greater complexity, faster development, improved sustainability, reduced cost, and more effective and efficient operation and maintenance of buildings. Traditional practice is not able to respond to these pressures.

- Preconstruction and Benefits to the Owner

Before hiring an architect or engineer, the owner must determine the specifics of the building he wants to build, and therefore dimensions, environments, types and finishes. In short, he needs to have a quote as exact as possible, in order to understand if he can afford it. If his answers can find an answer as certain as possible, the owner can start the project with relative certainty that the objectives will be achievable, therefore thanks to the BIM and database from which to draw, you can have very truthful cost estimates.

Developing a schematic model prior to generating a detailed building model allows for a more careful evaluation of the proposed scheme to determine whether it meets the building's functional, sustainability, and other requirements. Early evaluation of design alternatives using analysis/simulation tools increases the overall quality of the building.

When the owner uses Integrated Project Delivery (IPD) for project procurement, BIM can be used by the project team from the beginning of the design to improve their understanding of project requirements and to extract cost estimates as the design is developed. This allows design and cost to be better understood and also avoids the use of paper exchange and its associated delays.

- Benefits for Design

Earlier and More Accurate Visualizations of a Design. The 3D model generated by the BIM software is designed directly rather than being generated from multiple 2D views. It can be used to visualize the design at any stage of the process with the expectation that it will be dimensionally consistent in every view.

Automatic low-level corrections when changes are made to design. If the objects used in the design are controlled by parametric rules that ensure proper alignment, then the 3D model will be free of geometry, alignment, and spatial coordination errors.

Generation of Accurate and Consistent 2D Drawings at Any Stage of the Design. Accurate and consistent drawings can be extracted for any set of objects or specified view of the project. This significantly reduces the amount of time and the number of errors associated with generating construction drawings for all design disciplines. When changes to the design are required, fully consistent drawings can be generated as soon as the design modifications are entered.

BIM technology facilitates simultaneous work by multiple design disciplines. While collaboration with drawings is also possible, it is inherently more difficult and time consuming than working with one or more coordinated 3D models in which change control can be well managed. This shortens the design time and significantly reduces design errors and omissions. It also gives earlier insight into design problems and presents opportunities for a design to be continuously improved.

Easy Verification of Consistency to the Design Intent. BIM provides earlier 3D visualizations and quantifies the area of spaces and other material quantities, allowing for earlier and more accurate cost estimates. At any stage of the design, BIM technology can extract an accurate bill of quantities and spaces that can be used for cost estimation. In the early stages of a design, cost estimates are based either on formulas that are keyed to significant project quantities, for example, number of parking spaces, square feet of office areas of various types, or unit costs per square foot. As the design progresses, more detailed quantities are available and can be used for more accurate and detailed cost estimates.

Linking the building model to energy analysis tools allows evaluation of energy use during the early design phases. This is not practical using traditional 2D tools because of the time required to prepare the relevant input. If applied at all, energy analysis is performed at the end of the 2D design process as a check or a regulatory requirement, thus reducing the opportunities for modifications that could improve the building's energy performance. The capability to link the building model to various types of analysis tools provides many opportunities to improve building quality.

- Construction and fabrication benefits

If the design model is transferred to a BIM fabrication tool and detailed to the level of fabrication objects (shop model), it will contain an accurate representation of the building objects for fabrication and construction. Because components are already defined in 3D, their automated fabrication using numerical control machinery is facilitated. Such automation is standard practice today in steel fabrication and some sheet metal work. he accuracy of BIM also allows larger components of the design to be fabricated off-site than would normally be attempted using 2D drawings, due to the likely need for on-site changes (rework) and the inability to predict exact dimensions until other items are constructed in the field. It also allows smaller installation crews, faster installation time, and less on-site storage space.

The quick reaction to design changes, some updates will be made automatically based on the established parametric rules. Additional cross-system updates can be checked and updated visually or through clash detection.

Discovery of Design Errors and Omissions before Construction. Because the virtual 3D building model is the source for all 2D and 3D drawings, design errors caused by inconsistent 2D drawings are eliminated. In addition, because models from all disciplines can be brought together and compared, multisystem interfaces are easily checked both systematically (for hard and clearance clashes) and visually (for other kinds of errors). Conflicts and constructability problems are identified before they are detected in the field.

Synchronization of Design and Construction Planning. Construction planning using 4D CAD requires linking a construction plan to the 3D objects in a design and supplementing the model with construction equipment objects (shoring, scaffolding, cranes, etc.), so that it is possible to simulate the construction process and show what the building and site would look like at any point in time. This graphic simulation provides considerable insight into how the building will be constructed day by day and reveals sources of potential problems and opportunities for possible improvements (site, crew and equipment, space conflicts, safety problems, and so forth).

Synchronization of Procurement with Design and Construction. The complete building model provides accurate quantities for all (or most, depending upon the level of 3D modeling) of the materials and objects contained within a design. These quantities, specifications, and properties can be used to procure materials from product vendors and subcontractors (such as precast concrete subs).

- Post construction benefit

During the construction process the general contractor and MEP contractors collect information about installed materials and maintenance information for the systems in the building. This information can be linked to the objects in the building model and thus be available for handover to the owner for use in their facility management systems. It also can be used to check that all the systems are working as designed before the building is accepted by the owner.

Better Management and Operation of Facilities. The building model provides a source of information (graphics and specifications) for all systems used in a building. Previous analyses used to determine mechanical equipment, control systems, and other purchases can be provided to the owner, as a means for verifying the design decisions once the building is in use. This information can be used to check that all systems work properly after the building is completed.

A building model that has been updated with all changes made during construction provides an accurate source of information about the as-built spaces and systems and provides a useful starting point for managing and operating the building. A building information model supports monitoring of real-time control systems, as it provides a natural interface for sensors and for remote operation of facilities. Many of these capabilities are just starting to be implemented, but BIM provides an ideal platform for their deployment.

2.3.4. Main challenge of the new BIM approach

Improved processes in each phase of design and construction will reduce the number and severity of problems associated with traditional practices. Intelligent use of BIM, however, will also cause significant changes in the relationships of project participants and the contractual agreements between them. While BIM offers new methods for collaboration, it introduces new challenges with respect to the development of effective teams. How to permit adequate sharing of model information by members of the project team is a significant issue.

Where designers create their design using BIM and share the model, it may not have sufficient detail for use for construction or may have object definitions that are inadequate for extracting necessary construction quantities. This may require creating a new model for construction use. If the members of the project team use different modeling tools, then tools for moving the models from one environment to another or combining these models are needed. This can add complexity and introduce potential errors and time to the project.

Replacing a 2D or 3D CAD environment with a building modeling system involves far more than acquiring software, training, and upgrading hardware. Effective use of BIM requires that changes be made to almost every aspect of a firm's business (not just doing the same things in a new way). It requires some understanding of BIM technology and related processes and a plan for implementation before the conversion can begin. A consultant can be very helpful to plan, monitor, and assist in this process.

2.4. AUGMENTED, MIXED AND VIRTUAL REALITY

More and more new technologies are becoming established, and words like augmented reality and virtual reality are becoming more and more popular. But before going into these technologies and being able to talk about the possible implications in the various fields (in our case AEC) it is necessary to explain well the differences between these words.

***Virtual reality** (VR) is a simulated experience that can be similar to or completely different from the real world.*[5]

***Augmented reality** (AR) is an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.*[6]

***Mixed reality** (MR) is the merging of real and virtual worlds to produce new environments and visualizations, where physical and digital objects co-exist and interact in real time. Mixed reality does not exclusively take place in either the physical world or virtual world, but is a hybrid of reality and virtual reality.*[7]

[5] https://en.wikipedia.org/wiki/Virtual_reality
[6] https://en.wikipedia.org/wiki/Augmented_reality
[7] https://en.wikipedia.org/wiki/Mixed_reality

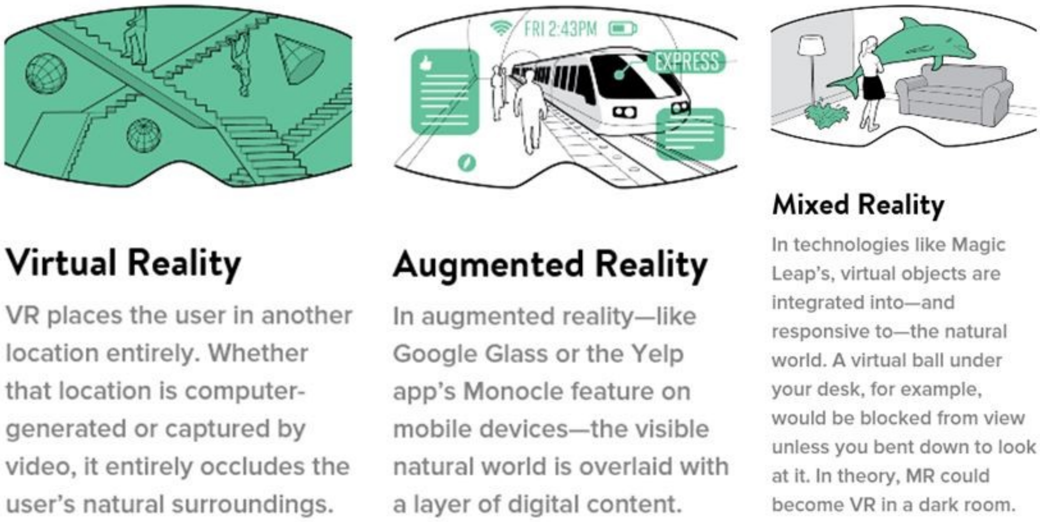

Figure 2-7, Graphics for the differences between Virtual Reality, Augmented Reality and Mixed Reality. Image from Wired[8]

[8] http://virtualmentis.altervista.org/glossario-gli-acronimi-del-virtuale-ar-vr-mr-rr-xr/

2.4.1. Evolution of AR/VR

The origin of **augmented reality** (AR) and **virtual reality** (VR) came way back in 1838, when Charles Wheatstone invented the stereoscope. This technology used an image for each eye to create a 3D image for the viewer.

Figure 2-8, Stereoscope, ca. 1900, with Stereograph no. 23 from Rome through the Stereoscope (1902), 'Sanctuary and Home of Art and Piety — Pantheon! Pride of Rome.

Augmented and virtual reality has origins surprisingly in the past, although the biggest steps forward have been made in the last 50 years in fact, the concept of VR could be traced at the mid of 1960 when Ivan Sutherland in a pivotal manuscript attempted to describe VR as a window through which a user perceives the virtual world as if looked, felt, sounded real and in which the user could act realistically.
From that first definition many others followed such as:

- *"real-time interactive graphics with 3D models, combined with a display technology that gives the user the immersion in the model world and direct manipulation" (Fuchs and Bishop, 1992);*
- *"The illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on a 3D, stereoscopic head-tracker*

displays, hand/body tracking and binaural sound. VR is an immersive, multi-sensory experience" (Gigante, 1993);

- *"Virtual reality refers to immersive, interactive, multi-sensory, viewer-centered, 3D computer generated environments and the combination of technologies required building environments" (Cruz-Neira, 1993).*[9]

As we can notice, these definitions, although different, highlight three common features of VR systems: immersion, perception to be present in an environment, and interaction with that environment. Specifically, immersion concerns the amount of senses stimulated, interactions, and the reality's similarity of the stimuli used to simulate environments. This feature can depend on the properties of the technological system used to isolate user from reality.

Finally, the user's VR experience could be disclosed by measuring presence, realism, and reality's levels. Presence is a complex psychological feeling of "being there" in VR that involves the sensation and perception of physical presence, as well as the possibility to interact and react as if the user was in the real world (Heeter, 1992).

- From Virtual to Augmented Reality

Looking chronologically on VR and AR developments, we can trace the first 3D immersive simulator in 1962, when Morton Heilig created Sensorama, a simulated experience of a motorcycle running through Brooklyn characterized by several sensory impressions, such as audio, olfactory, and haptic stimuli, including also wind to provide a realist experience. In the same years, Ivan Sutherland developed The Ultimate Display that, more than sound, smell, and haptic feedback, included interactive graphics that Sensorama didn't provide.
Furthermore, Philco developed the first HMD that together with The Sword of Damocles of Sutherland was able to update the virtual images by tracking user's head position and

[9] https://www.frontiersin.org/articles/10.3389/fpsyg.2018.02086/full

orientation (Sutherland, 1965). In the 70s, the University of North Carolina realized GROPE, the first system of force-feedback and Myron Krueger created VIDEOPLACE an Artificial Reality in which the users' body figures were captured by cameras and projected on a screen (Krueger et al., 1985). In this way two or more users could interact in the 2D-virtual space. In 1982, the US' Air Force created the first flight simulator [Visually Coupled Airbone System Simulator (VCASS)] in which the pilot through an HMD could control the pathway and the targets. Generally, the 80's were the years in which the first commercial devices began to emerge: for example, in 1985 the VPL company commercialized the DataGlove, glove sensors' equipped able to measure the flexion of fingers, orientation and position, and identify hand gestures. Another example is the Eyephone, created in 1988 by the VPL Company, an HMD system for completely immerging the user in a virtual world. At the end of 80's, Fake Space Labs created a Binocular-Omni-Orientational Monitor (BOOM), a complex system composed by a stereoscopic-displaying device, providing a moving and broad virtual environment, and a mechanical arm tracking. Furthermore, BOOM offered a more stable image and giving more quickly responses to movements than the HMD devices. Thanks to BOOM and DataGlove, the NASA Ames Research Center developed the Virtual Wind Tunnel in order to research and manipulate airflow in a virtual airplane or space ship. In 1992, the Electronic Visualization Laboratory of the University of Illinois created the CAVE Automatic Virtual Environment, an immersive VR system composed by projectors directed on three or more walls of a room.

More recently, many videogames companies have improved the development and quality of VR devices, like Oculus Rift, or HTC Vive that provide a wider field of view and lower latency. In addition, the actual HMD's devices can be now combined with other tracker system as eye-tracking systems (FOVE), and motion and orientation sensors (e.g., Razer Hydra, Oculus Touch, or HTC Vive).

Simultaneously, at the beginning of 90', the Boing Corporation created the first prototype of AR system for showing to employees how set up a wiring tool (Carmigniani et al., 2011). At the same time, Rosenberg and Feiner developed an AR fixture for maintenance assistance, showing that the operator performance enhanced by added virtual information on the fixture to repair (Rosenberg, 1993). In 1993 Loomis and colleagues produced an AR GPS-based system for helping the blind in the assisted navigation through adding spatial audio information (Loomis et al., 1998). Always in the 1993 Julie Martin developed "Dancing in Cyberspace," an AR theater in which actors interacted with virtual object in real time (Cathy, 2011). Few years later, Feiner et al. (1997) developed the first Mobile AR System (MARS) able to add virtual information about touristic buildings (Feiner et al., 1997). Since then, several applications have been developed: in Thomas et al. (2000), created ARQuake, a mobile AR video game; in 2008 was created Wikitude that through the mobile camera, internet, and GPS could add information about the user's environments (Perry, 2008). In 2009 others AR applications, like AR Toolkit and SiteLens have been developed in order to add virtual information to the physical user's surroundings. In 2011, Total Immersion developed D'Fusion, and AR system for designing projects (Maurugeon, 2011). Finally, in 2013 and 2015, Google developed Google Glass and Google HoloLens, and their usability have begun to test in several field of application.

- Virtual Reality Technologies

Technologically, the devices used in the virtual environments play an important role in the creation of successful virtual experiences. According to the literature, can be distinguished input and output devices (Burdea et al., 1996; Burdea and Coiffet, 2003). Input devices are the ones that allow the user to communicate with the virtual environment, which can range from a simple joystick or keyboard to a glove allowing capturing finger movements or a tracker able to capture postures. More in detail, keyboard, mouse, trackball, and joystick represent the desktop input devices easy to use, which allow the user to launch continuous and discrete commands or movements to the environment. Other input devices can be represented by tracking devices as bend-sensing gloves that capture hand movements, postures and gestures, or pinch gloves that detect the fingers movements, and trackers able to follow the user's movements in the physical world and translate them in the virtual environment.

Figure 2-9, Researchers with the European Space Agency in Darmstadt, Germany, equipped with a VR headset and motion controllers, demonstrating how astronauts might use virtual reality in the future to train to extinguish a fire inside a lunar habitat.[10]

On the contrary, the output devices allow the user to see, hear, smell, or touch everything that happens in the virtual environment. As mentioned above, among the visual devices can be found a wide range of possibilities, from the simplest or least immersive (monitor of a computer) to the most immersive one such as VR glasses or helmets or HMD or CAVE systems.

10 https://commons.wikimedia.org/wiki/File:Reality_check_ESA384313.jpg#/media/File:Reality_check_ESA384313.jpg

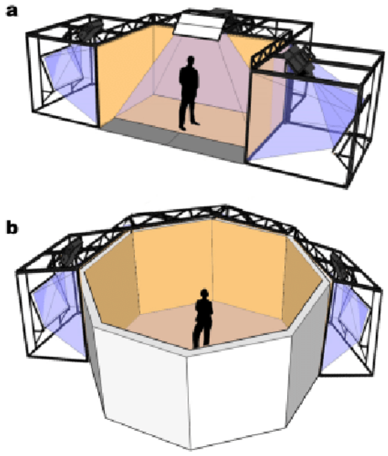

Figure 2-10, Immersive Virtual Environments (IVEs) a: CAVE (cave automatic virtual environment; 3 walls and a floor), and b: OCTAVE (octagon CAVE; 8 walls and floor) are immersive virtual environments and can be used in virtual reality experiments.[11]

Furthermore, auditory, speakers, as well as haptic output devices are able to stimulate body senses providing a more real virtual experience. For example, haptic devices can stimulate the touch feeling and force models in the user.

- Augmented Reality Technologies

Technologically, the AR systems, however various, present three common components, such as a geospatial datum for the virtual object, like a visual marker, a surface to project virtual elements to the user, and an adequate processing power for graphics, animation, and merging of images, like a pc and a monitor (Carmigniani et al., 2011). To run, an AR system must also include a camera able to track the user movement for merging the virtual objects, and a visual display, like glasses through that the user can see the virtual objects overlaying to the physical world. To date, two-display systems exist, a video see-through (VST) and an optical see-though (OST) AR systems (Botella et al., 2005; Juan et al., 2005, 2007). The

[11] Adi, Mohamad Nadim & Aljunaidy, Mais. (2020). The Usefulness of Using Virtual Reality to Assess Elderly and Dementia Friendly Hospital Design. IDA: International Design and Art Journal. 2. 137.

first one, disclosures virtual objects to the user by capturing the real objects/scenes with a camera and overlaying virtual objects, projecting them on a video or a monitor, while the second one, merges the virtual object on a transparent surface, like glasses, through the user see the added elements. The main difference between the two systems is the latency: an OST system could require more time to display the virtual objects than a VST system, generating a time lag between user's action and performance and the detection of them by the system.

Figure 2-11, An example of augmented reality application for gaming purposes, through a smartphone[12]

[12] https://cxocard.com/what-is-augmented-reality-gaming/

2.4.2. AR/VR/MR applications in AEC

Augmented Reality (AR) and Virtual Reality (VR) are technologies of utmost importance for the Architecture, Engineering and Construction (AEC) sectors as the built environment is intrinsically associated to three-dimensional (3D) space and AEC professionals rely heavily on imagery for communication. VR and AR —to a lesser degree— have been used by built environment professionals to support the visualisation of design, construction and city operations since around 1990s. AR is a technology that overlays information and computer-generated imagery on the real environment to enhance or augment the contextual perception of the user's surroundings.

Augmentations are visualised using a mobile device, tablet or a head-mounted display (HMD). On the other hand, VR is a technology that creates virtual environments entirely generated by a computer, replacing the user's perception of the surrounding environment with a virtual environment using HMDs, glasses and multi-display setups.

The main AR and VR applications are in the gaming and entertainment sectors, but marketing, tourism, sports, and education have experimented with AR and VR as well companies from a wide range of sectors are using AR and VR for training and productivity improvements.

However, AR and VR technologies are not yet robust and reliable enough to comply with real-life industrial requirements. Technical limitations are one of the main factors that limit adoption in the dynamic and rough environments typical in the construction sector. Other factors are also at play like that lack of awareness of the technology, poor usability, the large time commitment for implementation, and the unwillingness to accept a virtual substitute are issues that need to be addressed.
Regardless of the AR and VR level of technical maturity, there is the need to study the actual effectiveness of the AR and VR for particular construction tasks, and for the targeted development of implementation research.

Six general use-cases have been characterised. A brief description of the use-cases enriched with examples from literature are presented below: (1) Stakeholder engagement, (2) Design support, (3) Design review, (4) Construction support, which has four sub-categories construction planning, progress monitoring, construction safety, and operative support; (5) Operations and management, and (6) Training.

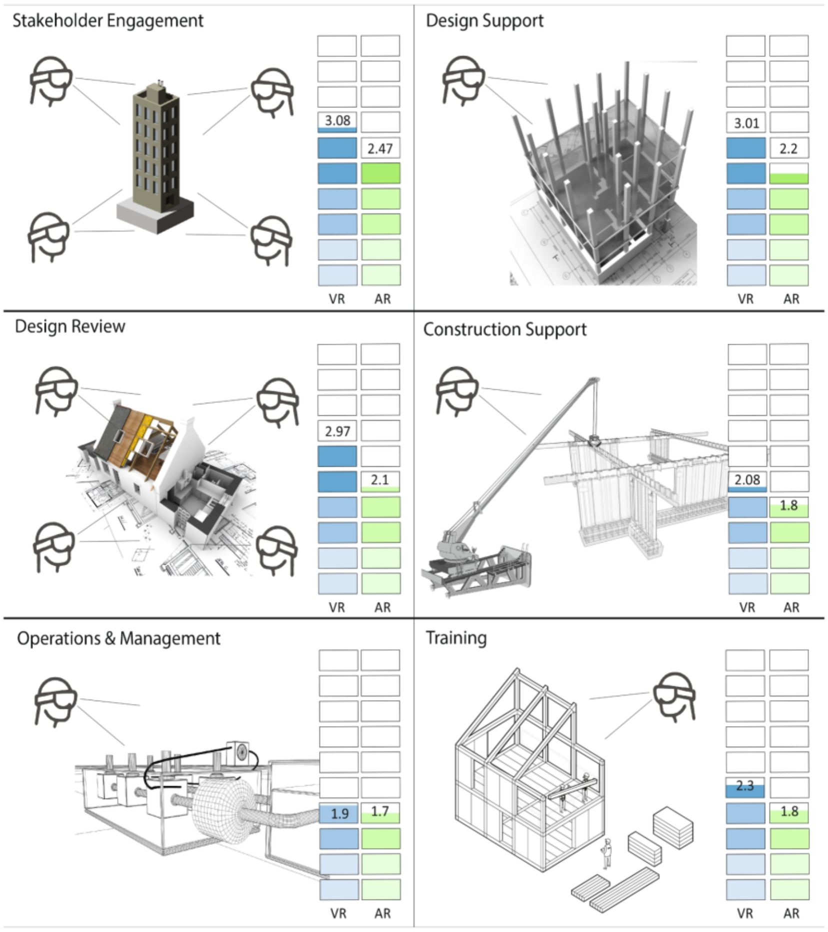

Figure 2-12, AR and VR cases in the AEC sectors and their estimated levels of adoption. The plots indicate the level of adoption in projects for the given use-case (1 = not used, 2 = early testing, 3 = basic implementation, 4 = partially used, 5 = fully implemented).[13]

[13] , "A research agenda for augmented and virtual reality in architecture, engineering and construction"

- Stakeholder engagement

AR and VR can be used to engage with potential clients or with the public to provide a more realistic representation of a built asset and to generate more relevant or informed feedback. AR and VR representations can give consumers an opportunity to better examine built-assets at real-scale, in an immersive environment, and provide a better understanding than pictures or videos.

For example, having a better understanding of the end-product will contribute to aligning the stakeholders' expectations with the actual design. Both AR and VR approaches for stakeholder engagement are the most used and easier to implement use-case. Nowadays, it is relatively easy to develop an AR mobile app that visualises a virtual model of a built asset on top of a table or a VR walkthrough of a built asset using only a mobile phone and a mobile VR headset.

Challenges. The main issues of using VR for stakeholder engagement are that (i) for most of the users the interface is not sufficiently user-friendly (e.g. a chaperone is always required), (ii) there is a sense of isolation, and (iii) VR experiences are not easily shared. The main AR challenge for stakeholder engagement is that the augmentations do not seem sufficiently real, and the immersive experience is poor. This is caused by four main issues (i) registration inaccuracies, (ii) inconsistent and unrealistic luminance of virtual objects, (iii) drifting errors, and unreliable location and motion tracking, and (iv) overlaying virtual objects at large distances from the user is problematic.

- Design support

AR and VR can support designers to identify the consequences of their design decisions and to have a better understanding of the final results.

Challenges. The main challenges of using AR and VR for design support are (i) that it is very difficult to translate the changes made using the AR and VR systems into Building Information Modelling (BIM) models, and (ii) that it is not possible to archive AR and VR outputs for later review or to record the experiences that the user had in AR and VR environments.

- Design review

AR and VR facilitate the communication of design intent, enables designs to be reviewed in a more efficient way; issues can be identified more easily, and sign off can be done more efficiently.

Challenges. Similar to design support, the main challenges of using AR and VR for design review include the difficulty to translate design changes to BIM models and to record the experiences and discussions that the users had within the AR and VR environments. A two-way seamless and automatic communication between BIM models used for construction and AR and VR models is required. These challenges have been partially addressed by the work of Dries et al.[14] which proposed an ontology that enables a bi-directional link between a BIM model and a VR application.

[14] OpenBIM Based IVE Ontology: An Ontological Approach to Improve Interoperability for Virtual Reality Applications, Advances in Informatics and Computing in Civil and Construction Engineering

- Construction support

The use of AR and VR for construction support can be grouped into four areas:

- **Construction planning**. The primary objective of AR and VR in this area is to anticipate potential problems and improve delivery. VR focuses on creating immersive construction simulations; while AR focuses on visualising virtual object to be constructed directly on sites.

  Challenges. The main challenges limiting AR and VR for construction planning are (i) the lack of interoperability between BIM systems and AR and VR models, and (ii) the difficulty to automatically update BIM models and construction schedules from the AR and VR systems.

- **Progress monitoring**. AR has the potential to improve significantly the ability to identify what has been built and what is missing in a quick and understandable manner. This is very important as early detection of schedule delays is critical to ensure timely delivery.

  Challenges. There are still many technical challenges to be resolved for AR-enabled progress monitoring including (i) automatic 3D reconstruction of building components from point clouds, and not only the creation of polygon meshes; (ii) reliable marker-less object recognition; and (iii) comparison and automatic update of as-built and as planned models. Challenges for VR include (i) the difficulty of managing various data sources and technology pipelines used in the construction site and for VR visualisations; (ii) the lack of integration between data standards that make difficult the integration of BIM data, photogrammetry and VR platforms; and (iii) the lack of ways to validate the progress monitoring data (i.e. does the VR environment truly reflects reality), and lack of an indication of accuracy.

- **Construction Safety**. Construction safety is one of the clearest use-cases for AR and VR. AR can be used to provide safer working environments by contributing to hazard identification, safety inspection; and VR can support safety education. Li et al.[15] presented are view of the AR and VR applications in construction safety, in which defined three main application domains, i.e. hazard identification, safety training and education, and safety inspection and instruction. Moore and Gheisari[16] also carried out a review of the use of AR and VR for construction safety noting that AR and VR help workers reduce risks and carry out tasks in a safer manner

  Challenges. Lack of customised hardware, lack of interoperability among systems, uncomfortable devices, and lack of standardised evaluation limit the effectiveness of both AR and VR for construction safety.
- **Operative support**. AR is the ideal technology for this area, as it focuses on supporting workers to carry out a task in the most efficient manner. AR focuses on finding ways to provide more contextual information to site workers; while VR focuses on teleoperation of construction equipment.

  Challenges. The main issues of using AR for operative support are (i) the lack of safety-approved hardware, which bars large-scale deployment; (ii) the low accuracy and unreliable tracking and mapping that are not at a level that will ensure correct assembly and construction; (iii) short battery life of devices, which significantly diminishes usability (HMDs batteries usually last only 30 min); and (iv) the potentially limited internet access on construction sites, which would impede connections with enterprise systems and federated BIM models to get information, update and record changes. The main challenge for VR teleoperation systems is that while they increase safety, they also highly reduce efficiency, as

[15] "A critical review of virtual and augmented reality (VR/AR) applications in construction safety"
[16] "A review of virtual and mixed reality applications in construction safety literature, Safety"

the operators take significantly more time to carry out the same task[17]. This is caused by the latency of communication between the construction equipment and the remote operator, unsatisfactory visual information, and lack of tactile and body sensory feedback.

- Operations and management

AR has great potential to support building operations and management because it can provide useful information to site workers that operate and maintain the facilities. VR can provide a way to operate the facility remotely in an immersive environment. A combination of both technologies can support field and remote office workers at the same time and improve collaboration repair, and inspection tasks by directing technicians to the specific equipment, showing the tasks to be completed and providing technical information in context. For instance, Irizarry et al.[18] presented an AR system that provides information stored in BIM models to users for supporting facility management tasks.

Challenges. Similar to construction support, AR systems for operations and management face challenges related to tracking and registration, collaborative interfaces, context-awareness, and information visualisation methods. The main challenges facing the use of both AR and VR for facility management are the lack of integration with other facility management systems, the low accuracy and speed for updating information across several systems, and the difficulty to archive and revisit AR and VR experiences.

[17] "Development of a tele-operation simulator based on virtual reality environment for advanced unmanned construction, in: 2013"

[18] "InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach"

- Training

VR can provide realistic scenarios in which the users acquire knowledge and skills from performing simulations of real activities rather than acquiring general information from a decontextualized body of knowledge[19]. Both AR and VR technologies can reduce the cost of training, by simulating the use of expensive equipment, simulate dangerous environments, reducing travel costs, as well as improving health and safety.

Challenges. The main challenges of using AR and VR for training are (i) that there is a shortage of experts to produce AR and VR content, (ii) a lack of systematised evaluation processes, and (iii) lack of integration with existing qualification standards.

[19] "Situated cognition : social, semiotic, and psychological perspectives."

3. METHODOLOGY

This chapter describes in a more technical way the technologies and methods that I have chosen to use in order to create the information system. The first chapters concern the digitization of the existing coherent with it and in which it is possible to insert all the physical and real information, while the second part consists in the creation of the virtual "game" space where it is possible to program each necessary element knowing the right language such as information curtains, interactive elements and much more that you want to display through the Mixed Reality Hardware.

3.1. PHOTOGRAMMETRY

For my research I used **Meshroom** by AliceVision is a free, open-source 3D Reconstruction Software based on the AliceVision framework. The reason why I chose this software is mainly for the features it offers, and for being open source.

Photogrammetry is the science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring and interpreting photographic images and patterns of electromagnetic radiant imagery and other phenomena.[20]

Photogrammetry is the science of making measurements from photographs. It infers the geometry of a scene from a set of unordered photography's or videos. Photography is the projection of a 3D scene onto a 2D plane, losing depth information. The goal of photogrammetry is to reverse this process.

[20] https://en.wikipedia.org/wiki/Photogrammetry

The dense modeling of the scene is the result yielded by chaining two computer vision-based pipelines:
“Structure-from-Motion” (SfM) and “Multi View Stereo” (MVS).[21]

1. **NATURAL FEATURE EXTRACTION.** The objective of this step is to extract distinctive groups of pixels that are, to some extent, invariant to changing camera viewpoints during image acquisition. Hence, a feature in the scene should have similar feature descriptions in all images. The description, which is typically stored in 128 bits, consists of a statistic of gradients computed in regions around the key point. The region size is determined by the key point scale and the orientation is determined by the dominant axis. As the number of extracted features may vary a lot due to the variability of textures complexity (from one image to another or in different parts of the image), a post-filtering step is used to control the number of extracted features to reasonable limits (for instance between one and ten thousand per image). We use a grid filtering to ensure a good repartition in the image.
2. **IMAGE MATCHING.** The objective of this part is to find images that are looking to the same areas of the scene. For that, we use the image retrieval techniques to find images that share some content without the cost of resolving all feature matches in details. The ambition is to simplify the image in a compact image descriptor which allows to compute the distance between all images descriptors efficiently.
3. **FEATURES MATCHING.** The objective of this step is to match all features between candidate image pairs. First, we perform photometric matches between the set of descriptors from the 2 input images. For each feature in image A, we obtain a list of candidate features in image B. As the descriptor space is not a linear and well-defined space, we cannot rely on absolute distance values to know if the match is valid or not (we can only have an absolute higher bound distance). To

[21] https://alicevision.org/

remove bad candidates, we assume that there’s only one valid match in the other image.

4. **STRUCTURE FROM MOTION.** The objective of this step is to understand the geometric relationship behind all the observations provided by the input images, and infer the rigid scene structure (3D points) with the pose (position and orientation) and internal calibration of all cameras. The Incremental pipeline is a growing reconstruction process. It first computes an initial two-view reconstruction that is iteratively extended by adding new views. First, it fuses all feature matches between image pairs into tracks. Each track is supposed to represent a point in space, visible from multiple cameras. However, at this step of the pipeline, it still contains many outliers. During this fusion of matches, we remove incoherent tracks.

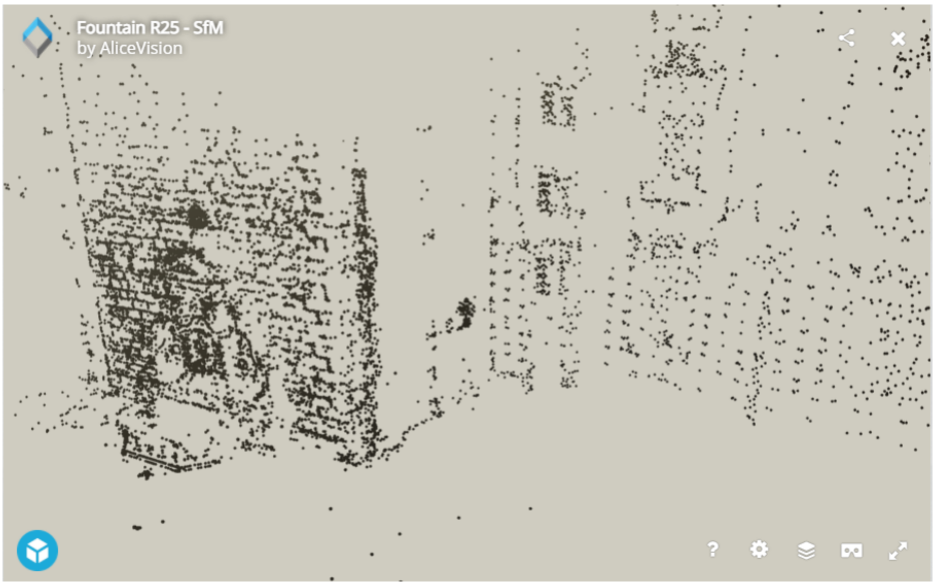

Figure 3-1 Fountain R25 Structure from Motion by Alice Vision

5. **DEPTH MAPS ESTIMATION.** For all cameras that have been resolved by SfM, we want to retrieve the depth value of each pixel. Many approaches exist, like Block Matching, Semi-Global Matching (SGM), or ADCensus. We will focus on the SGM method implemented in AliceVision.

6. **MESHING.** The objective of this step is to create a dense geometric surface representation of the scene. First, we fuse all the depth maps into a global octree where compatible depth values are merged into the octree cells. At this point, the mesh can also be simplified to reduce unnecessary vertices.
7. **TEXTURING.** The objective of this step is to texture the generated mesh. If the mesh has no associated UV, it computes automatic UV maps. AliceVision implements a basic UV mapping approach to minimize the texture space.

Figure 3-2 Fountain R25 Texturing by Alice Vision

8. **LOCALIZATION.** Based on the SfM results, we can perform camera localization and retrieve the motion of an animated camera in the scene of the 3D reconstruction.

For the success of a correct photogrammetry these are the steps to follow.

The success of a good photogrammetry scan depends on the right planning. This means a lot more than just fully charged camera batteries and bringing the camera tripod along. And not just good overcast weather or proper studio scan setup. Before you start shooting, first you will need to estimate how, and from where you will shoot your object.

You will need to examine your object, the lighting conditions and the available routes around the object if you shoot outdoors. It is good to have enough moving space around the object you are planning to shoot. You should have about 3 to 5 meters of available space around the object, and for the close-up shoot, you'll need to get to about 50cm from the object (for objects up to 3 meters in height).

- **Acquiring**. Good scanning practice: at least one loop around the object in 10-degree increments (approx. 36 images), where the whole object fits in the image. For better results, you can make more loops from different elevation levels. These images give the photogrammetry software a "basic frame". And this "frame" will be used for alignment and depth calculation of the more close-range shots.

  Next is the mid-range and close-range shots: if the first loop is at 3m away from the object, the mid-range is at 1.5m and the close-range is about 50cm. The mid-range shots connect the far distance loop and close-range images.

  On the middle and close-range shots, we need to remember about ALL surfaces. Every side of the scanned object needs to be shot: back, top, underneath, inside, etc. And every point of every surface needs to be seen in at least 2-3 images, taken one straight and two from a slight (10°-15°) angle to surface.

  Every shot needs to overlap with the next in at least 60% (and 80% or more is even better).

In some lighting conditions, for example, an object in a cave and one side darker than other, better use other technique. Shoot from below, move the camera up shoot again and so on. After that, take a small sidestep and repeat vertical movements but from the top to the bottom. Sidestep and again from below to top.

We need to remember that the images need to be as sharp as possible. Also, the depth of field needs to be as big as possible. If you are using a DSLR or a mirrorless camera, you should already know how to achieve this.

You can even use a good smartphone. The iPhone has a good camera that can be used for high-resolution photogrammetry scan with sub-millimeter resolution. Only achieving a good texture is a more difficult step in post-processing.

- **Pre-processing.** The human eye can see much more details than any photogrammetry software. That is why we need to apply pre-process - we'll help the photogrammetry software with the identification of details, especially in the shadowy and lighted areas.

  We'll need to fix the exposure, to lighten the shadowy parts and darken the lighted areas. We also can remove the chromatic aberrations. Remove the noise and sharpen the image. But be careful as the image CANNOT be distorted in any way.

  At this stage it is also necessary to look at the various photos taken and discard the superfluous ones.

- **Processing.** Now the photos taken are ready to be processed by the software and perform all the steps described above.

3.2. 3D MODELING

As a software for 3D modeling of particular elements, I chose **Rhinoceros** because being a Cad program it allows me to have the flexibility to create any non-standard shape with ease, as well as being a precision modeling program.

Rhinoceros is also one of the most popular 3D modeling software for manufacturers is Rhinoceros 3D, also known as Rhino. Based on NURBS (Non-Uniform Rational Basis Splines) geometry, this surface modeling software is commonly used for architecture, prototyping, engineering, jewellery and industrial, graphic, naval and automotive design.

The software was created by Robert McNeer & Associates, a Barcelona-based company dedicated to sales, training, marketing and support for software in Europe, the Middle East and Africa. Rhinoceros 3D was originally a complement to the AutoCAD software developed by the multinational company Autodesk.

Rhinoceros 3D is a CAD software with a multitude of complex 3D modeling tools, which allow you to create unimaginable shapes with great precision and detail, whether from a drawing, a sketch or even a 3D scan. The software is compatible with most design, drafting, CAM, prototyping, rendering and illustration programs.

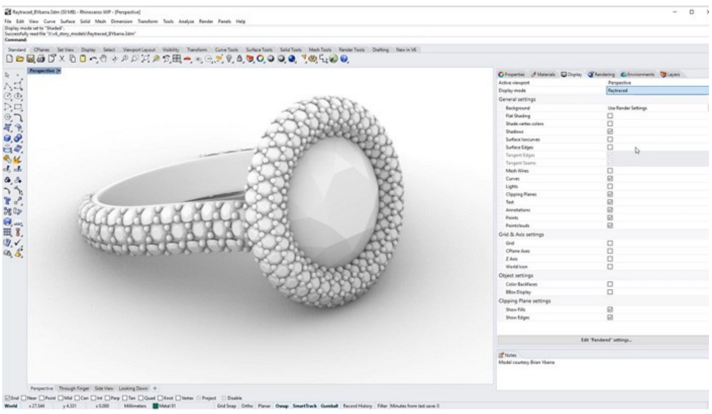

Figure 3-3 Rhinoceros example of capabilities

3.3. BIM MODELING

For BIM modeling the choice fell on Autodesk **Revit**, because it is one of the most complete software but also one of the most used in the world.

Autodesk Revit is a building information modelling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing (MEP) engineers, designers and contractors. The original software was developed by Charles River Software, founded in 1997, renamed Revit Technology Corporation in 2000, and acquired by Autodesk in 2002. The software allows users to design a building and structure and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. Revit is 4D building information modeling capable with tools to plan and track various stages in the building's lifecycle, from concept to construction and later maintenance and/or demolition.

Revit is software for Building Information Modeling. Revit supports a multidiscipline design process for collaborative design. Its powerful tools let you use the intelligent model-based process to plan, design, construct, and manage buildings and infrastructure.

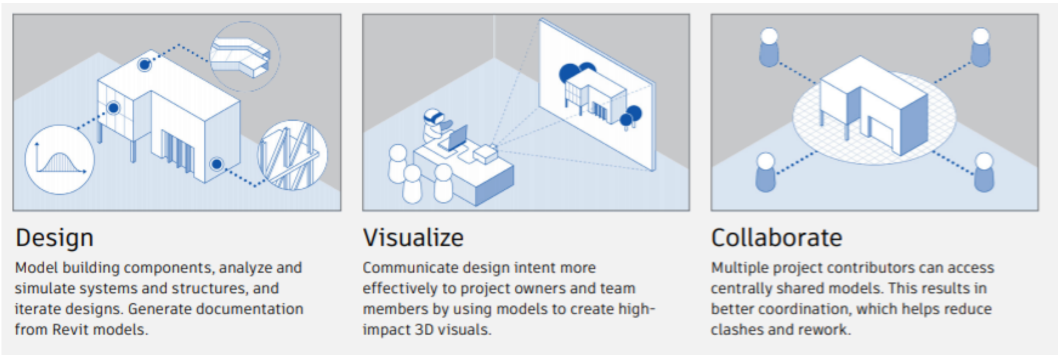

Figure 3-4 Some features of Revit

Revit for mechanical, electrical, and plumbing (MEP) engineers Design MEP building systems with greater accuracy and in better coordination with architectural and structural components, using the coordinated and consistent information in the intelligent model. Design, model, and document building systems in the context of a full building information model, including architectural and structural components. Conduct simulations and interference detection earlier in the design process. Use conceptual energy analysis data for engineering-driven calculations. Model for MEP fabrication with tools that automate the fabrication model layout. Prepare a model for detailed coordination of fabrication and installation.

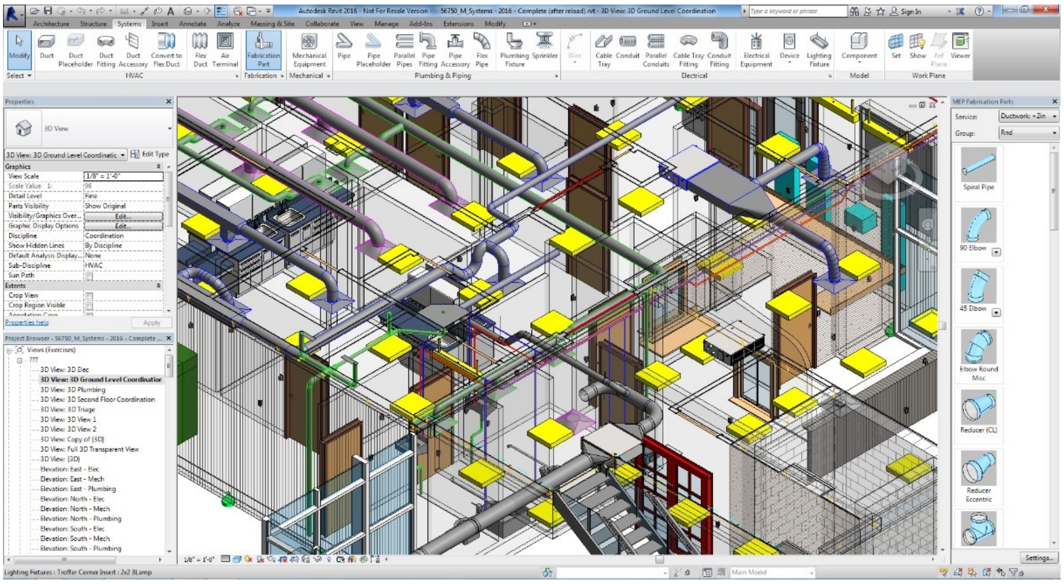

Figure 3-5 Revit for MEP[22]

[22] https://cadblog.co.uk/2015/08/27/new-to-autodesk-revit-mep-2016-fabrication-detailing/

3.4. MIXED REALITY HARDWARE

Microsoft **Hololens** is a mixed reality viewer designed and developed by Microsoft. The headset is nothing more than a wearable helmet with some sort of thing of built-in smart glasses capable of making the user view holograms in the real world (see fig.3-6).

Figure 3-6 Microsoft Hololens

The helmet is referred to by Microsoft as a "Holographic computer", as it was designed with the belief that "the holograms are the future in the evolution of information technology. The device gives the possibility for the user to be free with both hands, so it is a system hands-free, which is a great advantage, making Hololens a device always wearable, to carry out everyday actions, from the simplest to the most complex, and not a device usable only in certain moments of the own day.

The device is wearable by everyone, this is made possible by a regulator glasses width manual, which allows you to tighten or widen the circumference. As for the weight of the device, it is distributed homogeneously and not more on the front side than it is can think as soon as you see the device. This makes Hololens more comfortable, in line with the thought of wearing it often. The viewer creates a kind of new reality, precisely mixed reality, thus reaching a middle point, an intersection, of an almost higher level, between augmented reality and virtual reality. As described above, virtual reality projects the user into a parallel world, isolating it from reality, instead reality augmented allows to the user to experience their own reality, but having digital information and content such in front of their real vision. Microsoft Hololens does something more creates digital objects, called holograms, making them part of the world physical, almost without letting the user notice the difference between real and virtual, making these objects look like part of the real world.

Analysing the technical details of Hololens, it turns out to be a real device. powerful mind. Neither needs wires, nor a computer that is always connected, it is therefore a totally independent device. The device currently has Windows 10 as OS, and is equipped with a 16.5Wh battery, CPU and GPU, 2GB of RAM and 64GB of memory, 802.11 Wi-Fi and Bluetooth to connect respectively to the internet and with any device, also exploits Bluetooth Low Energy to connect to the clicker, an accessory provided by Microsoft to facilitate scrolling and selection in the interface windows.

The real power of Hololens lies in the analysis of the world around him, however perform this function Microsoft has placed various sensors in the device, such as accelerometer, gyroscope and magnetometer, enclosed in an IMU (Inertial Measurement Unit), together with four cameras to understand the world around to the device, and a depth chamber, to obtain a complete view of what is there and what is happening around Hololens. An HPU has been created, that is a Holographic Processing Unit, in order to combine the information collected from the depth chambers and the data collected by the IMU. The Holographic Processing Unit is also able to manage the input gestures made by the user and voice inputs. Alex Kipman, as Hololens Chief Inventor, has stated that "HPU is capable of processing terabytes of information" by Hololens sensors in real time. This data already leaves us to imagine the power of that device. In addition to the sensors, a crucial part of the device are the lenses. Hololens incorporates very advanced lenses, precisely lenses see-through holography, or lenses that allow you to look beyond of the same, not covering the real world as it happens in a device of virtual reality. Together with the same, a double light engine is used, and a holographic resolution equal to 2.3M of total light points. The functionalities of the sensors, together with the super advanced optical lenses, allow the vision of holograms that are a real part of the world. In the device there is a 2.4MegaPixel camera, to take pictures at any time, and one 1.1MegaPixel video camera, to capture one's vision of the holographic world, as well as speakers to reproduce sounds as if they belonged to the real world. Hololens is rechargeable via microUSB port, and can be used even during the charging period, it is finally stated that the weight of the devices 579 grams

The main question, dictated by curiosity, remains, as Hololens does to do all that. Holograms are nothing more than three-dimensional representations made by lights and sounds, of anything, such as characters, program windows, or objects.

It is therefore understood that everything is represented as a hologram. Initially the device acquires more information possible about the real world, understanding how the room around the user is made, whether or not they are present and in what position any objects are located real. Information about the world is captured at any time in continuously from the device, making a real mapping of the space. Continuous real-time mapping is basically dictated by the fact that the user can and must move while wearing glasses, this it implies that if he turns his head, or goes to a different room, he will be in one position different from its previous one, and is located in a different point of the environment, so glasses, in order to continue to make the experience real, they need to know where the user is and what surrounds him at all times, and this is possible from the environmental chambers and sensors on the device. The device will therefore be able at any time to have details on the environment surrounding, and at each survey it will update its data. Having a vision world, Hololens is able to place holograms in the world itself, this action is called “pinning”, which means to pin. Whenever that the user will want to place a hologram in the world, the first action that this is exactly what he is asked to do, that is, to indicate to the device where he wants to place his hologram. The hologram can remain fixed in that position, while the user moves to another part or can also follow the user during his travels. The user will be able to give inputs to the device by making hand gestures or using the voice, and the device is in able to detect them. This allows you to interact with the holograms by unfolding actions on them, or to interact with the device, asking it for example of opening the main menu, or with the world itself, to place precisely the holograms. This is the way to interact with the device, it comes thus abandoned the concept of mouse and click on a screen, and they will be hands to click or any other action.

3.4.1. Virtual twin model alignment and reality

After capturing real-world data, modelling all the surface in BIM also the internet Hub were imported the next significant contribution of this research is to estimate the user orientation in real time by scanning the user environment. The method to match the detected planes with their corresponding virtual planes and the alignment process is now described.

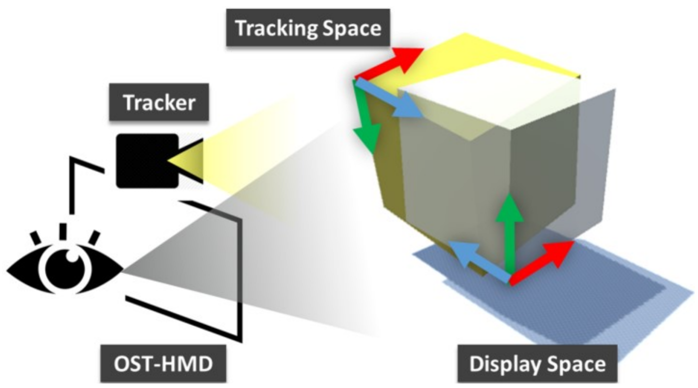

Figure 3-7 Head- anchored tracking system[23]

At their core, mixed reality apps place holograms in your world that look like and sound real objects. This involves precisely positioning and orienting those holograms at meaningful places in the world, whether the world is their physical room or a virtual realm

[23] Alignment of the Virtual Scene to the Tracking Space of a Mixed Reality Head-Mounted Display

you've created. Windows provides various real-world coordinate systems for expressing geometry, which is known as spatial coordinate systems.

With the HoloLens, even though its spatial mapping and integrated IMU (Inertial Measurement Unit) sensing enables the user to create stable virtual objects in the real world, there has not yet been a systematic work to properly align the created virtual content with the world in a dynamic setting, which is required in many augmented reality applications. Although the Vuforia SDK[24] has implemented image-tracking support on the HoloLens, it does not completely address the alignment between virtual content and the user's view.

First of all, therefore, let's talk about spatial coordinates and coordinate systems.

Device support

Feature	HoloLens (1st gen)	HoloLens 2	Immersive headsets
Stationary frame of reference	✓	✓	✓
Attached frame of reference	✓	✓	✓
Stage frame of reference	Not supported yet	Not supported yet	✓
Spatial anchors	✓	✓	✓
Spatial mapping	✓	✓	✗
Scene understanding	✗	✓	✗

Figure 3-8 Device support[25]

You can design Mixed reality apps for a broad range of user experiences, from 360-degree video viewers using headset orientation to full world-scale apps and games using spatial mapping and spatial anchors:

[24] https://www.ptc.com/it/products/vuforia
[25] Docs.microsoft.com

Experience scale	Requirements	Example experience
Orientation-only	**Headset orientation** (gravity-aligned)	360° video viewer
Seated-scale	Above plus **headset position** based on zero position	Racing game or space simulator
Standing-scale	Above plus **stage floor origin**	Action game where you duck and dodge in place
Room-scale	Above plus **stage bounds polygon**	Puzzle game where you walk around the puzzle
World-scale	**Spatial anchors** (and typically spatial mapping)	Game with enemies coming from your real walls, such as RoboRaid

Figure 3-9 Mixed reality experience scale

The Stage frame of reference isn't yet supported on HoloLens. A room-scale app on HoloLens currently needs to use spatial mapping or scene understanding to find the user's floor and walls.

Spatial coordinate systems. All 3D graphics applications use Cartesian coordinate systems to reason about the positions and orientations of virtual objects. These coordinate systems establish 3 perpendicular axes along which to position objects: and X, Y, and Z axis. In mixed reality, your apps reason about virtual and physical coordinate systems. Windows calls a coordinate system that has real meaning in the physical world a spatial coordinate system.

Stationary frame of reference. The coordinate system provided by a stationary frame of reference works to keep the positions of objects near the user as stable as possible based on the world, while respecting changes in the user's head position. For seated-scale experiences in a game engine such as Unity, a stationary frame of reference is what defines the engine's "world origin.".

Stationary frame of reference is a point in the world on which the coordinate system of an application for Hololens is built. This point it is generally calculated in relation to the position of the device, and is also a benchmark for the same. In case you want to place a hologram in a fixed point in the world, you will have to use one stationary frame of reference, i.e. a fixed reference frame. This means that the hologram will need to know a fixed point in the world, in which it must remain even if the device moves in the environment. It comes calculated a distance from that point, expressed in a vector containing the three dimensions of the coordinate system, in which it will come after placing the hologram, which is generally in front of the user or in any case in his field of vision. The application will continue to scan the environment, and processing the information obtained, will be able to update its position as soon as it recognizes more data complete on the environment, thus going to refine the position calculated for the hologram. The updating of space data could produce shifts with respect to the original position of the hologram, becoming such a problem, and Microsoft Hololens takes advantage of spatial anchors to solve these errors.

Attached frame of reference. This mode is used if we do not want to fix the hologram in a stable point in the world, but if we want to keep it linked to the user. The hologram will be able to follow the user to each of his shift. There are two types of latches, one body-locked, and another head-locked. A body-locked hologram follows the position of the device, remaining at a fixed distance from it. A head-locked hologram instead remains at a fixed distance from the user, but will result to always visible in his visual field, because it is linked to the position of the head. It is not recommended to use head-locked holograms, as they make the experience less real, given that in reality a you will never have a fixed object in your field of vision. A body-locked hologram can or have multiple uses instead: if we found ourselves in a video game, and if we wanted to play as a team with a hologram, it could he would like to follow us on a mission during all our travels. In this reference system the origin is always placed in the position of the device. This feature makes the reference system the only one that can be used in the case where Hololens does not know where he is in the world, and therefore he is not more able to hold the positions of the holograms.

Spatial anchors. As just mentioned, Spatial Anchors are for eliminate slight displacements from the original position of the hologram following the updating of data on the surrounding environment. The hologram can or be placed using a spatial anchor and it will stay fixed at that point, like if it were anchored. The Spatial Anchor is created starting from the Stationary Frame Of Reference, and at the point that was previously calculated as distance, a new frame of reference is created, which will remain fixed in that point. From the moment an anchor is placed, it will not be possible more to move it.

The main difference between an anchor-based reference system and one stationary frame of reference concerns the method of updating the position. It is inevitable and indeed natural that the device updates the positions of its objects, as it does not know the environment perfectly at the time of positioning the hologram, but acquires information in a way dynamic as the user moves around the world. When necessary, anchors update in relation to other anchors used or in relation to spatial reference systems, this ensures that it does not come sharply changed the position causing a drift effect, but that the hologram remains precisely in the same place. In the stationary frame of reference, the position relative to that of the user is updated, while in the spatial anchors the position relative to its origin is updated, thus, obtaining more precise results. It is therefore a positioning method accurate to perform such a function. Anchors are a system excellent positioning for two other reasons as well. It is possible to save the anchors and therefore a certain position in the world, before the shutdown of the device, in order to keep the data and restore them at the time of switching on, finding the hologram in the same place where we left it.
The data relating to the anchors are saved in a store and identified by a unique key. It is also possible to share information relating to an anchor between multiple devices. This way the two devices will be able to know the same information about that part of the environment, if they display the same hologram, it will be you can see it in the same point for both.

Up to now we have introduced the topic in a generic way, without describing the associated problems of Handling tracking errors which may be caused by the following points:

- The room is dark.
- If the surroundings don't have enough texture.
- if there are lots of dynamic changes in the environment, such as many people walking around in the room.
- Tracks incorrectly because the environment has changed significantly over time.
- Tracks incorrectly due to identical spaces in an environment.

3.4.2. Status of MR applications for Hololens

A brief summary of the applications considered for the development of the research. Types of mixed reality apps one of the advantages of developing apps for Windows Mixed Reality is the spectrum of experiences the platform can support. From fully immersive, virtual environments, to light information layering over a user’s current environment, Windows Mixed Reality provides a robust set of tools to bring any experience to life. It's important for an app maker to understand early in their development process as to where along this spectrum their experience lies. This decision will ultimately impact both the app design makeup and the technological path for development.

For our purposes Enhanced environment apps is the kind of mixed reality that is being researched. This approach is popular for apps where the contextual placement of digital content in the real world is paramount and keeping the user’s real world environment "present" during their experience is key.

Mixed reality is a very vast world, the possibilities are endless, and there are many ways to go. So, we started by choosing the 3D engine, downloading the tools and starting the programming.

The tools therefore used for the development of the research test are:

- **MRTK toolkit,** is an amazing open source toolkit available since the first version of HoloLens. The toolkit would not have reached its current levels without the constant contribution and commitment of the Microsoft developer community. Over the past three years, we've gained feedback from the developer community and built MRTK v2 with key needs and recommendations in mind. MRTK for Unity is an open source cross-platform development kit for mixed reality applications. The easiest way to install the Toolkit is with the new tool's application for the mixed reality feature. Follow the installation and use instructions and select the mixed reality Toolkit Foundation package in the Mixed Reality Toolkit category.
- **Unity 3D,** is one of the leading real-time development platforms on the market, with underlying runtime code written in C++ and all development scripting is done in C#. Whether you're looking to build games, movies and animation cinematics, or even render architectural or engineering concepts in a virtual world, Unity has the infrastructure to support you. [26]

As already described above, they are not the only applications available, but only those chosen by me for the development of the thesis, since they are already used in the research works of the DICEA department and therefore I would have had support when necessary.

[26] https://docs.microsoft.com/en-us/

3.5. GAME ENGINE

Unity 3D is a game engine based on C # programming and was chosen for its ease of learning, but also the infinite possibilities it offers, you just need to program to get what you want. Combined with the use of the MRTK toolkit is easiest way to develop in Unity is with the Mixed Reality Toolkit. MRTK will help you automatically setup a project for Mixed Reality and provide a set of features to accelerate your development process.

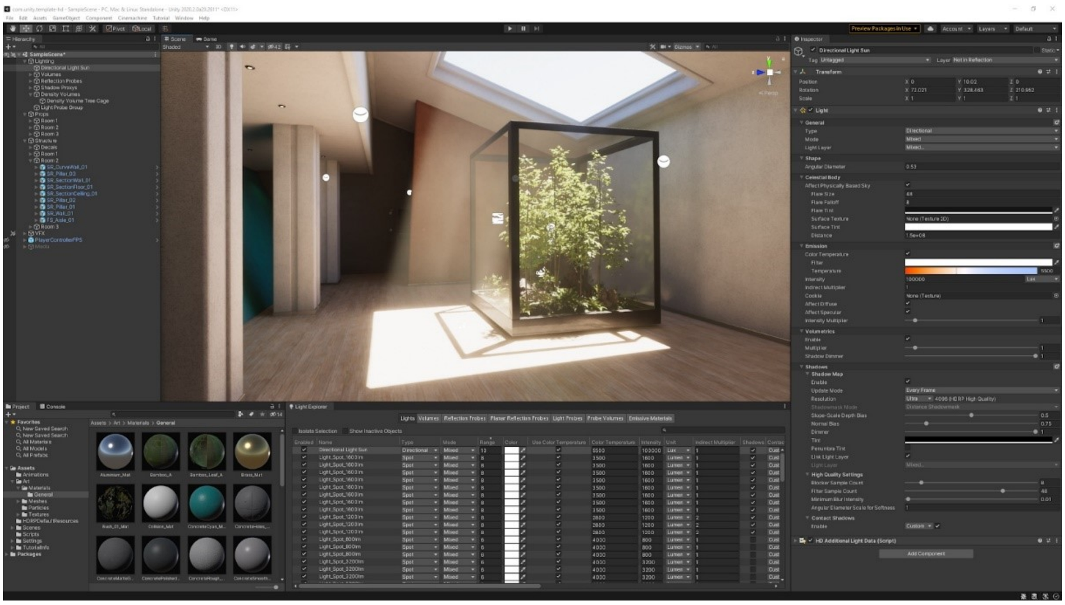

Figure 3-10 Unity 3D interface example[27]

So, in this phase of programming and structuring the BIM project within the game engine, use was made of:

- **Unity 3D 2019,** as a game engine
- **Visual studio code,** is a streamlined code editor with support for development operations like debugging, task running, and version control.
- **MRTK toolkit,** to be able to interface Unity with Hololens.

[27] https://unity3d.com/beta/2020.2b

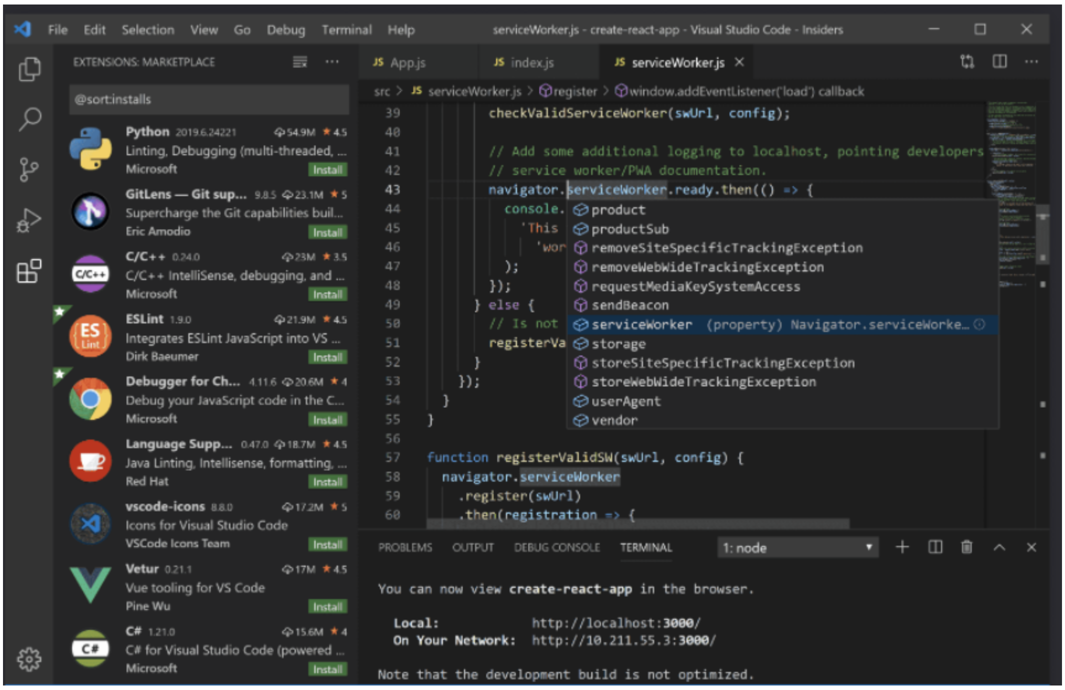

Figure 3-11 Visual Studio Code interface example[28]

In this phase it was therefore tested how the interface between the environment in Unity and the Hololens takes place. However, before importing the BIM and the department hub, there is a fundamental problem to be addressed and one of the key aspects of the research carried out, namely the alignment of the virtual model to reality.

[28] https://code.visualstudio.com/

4. APPLICATION DEVELOPMENT

The purpose of this thesis work is the research related to a simple question: is it possible today to create an information system supported by Mixed Reality that follows lean principles? And if so, can this system help in the digitization of a complex and traditionalist sector such as construction (AEC)?

As already mentioned in the previous chapters, this sector has obvious difficulties in implementing new technologies, mainly due to two factors:

- Companies in the AEC sector are almost entirely small (PMI/SMEs), and have obvious limits and difficulties in approaching new technologies.
- The construction sector is also a traditionalist sector, where innovations take many years to implement.

Every year millions of € are burned and wasted due to the inefficiencies of the system, such as poor design, errors, delays, management difficulties etc. and these inefficiencies are even more marked and evident in the facility management of large structures and plants (universities, infrastructures, airports, hospitals etc.). 85% of the total project cost is spent in operation and maintenance (O&M)[29] and includes the longest phase of any building system.

The amount of economic resources allocated for maintenance are caused by various factors such as:

- The little time dedicated to post-construction design, with maintenance plans and clear drawings of the as built.
- Not exhaustive reports of the plants built. Often, they are just 2D schematics that don't represent clearly in 3D.

[29] E. Teicholz, "Bridging the AEC technology gap," IFMA Facility Management Journal, March April, 2004

- Difficult to locate the actual onsite position of the asset, which is tedious and time consuming.
- The documents present are often still on paper, making it difficult to find and are not updated with the current maintenance status.

These and other reasons are the cause of the inefficiencies related to the maintenance and management of the building. Therefore, it becomes necessary to design an information system, capable of making these Operation and Maintenance processes more efficient and sustainable, and this is the purpose of the research carried out.

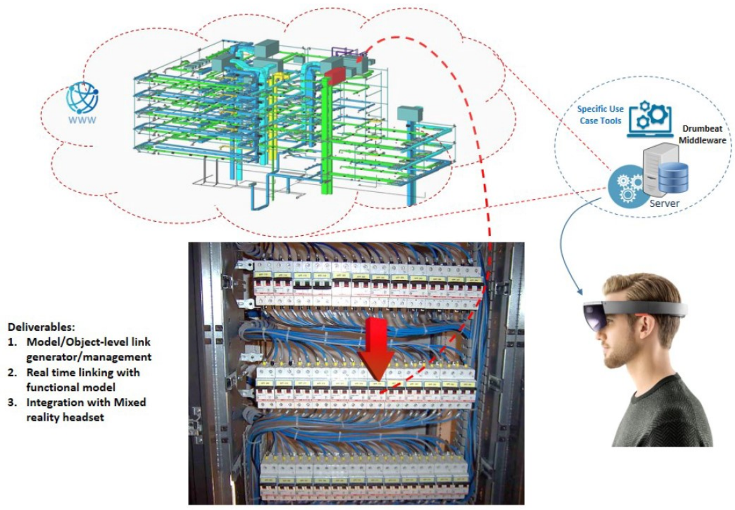

Figure 4-1 Mixed Reality assisted Facility Systems Maintenance (PRIN 2018)

Starting from these assumptions and with the xxx image in mind, the research started from the design of the architecture of the information system based on current technologies, previously exposed in the previous chapters.

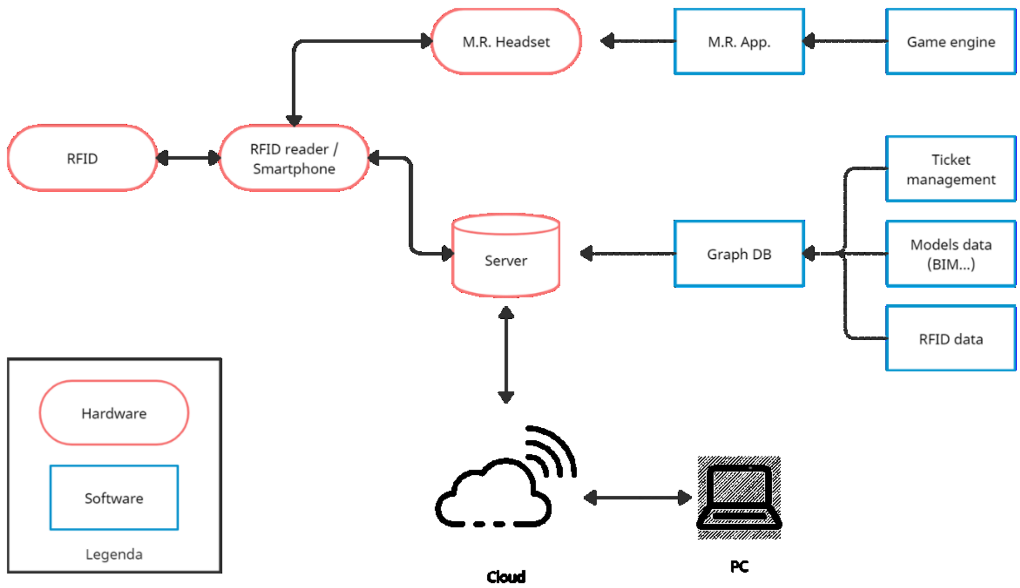

Figure 4-2 Architecture of the designed information system

The key points of the research therefore took place in three main points as follows:

- Digitization of the as-built.
- Creation of the digital twin.
- Final tests, and conclusions.

The research was carried out within the DICEA department of the univpm due to the restrictions of covid-19, and concerned a part of the related internet network system.

4.1. DIGITALIZATION OF THE AS-BUILT

The first part of the work carried out was to digitize the department, starting from the existing floor plans up to the 3D model. To carry out the digitization various techniques were tried, from the more traditional ones such as direct geometric relief, and others more experimental such as photogrammetry.

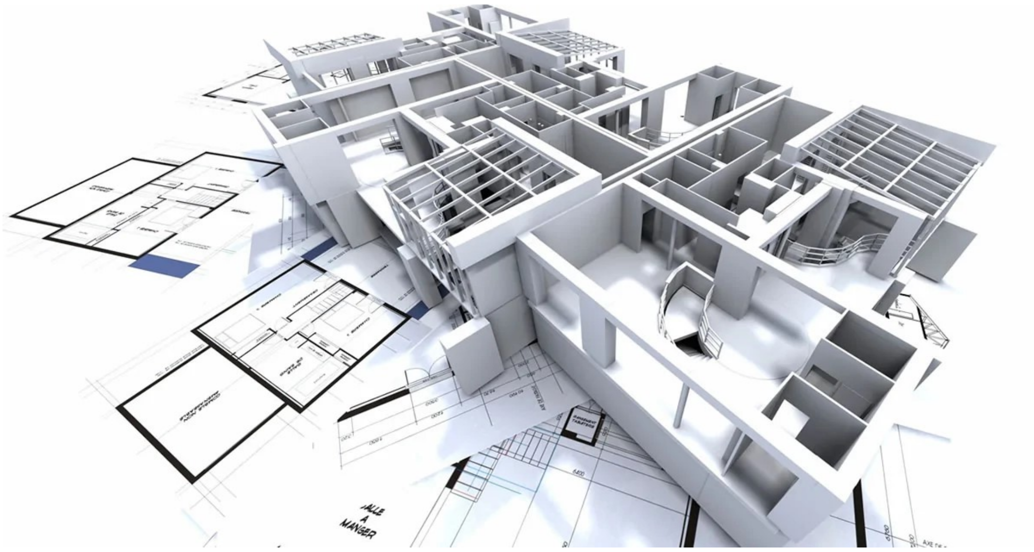

Figure 4-3 Digitization of building

4.2. DIRECT SURVEY

The direct survey of the department was carried out with the aid of simple measuring instruments, such as the meter, the laser distance meter. The relatively simple method was the basis for the modeling of the geometric elements present such as walls, doors etc.

Particular attention was paid at this stage to avoid errors as much as possible, as the presence of gross errors, of the order of a centimetre, would have compromised the quality of the entire research. In addition to the floor plan itself, and the structural elements present, the particular object of the survey was the Network Hub present (photo ...). The Hub survey was even more precise and detailed than the rest to be able to test the alignment capabilities of mixed reality in the subsequent phases.

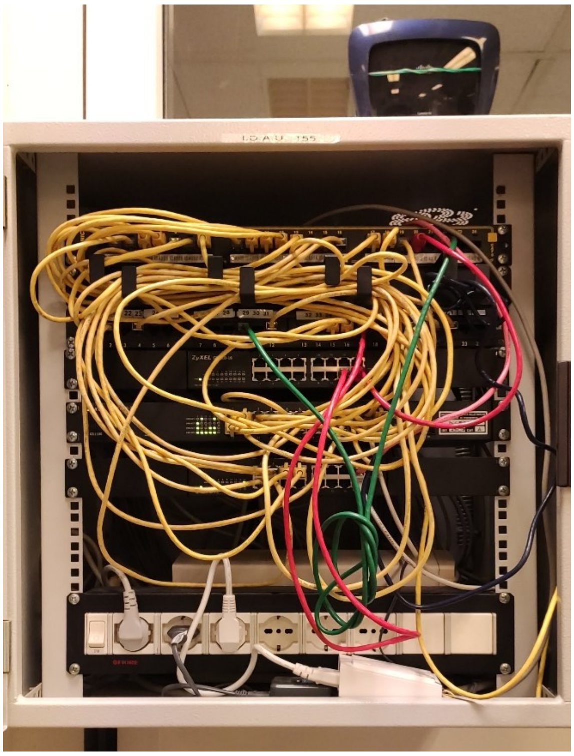

Figure 4-4 DICEA network hub

4.3. PHOTOGRAMMETRY

For the execution of the photogrammetry test, the following instruments were used:

- **Meshroom** is a free, open-source 3D Reconstruction Software based on the AliceVision framework.
- **Blender** is the free and open source 3D creation suite. It supports the entirety of the 3D pipeline—modeling, rigging, animation, simulation, rendering, compositing and motion tracking, video editing and 2D animation pipeline.[30]
- **Xiaomi mi9t** a mid-range smartphone as a photographic tool.

Before using this workflow for the DICEA internet Hub, I wanted to test the capabilities of the software and hardware.

With 63 photos of an outdoor fountain and the following shooting parameters:

- Dimension: 1846x4000 pixels
- Resolution: 72 dpi
- Bit depth: 24
- F-stop: f/1.8
- Exposure time: 1/250 sec
- ISO: 800
- Focal length: 26 mm
- Flash: no

[30] https://www.blender.org/

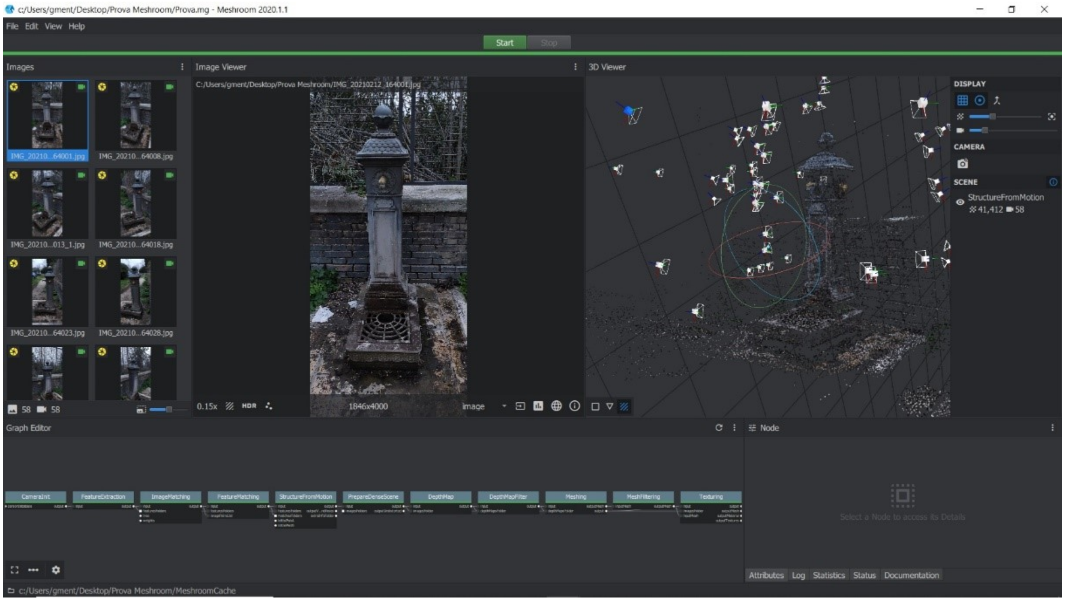

Figure 4-5 Fountain test, Meshroom process

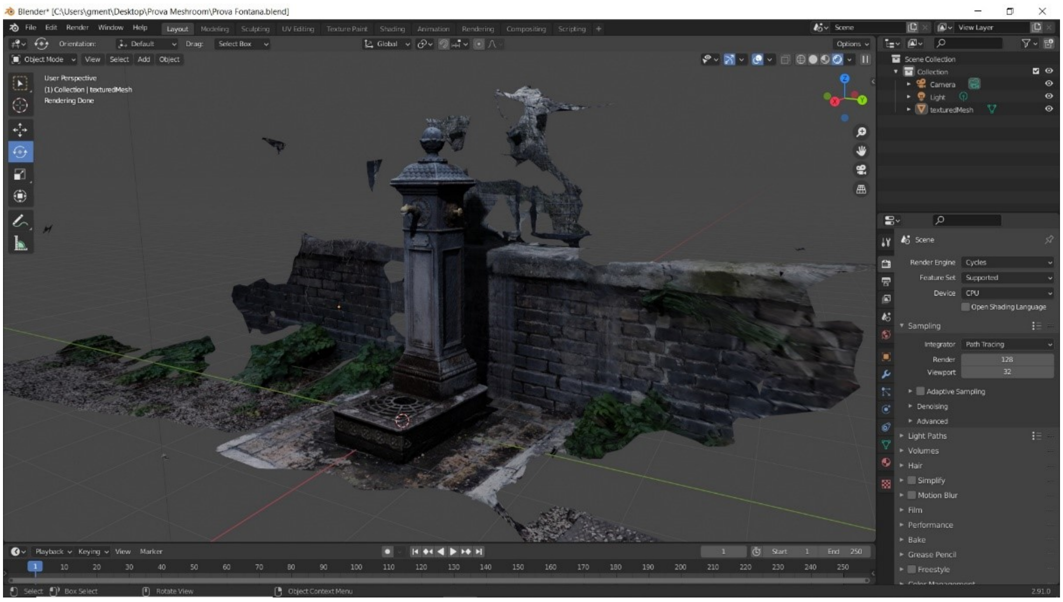

Figure 4-6 Fountain test, open in Blender 2.91

An amazing result, which prompted me to try this process, albeit elaborate, but less energy-intensive and expensive than manual modeling, and above all with results comparable to real life.

I then took 74 photos at the Internet Hub with the following parameters:

- Dimension: 1846x4000 pixels
- Resolution: 72 dpi
- Bit depth: 24
- F-stop: f/1.8
- Exposure time: 1/60 sec
- ISO: 800
- Focal length: 26 mm
- Flash: no

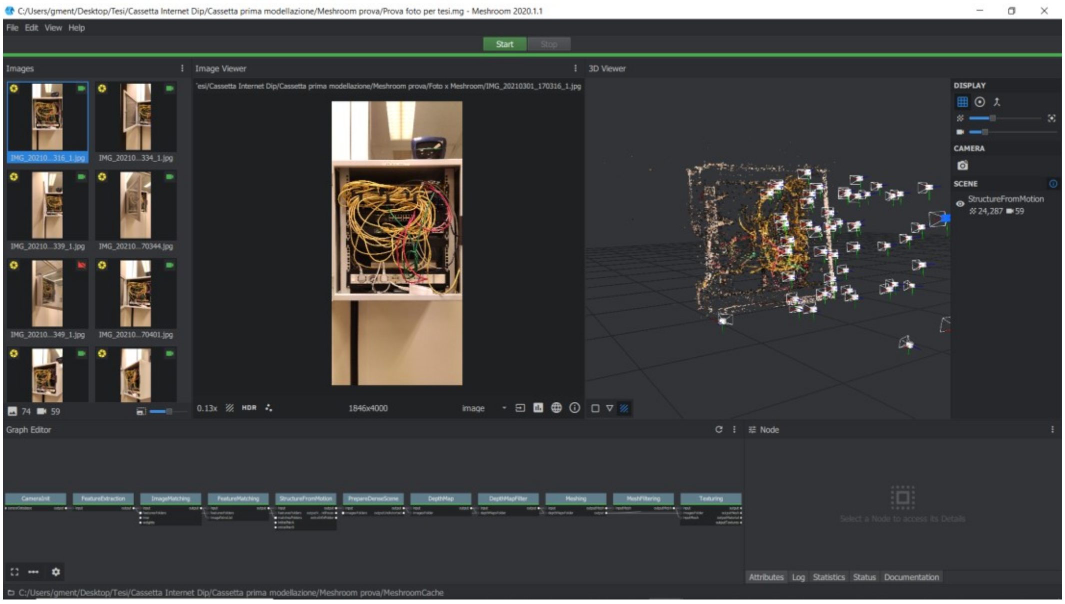

Figure 4-7 DICEA network hub Meshroom process

Once we finished the process in the Meshroom we imported the result into Blender. With these results.

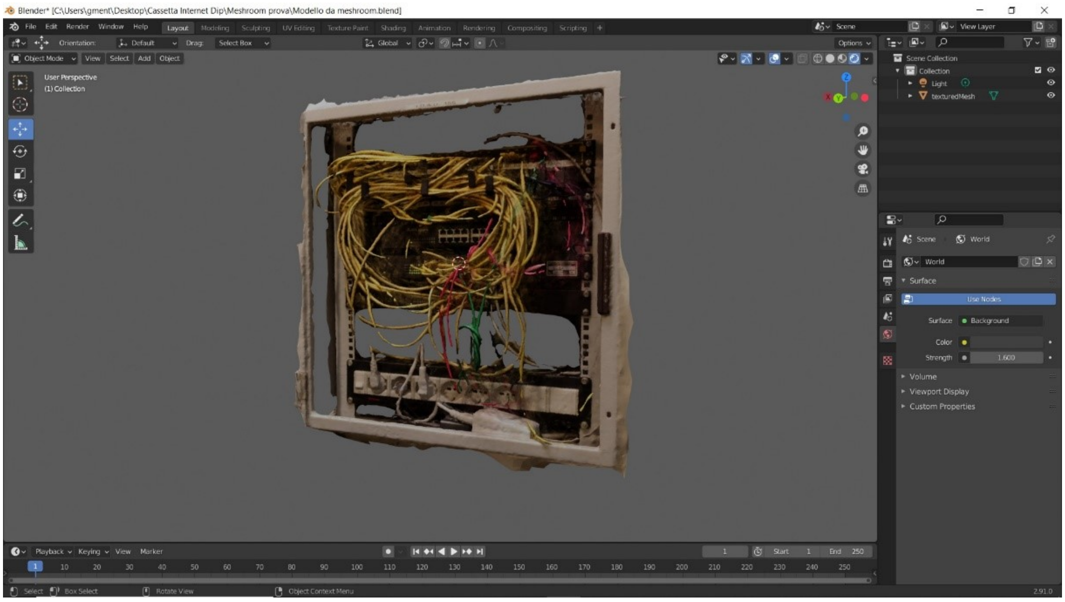

Figure 4-8 DICEA network hub open in Blender 2.91

The result, although not the worst, is certainly not positive and usable for the purposes of modeling through photogrammetry and not manually. This not very encouraging result is due to two fundamental reasons:

1. Photogrammetry encounters limits as the image is too complex and not very different from one point to another like leaves and grass, and in my case the cables in the foreground.
2. The second reason is that the HUB is located close to the wall and therefore during the capture it was not possible to turn around it.

This test through photogrammetry has taught us that it is certainly a very interesting and perfect technique in some contexts, for example in a construction site with little complexity and capturing images through a 360 camera, but also its (current) limits.

4.4. 3D MODELING INTERNET HUB

Having ascertained the difficulties of returning the DICEA internet Hub with the photogrammetry, we moved on to manual three-dimensional modeling, starting from the direct survey already carried out previously, assisted by further measurements performed in order to know exactly the geometry of the HUB.

For 3D modeling I used:

- **Rhinoceros 3D** is a commercial 3D computer graphics and computer-aided design (CAD) application software developed by Robert McNeel & Associates, an American, privately held, employee-owned company founded in 1980. Rhinoceros geometry is based on the NURBS mathematical model, which focuses on producing mathematically precise representation of curves and freeform surfaces in computer graphics (as opposed to polygon mesh-based applications).[31]
- **Blender** is the free and open source 3D creation suite. It supports the entirety of the 3D pipeline—modeling, rigging, animation, simulation, rendering, compositing and motion tracking, video editing and 2D animation pipeline.

In this case modeling requires knowledge of the software, and of the working hours. The quality of the result is therefore given by the skills of the modeler, by the degree of definition to be obtained, and by the time available for the execution of this phase.

Another relevant aspect of 3D modeling is that the more accurately the object is made the heavier it becomes in terms of "bytes". In the case study, the model produced has a weight of 28.4 MB (29,807,835 bytes) and the degree of detail is not too high, as it is irrelevant in the experimentation.

[31] https://en.wikipedia.org/wiki/Rhinoceros_3D

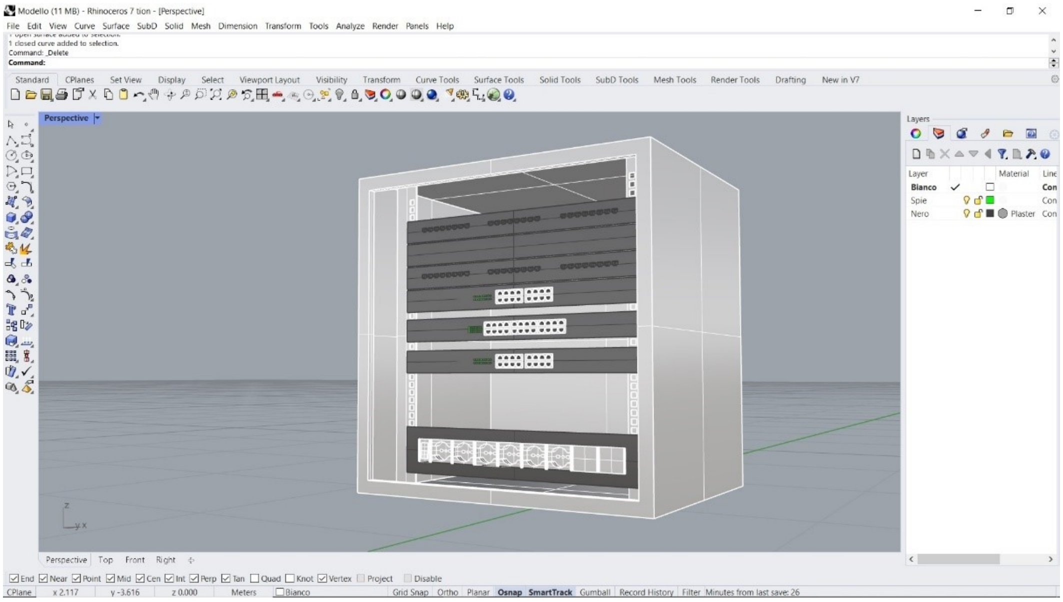

Figure 4-10 DICEA network hub modelled in Rhinoceros 7

Once modelled in Rhinoceros we tried exporting to .fbx and .DAE and .obj. One of the strengths of these software is the vastness of the formats they can handle.

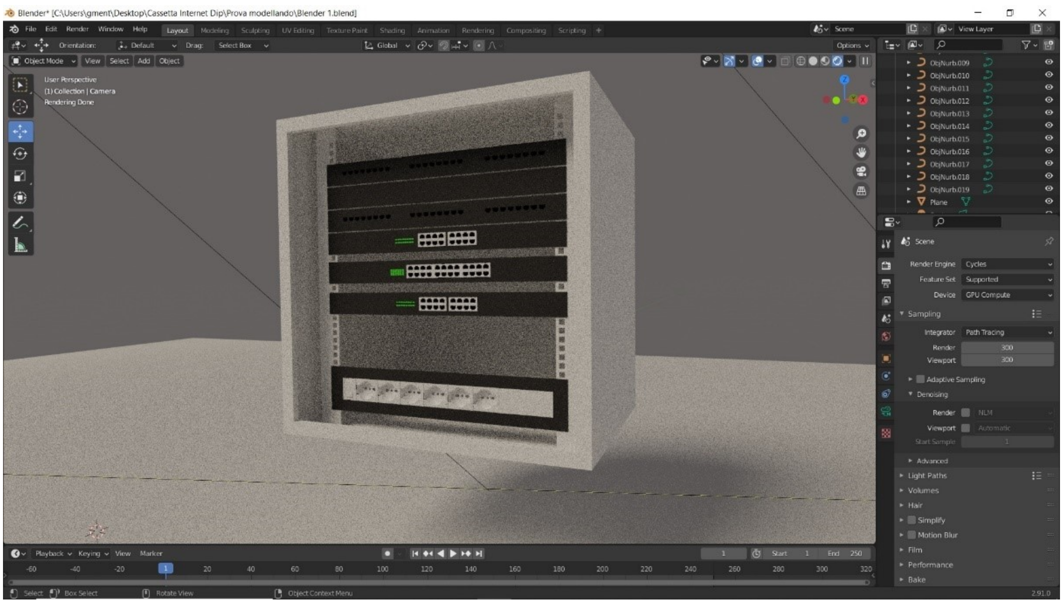

Figure 4-11 DICEA network hub visualized in Blender 2.91

The result obtained is acceptable and comparable to reality. This modeling was necessary in order to create a clone of the existing Hub, since it is not a standard object and it cannot be found in any library or file.

4.5. BIM MODELING

Once the network hub was created, and the geometric survey of the department was carried out, it was the turn of the BIM modeling of the environment. Although as widely explained in the previous chapters, that is, that BIM is not simply a software, but rather an information modeling process, now it is also necessary to go down to the software level and the choice fell on Revit for its popularity and the ability to manage MEP information and modeling.

For BIM modeling I used:

- **Autodesk Revit** is a building information modelling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing (MEP) engineers, designers and contractors. The original software was developed by Charles River Software, founded in 1997, renamed Revit Technology Corporation in 2000, and acquired by Autodesk in 2002. The software allows users to design a building and structure and its components in 3D, annotate the model with 2D drafting elements, and access building information from the building model's database. Revit is 4D building information modeling capable with tools to plan and track various stages in the building's lifecycle, from concept to construction and later maintenance and/or demolition.[32]

Also, in this case, albeit with a lower level of precision given the extension of the modeling, the level of detail and error committed is given by the accuracy of the geometric survey, since even if there are plans available, the built is always different from the projected one, and therefore there are problems of non-alignment, out-of-lead deviations due to changes in work etc.

The file produced by the modeling has a weight of 46.1 MB (48.381.952 bytes) made in Revit 2021.

[32] https://en.wikipedia.org/wiki/Autodesk_Revit

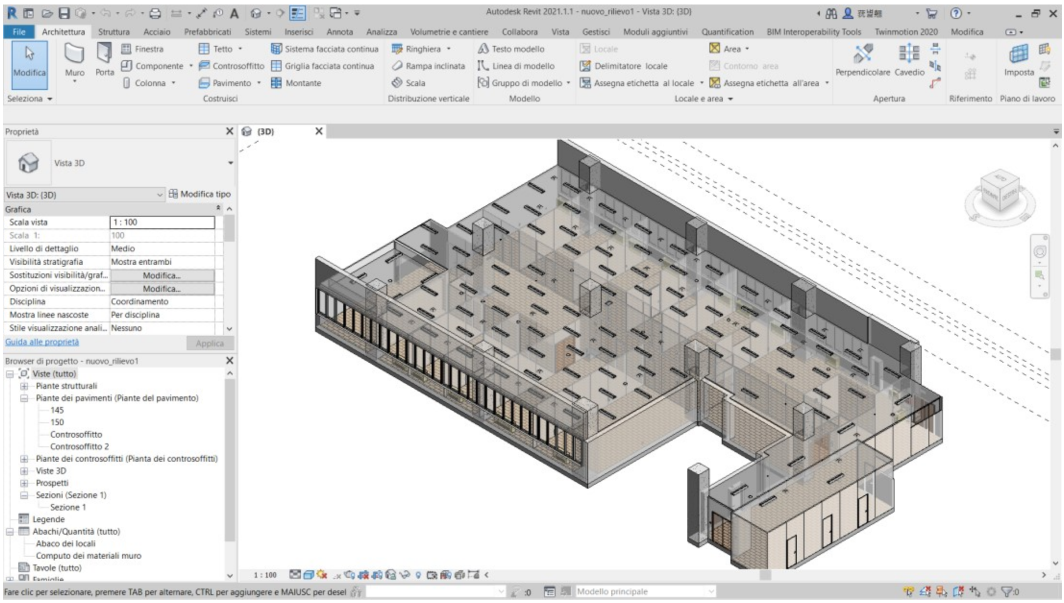

Figure 4-12 DICEA department in Revit 2021

At this stage, the internet connections between the Hub and the various rooms have not yet been modelled, but the geometric and functional base has been created, visible without removing the false ceiling.

The need or the advantage of BIM modeling may not appear immediately clear, but just think that every element created virtually in this way has a description with parameters and information, which are not lost even by exporting the file from .rvt to .ifc or the format BIM used as an international standard. This advantage then allows you to extrapolate and find exactly what you are looking for among thousands of elements, and to be sure that there are no problems related to bad modeling and human error.

Once we have modelled what is not visible, we have proceeded to model a small part of the network connection between the Hub and one of the rooms of the department, as you can see in the following image 4-13.

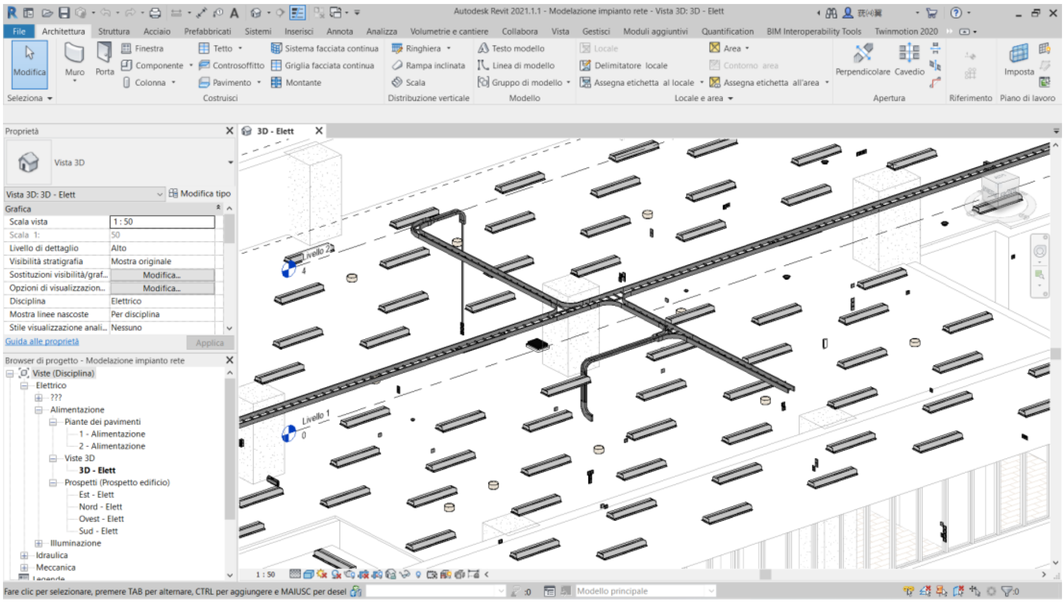

Figure 4-13 DICEA department Network modelled in Revit 2021

4.6. CREATION OF THE DIGITAL TWIN

A digital twin is the virtual representation of a physical entity, living or non-living, of a person or even a complex system. The digital component is somehow connected with the physical part, with which it can exchange data and information, both in synchronous mode (in real time) and asynchronously (in subsequent times).

The digital twin can evolve to become a true digital replica of potential and actual physical resources (physical twin), processes, people, places, infrastructures, systems and devices that can be used for various purposes. The digital component can include all information relating to the life cycle of the physical elements it represents.[33]

The concept of digital twin is therefore congenial to thesis research. That is, our goal, which consists in the experimentation of a possible information system capable of helping the management of buildings for facility management, requires that the as-built is in connection with the virtual, and that this exchange of information takes place continuously, and that the changes of the first are connected to the changes of the second.

And so, the goal was to test the application of Mixed Reality whether it is possible or not to reach this level of connection between the two "worlds".

---

[33] https://it.wikipedia.org/wiki/Gemello_Digitale

Before explaining what was the hardware used for the research carried out, it is necessary to clarify the choice of the thesis title, as augmented reality is formally wrong, because in reality we are talking about mixed reality, but the first was chosen. in order not to confuse the audience not very accustomed to these issues.

For the application in the field of mixed reality we used:

- **Microsoft Hololens 1 (2016)** are a pair of mixed reality smartglasses developed and manufactured by Microsoft. HoloLens was the first head-mounted display running the Windows Mixed Reality platform under the Windows 10 computer operating system.

Figure 4-14 Microsoft Hololens [34]

It is a very advanced technology so much so that the first version used for this research is a version called for developers. In fact, they represent the hardware but what they are capable of doing depends only on the programming and development of related software.

[34] https://www.microsoft.com/en-us/hololens

But how does it work?
The Hololens has a plethora of optical sensors, with two on each side for peripheral "environment understanding" sensing, a main downward facing depth camera to pick up hand motions, and specialized speakers that simulate sound from anywhere in the room. The Hololens also has several microphones, an HD camera, an ambient light sensor, and Microsoft's custom "Holographic Processing Unit" that they claim has more processing power than the average laptop. All this comes together to sense the spatial orientation of the unit in the room, track walls and objects in the room, and blend holograms into the environment.[35]

This is just a small summary to understand how the Hololens work, as having a more in-depth discussion refers to the previous chapter and to external discussions.

The whole point is to understand that this technology is in an early stage and as described by Microsoft it is an open invitation to all developers.

Recalling the issues addressed in the previous chapter, the main problems are listed:

- The room is dark.
- If the surroundings don't have enough texture.
- if there are lots of dynamic changes in the environment, such as many people walking around in the room.
- Tracks incorrectly because the environment has changed significantly over time.
- Tracks incorrectly due to identical spaces in an environment.

These alignment problems are very important for our use and therefore a solution has been studied to overcome these shortcomings of the Hololens.

[35] 7 Things about Microsoft Hololens, Grand Valley State University

The research carried out in order to overcome the limitations imposed by Hololens regarding alignment was to replace the Anchors that are automatically placed with fixed Tags created by us. The main feature of these Tags is that being modelled manually and positioned in the "virtual" world they cannot change position due to the Hololens.

This solution therefore requires that the virtually positioned tags are then also positioned on site with the same precision.

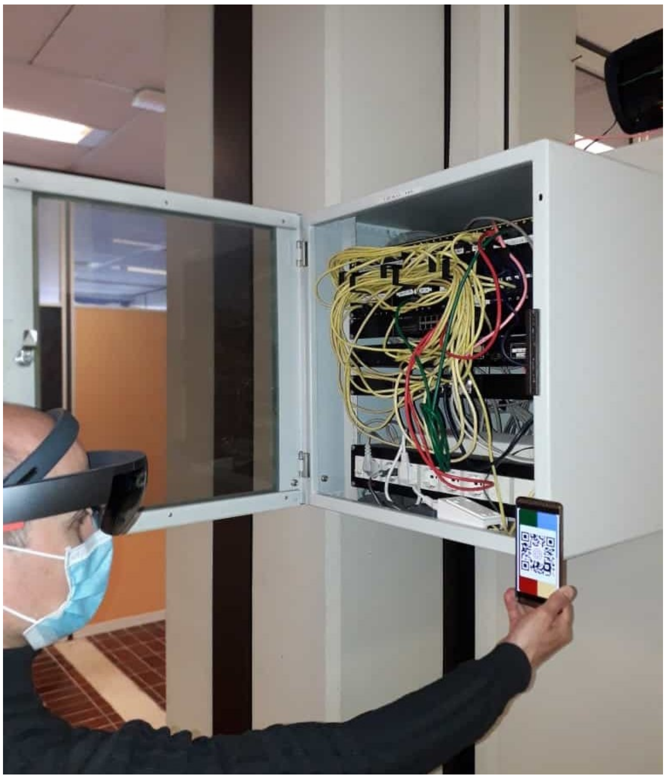

Figure 4-15 Hololens alignment with the Anchor (Tag)

The positioning of the tags and therefore their design is fundamental for the functioning of the system. The tags can be both printed, virtual and displayed as in the photo via smartphone, or even be associated with RFIDs.

One of the limits of these tags is of a functional aesthetic type, that is, it is unthinkable to place hundreds of them inside buildings. But the most immediate solution is to replace them with RFIDs, small metal disks, which can always be positioned in coordinated places known in the world but hidden from view. For example, behind the switches, or in any case fixed positions that do not vary over time.

In electronics and telecommunications, radiofrequency identification (in English Radio-Frequency IDentification, acronym RFID) is a technology of recognition and validation and / or automatic storage of information at a distance. It is based on data storage in particular passive electronic devices capable of answering proximity calls from active devices, both fixed and portable, called readers or readers.

The identification and exchange of information between the two elements takes place via radio frequency. One of the most recent RFID implementations is the Near Field Communication standard, which allows data exchange between two devices at a distance of about 10 cm but with a transmission speed of about 424 kbps.[36]

Summarizing the chapter, the Hololens in order to align the virtual with the real work in the following way:

- The horizontality is correctly recognized by the hardware after a first scan of the environment.
- The position of the hardware in the world is known.
- In order to fix the last degrees of freedom, two anchors are needed, the first to lock the rotation in the two remaining dimensions (therefore excluding the vertical axis) and the second tag to spatially fix the model.

Therefore 2 Tags are necessary for the minimum purpose, the more there are and the more precise the alignment will be. The level of precision of the overlap as you can see from the

[36] https://it.wikipedia.org/wiki/Identificazione_a_radiofrequenza

photo is remarkable, with deviations of less than one cm. The measurement of the error is not so immediate and certain, but it can be said with certainty that for the use envisaged in this thesis they are more than excellent.

Figure 4-16 Hololens alignment of the DICEA internet Hub

The level of precision of the overlap as you can see from the photo is remarkable, with deviations of less than one cm. The measurement of the error is not so immediate and certain, but it can be said with certainty that for the use envisaged in this thesis they are more than excellent.

5. RESULTS

Numerous tests were carried out during the research, but the most important is the final one in which it was tested whether the entire system works or not. Following are the photos relating to the last test performed.

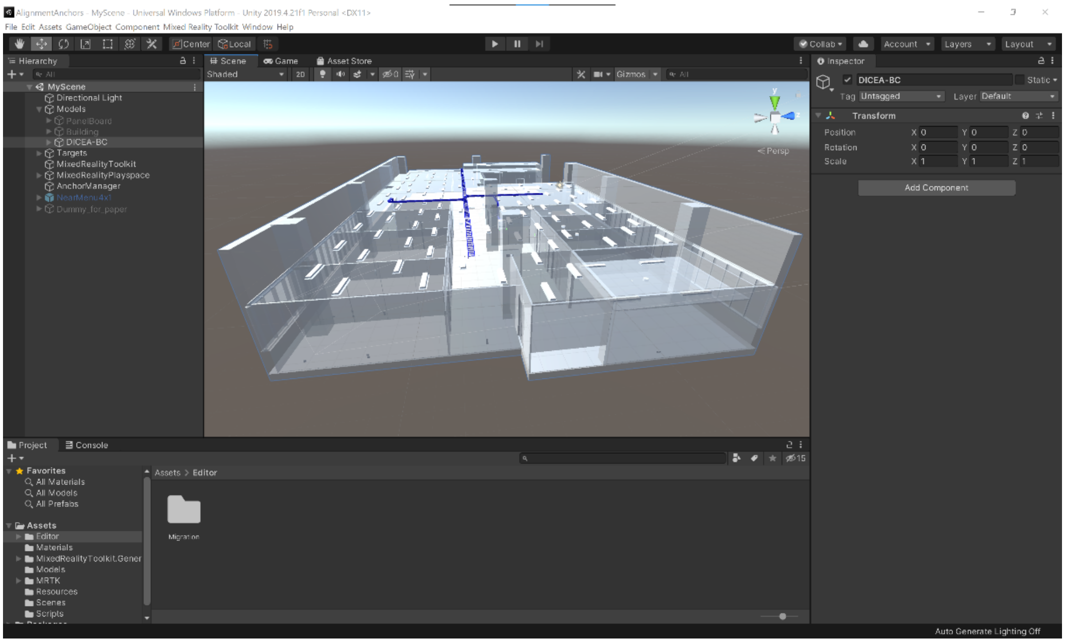

Figure 5-1 Final model in Unity 3D

Figure 5-2 Hololens alignment with the Tag

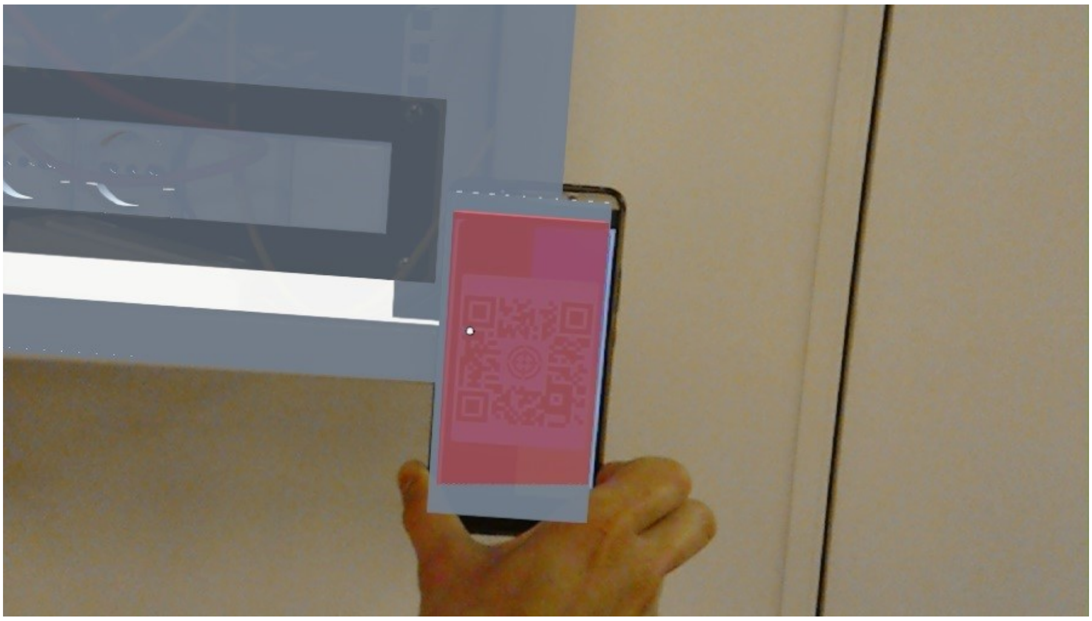

Figure 5-3 View of the Tag from the Hololens

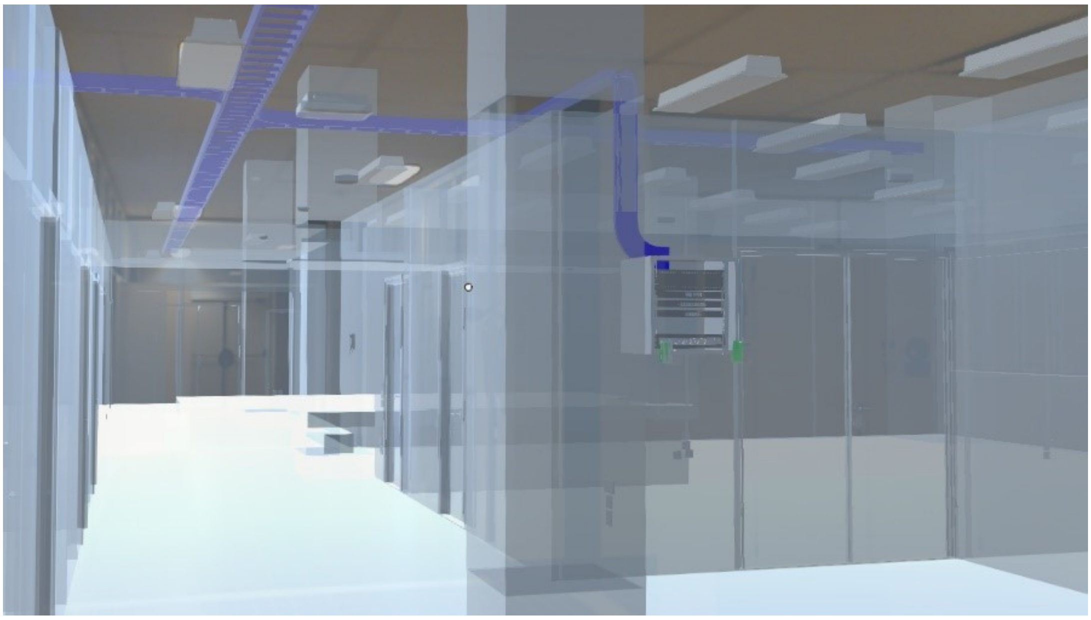

Figure 5-4 Overall view from the Hololens

The research has therefore demonstrated the possible roadmap to follow for the creation of the Digital Twin and has shown that the alignment of the Hololens is sufficient to support the facility management processes.

It is therefore clear that the time available to pursue the objective of the thesis was too little from the start, but this did not prevent the carrying out of important tests, such as those relating to the "failure" of photogrammetry 3d modeling, and again how BIM is the foundation of any future development in this area, and how Unity is a great environment (for those in the IT sector) to create the perfect system.

One of the central themes was therefore alignment, and that can be said with certainty that at the moment it is not a problem. Certainly, the Tags must be designed and positioned on site, but once they are placed and the Hololens are hooked to them, the game is done, and this also allows to overcome the current criticalities of the Hololens mentioned above.

6. CONCLUSIONS

The conclusion of the thesis research is that to date the technology at our disposal is mature for the creation of an information system supported by the use of Mixed Reality.

They are still sophisticated tools that require specific and interdisciplinary knowledge, ranging from construction and civil engineering to information technology. But if the research and use of these applications increase the whole process will become easier and within everyone's reach.

Our research has therefore demonstrated some of these fundamental steps in order to create this new system, and an important point has been solved, namely the alignment via Tag, overcoming the shortcomings of Hololens.

Furthermore, considering that in the near future BIM design is applied daily, and Hardware such as Hololens have improved following important updates (Hololens 2 is already present), the system will become more and more user friendly and within everyone's reach.

Finally, if it is true that the technology is ready, it certainly cannot be said that the building stock is. There are still too few buildings detected and returned in BIM modeling and this sector, architectural survey and digitalization will be in a growing boom.

I like to conclude this work with a quote about scientific research.

"If we knew (exactly) what we are doing, it would not be called research."
Albert Einstein

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