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**SVILUPPI DI MODELLI BIM AUMENTATI PER LA
GESTIONE DEL PATRIMONIO COSTRUITO**

**DEVELOPMENT OF AUGMENTED BIM MODELS FOR
MANAGEMENT OF BUILT ENVIRONMENT**

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Abstract

La seguente tesi si propone di studiare il possibile sviluppo tecnologico nell'industria delle costruzioni e più nello specifico del patrimonio costruito. L'intento è quello di garantire una gestione del costruito tramite l'implementazione di modelli BIM con la realtà virtuale, creando così un nuovo sistema di rilievo, modellazione e gestione che riduce notevolmente i tempi di elaborazione ed abbatta i costi.

Questa metodologia è stata applicata nel "Dipartimento di Costruzioni" del DICEA all'interno dell'Università Politecnica delle Marche, in cui è stato sviluppato un sistema di acquisizione e gestione di dati ed informazioni tramite fotogrammetria e digitalizzazione. La prima fase è stata la ricerca di documentazione a riguardo, concentrandosi principalmente sui problemi principali di questa industria e ricavandone lo studio di una nuova metodologia di lavoro. In seguito si è svolta l'applicazione pratica all'interno dell'Università, dove sono stati eseguiti dei rilievi sia geometrici che fotografici, mediante i quali è stato modellato l'ambiente BIM. Tramite l'uso di un Game Engine e di un linguaggio informatico, il modello 3D è stato aumentato grazie all'allineamento delle fotografie equirettangolari con la scena geometrica. L'allineamento è ottenuto tramite il metodo dei minimi quadrati, un processo analitico probabilistico, che fornisce la soluzione ottimale della pose estimation. In conclusione, si è ottenuto un modello BIM as-built, aumentato tramite la fotografia, il quale è misurabile ed implementabile ulteriormente, inserendo dettagli ed informazioni quando necessario. In questo modo è possibile ridurre drasticamente i tempi di rilievo di elementi MEP o dettagli, inserendoli più precisamente. La parte conclusiva di questa ricerca è stata l'individuazione dei benefici e possibili sviluppi futuri della metodologia proposta.

CHAPTER I

Introduction

The term built environment refers to the human-made surroundings that provide the setting for human activity, ranging in scale from building to neighbourhoods and cities. Currently, built environments are typically used to describe the interdisciplinary field that addresses the design, construction and management. The management of existing buildings starts with the acquisition of the structure geometries, the earned data elaboration and the 2D design production or the development of a 3D model, reconstructing the environment and its properties. From this information, it is possible the planning of the future works or interventions that can be actuated in the construction. Depending on the tools and procedures used, there are two different metric surveying methods: the direct and the indirect. The first, also called trilateration, is based on the detection of some significant points of the structure and the elaboration of the spatial measures through the triangle figure use. The other technique to obtain the geometric model of the buildings is through indirect methods like photogrammetry. Photogrammetry is the science of acquiring information with the process of recording, measuring and interpreting photographic images. Photogrammetric surveying is used for high precision surveys, to receive a large amount of information, for large surveying or in presence of considerable complexity of architectural forms and for inaccessible buildings. It allows the detection of the measure and the representation of structures and the simultaneous computation of several points, without having physical contact with them. The camera is the principal tool of photogrammetry, it can reproduce the ambient with a single image (equirectangular photo) or with a set of pictures (overlapping them). With the use of photogrammetry it is possible to obtain the complex geometries of the environment in the form of a point cloud. A point cloud is a set of data points in space. The points may represent a 3D shape or object. Each point position has its set of Cartesian coordinates (X, Y, Z).

The amount of data required in the first surveying stage is enormous and its management is really difficult with the increase of the built environment dimension. Also, the time necessary to make the traditional surveys, with both direct or indirect techniques, usually is long and can be dilated over time, because of different reasons, like the weather for the externals or like the request of accessibility documentation. Another problem of the existing surveying methods is the use of the acquired data only for the geometries losing the possibility to make these smart.

These problems even occur in the modelling stage, both in the traditional 2D design or in BIM. The Building Information Modelling is the most recent stage of a revolutionary path that has profoundly transformed in the last thirty years the world of design in the construction industry in all its various forms: architectural, engineering and management. BIM involves a new way of approaching the conception, execution and maintenance of the work. This new approach is useful for the planning of the construction phase, execution time and costs and maintenance works. The information is considered as part of a single process extended along the entire life cycle of the product, that prevents and reduces errors or inconsistencies. Each phase of the development, execution and management of the project draws evident advantages from the adoption of the BIM approach compared to traditional methods of project management, in terms of operational flow productivity and precision. In the design phase, in particular, the use of BIM allows the creation of virtual models that improve and expand the data management and the information quality, allowing designers to work in a collaborative way, on shared technical choices, with an immediate identification and resolution of project inconsistencies. The BIM model also allows to carry out simulations or precise calculations of materials, automatically generate component schedules, perform advanced calculations related to different aspects of the project (lighting, energy requirements, acoustic performance, etc.). Overall, the high degree of precision, the information detail and the consequent improvement in the efficiency of all stages of the process. Despite all these advantages acquired in the design phase and 3D model development of the built management, the designing stage still has many issues that retards the works and increases its costs.

As I said before, one of the main issues that still appears in the early stages of the design is the considerable time and expense required to generate the building construction plan. In the BIM design, the amount of data acquired in the preliminary phases of the project is extremely high and normally the time for its elaboration and management is limited. In this stage, the level of detail required for the models is unknown, so the planners must develop designs that contain a lot of information and data still in the first building model. The BIM modelling of the geometries and the integration with their properties require time, which is usually limited and leads to inaccurate or incomplete drawings. All the errors, missing elements or inconsistencies need to be reworked during the development of the project. Those problems create a slow start process and future issues due to the constant rework and change of the project model. Sometimes the model's high level of detail is unnecessary or unrequired, with obsolete elements or objects modelled, wasting a lot of work.

Starting from the analysis of the built environment management and its principal issues, this thesis aims to speed up the buildings surveying and modelling preliminary works. The scope is to postpone how later is possible the elaboration of the 3D model, its properties and level of detail. The proposed methodology combines photogrammetry, Building Information Modelling and Virtual Reality by using Game Engine (GE) software. It starts with a low detailed surveying, only acquiring, with direct techniques or with point cloud tools, the structure geometries, without taking the information of details or secondary elements. Then a high number of equirectangular pictures are taken using a 360 camera. The equirectangular panoramic photography is a photographic technique that allows the creation of pictures, which cover an angle of 180° in vertical and 360° in horizontal. This procedure consents to develop a low detailed BIM model that will be enriched through the panoramic images.

The augmented BIM model is developed using a Game Engine and the photogrammetry to create a perfectly aligned environment between the 3D geometries and the equirectangular pictures. As GE was selected Unity3D because of its simple interface, the free version and the large amount of data that could contain.

In Unity the panoramic images are first mapped with the equirectangular projection onto spheres with platonic polyhedric meshes (constructed by congruent, regular, polygonal faces and with the same number of faces meeting at each vertex). The equirectangular projection is a simple map projection that transforms planar coordinates into spherical coordinates. Inside the mapped images is settled the camera, which allows their 3D visualization. The camera pose estimation and alignment was analytically achieved with the help of Collinearity equations, Ordinary Least Squares and probabilistic principles, solving the Perspective-n-Point problem. The P-n-P problem originated from camera calibration, has the purpose to determine the position and orientation of the camera with respect to a scene object from n correspondent points. The analytical process was first developed inside MATLAB then converted as a C# function code.

After the camera alignment, was developed a software, that allows the navigation between the pictures, the measurement of the ambients directly from the images and the precise positioning of the detailing elements on the model. The navigation of the model is allowed by changing the coordinates in the environment of the camera, translating it inside the different spheres. The measurement tool is developed through the difference between the coordinates of the two selected points, while the placement of objects in the scene is implemented using the spatial coordinates for the importation and then transforming the object, with translation and rotation.

The proposed methodology was applied inside the UNIVPM DICEA department, taking as case study the Construction department. The surveying was developed using the GeoSLAM tool to take the point cloud and the Ricoh Theta 360 camera for the photographic documentation. The final result was the creation of a software which achieves the enrichment of the poor 3D BIM model with the equirectangular pictures.

The main target reached by the defined approach is the postponed built environment modelling, only when required, that minimizes the amount of errors. Now the photogrammetry is used not only as a geometric tool, but also to procure data and information from the environment, delaying the metric surveying of the detailing elements. This methodology is a professional working method which achieves time saving and consequently working costs reduction.

CHAPTER II

Literature review

The construction industry provides over 18 million direct jobs in the world economy around the 7% of the global workforce, contributes also to about 9% of the EU's gross domestic production (GDP) and 6-9% of the global GDP, creates new job opportunities and influences economic and social growth. The amount of workers involved in the building sector only in Italy is approximately one and a half million and the number of companies is nearly a half million, making the building sector one of the most productive and prolific industry of the country.

From the beginning of the 21st century the construction process has developed by including new equipment and technologies which enable the simplification of the whole working process, meanwhile reducing the time required from the preliminary design, during the project and until the commissioning phase. In modern architecture, engineering and construction (AEC), with the introduction of Building Information Modelling (BIM), an optimization of planning, realization and management of the construction has been achieved. BIM helps the project's groups to develop a virtual model of the buildings and to control the construction steps by creating an archive with all needed information that could be used also during the building life cycle management. Nowadays the digitalisation of the construction industry is changing the whole working method, through the introduction of new tools and technology. One of the most recent and innovative is the Extended Reality (XR), that can help to speed-up the project development and the managing of the structures. With the cooperation between BIM and XR the construction industry can significantly reduce the costs, making a more efficient and productive process.

2.1. Context analysis

The construction industry, despite its arrival to a certain level of optimization of designs, workings, phases of construction and management, is still far from the industrial production model, which merges the various phases by considerably improving the development and production. This system is not fully replicable in constructions for the complexity of the final product and for the work pattern, which starts from the surroundings analysis, the surveying, the conceptual design and develops until the final project which gets printed in 2D before starting the works.



Fig. 1 - Stages of construction projects

The linear scheme is also found in the stakeholders who usually operate by individuals or small groups, coordinated only by a few key figures that match the various phases in a particular way during modest projects or in small planning companies. This previous working method is disappearing with time since it is being replaced rapidly by the interoperability introduced by technological developments which did encourage a connected context through globalization; the various stakeholders communicate more with each other and have a broader view of the construction world with interrelated tasks. The Performing Organization could be different according to features of the project and it can change from functional structure (an hierarchy in which an employee has a clear superior) to opposite project organization (the members of the project group are often allocated in the same office and have more autonomy). Between these two typologies we can find the matrix structures, which are mixed and could be more functional or more project structures.

The first stage to start the project is the research by the client for an architect to establish the design and to develop the first project requirements. Afterwards the client selects from a series of bids the general contractor. This method is called Design-Bid-Build (DBB)

and is used in the major percentage of building, creating the most competitive approach and obtaining the lowest possible price for the construction. With the development of BIM a new type of contract establishing was born with the Integrated Project Delivery (IPD) where all the parts involved collaborate with the owner. The goal of this process is for the project team to work together through cooperative software to reduce as much as possible the errors due to misunderstandings, the time occurred for the design and the engineering as well as the costs of the whole project.

The new complex Performing Organizations have changed the work pattern into a compound system, where a multitude of subjects are able to participate in a certain project. The interaction between these subjects is more intricate than before. All the various groups that are part of the process are now interconnected in different ways, allowing subjects from all over to be able to have a say in each other's choices and throughout the steps of the project.

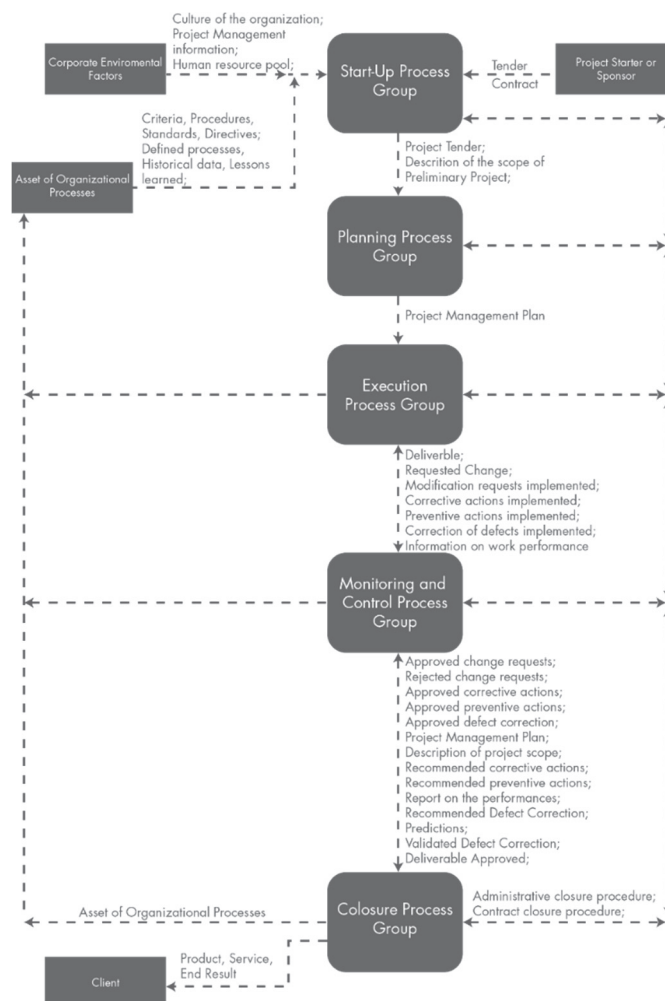


Fig. 2 - Interactions between stakeholders

During the construction stages we can find different subjects interrelated between them over time. In the early phases there is a light interaction among the Start-up Process Group (project starter, client, sponsor...), the planners and the Monitoring and Control Process Group. The project starters at the beginning examine the cost analysis and conduct feasibility studies on the outlining schedule. The level of cooperation increases rapidly in the intermediate stage between the end of the planning and the start of construction; this is the most critical situation, where all the subjects involved are constantly in communication with each other with the aim to conclude the building process. During this period many problems can be caused by delays of furniture, planning corrective or preventive changes, which delay work progress or even lead to lawsuits between various parts in a project team or to the total failure of the construction. In the ending stages with the project closure getting closer, the level of process interaction decreases quickly until the end.

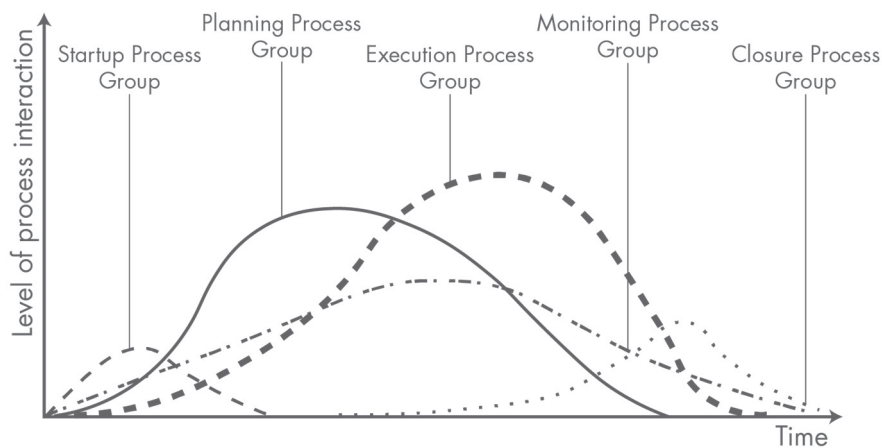


Fig. 3 - Level of process interaction over time

The development can also be found in the interaction between the planners and the technological devices: if before, the only way to modify the project was by human work, nowadays planners speed up the process using digital cameras or lasers and the opportunity to create faster views from 3D models. The use of twin models is also functional for the information that can be stored inside, and for the complete point of view of the design.

In terms of costs, the amounts of the project could be described in three different stages: the early phase characterized by the costs of the employees and planners' work; the intermediate stage with an increasing expenditure due to a major number of workers and the payments of the materials, facilities and work equipment; the final stage where the labor amounts decrease until the end of the project. Cost analysis is one of the principal reasons for the failure of the final realisation. Indeed, insufficient funding could stop the construction process .

2.1.1. Actual business investments:

The introduction of new technologies has been slow and also the adoption of new improved business practices has been limited only to larger firms. The main reason for the strong grip on the industry of the paper use and the 2D CAD drawings is the requirement of submittals for construction permit reviews by all local authorities.

A sustainable and competitive construction industry can bring many benefits to the society and the economy in the form of a better quality of life and jobs. In an European Union's research called "Views on Construction - 2020 and beyond", some reporters asked many specialists of the sector about the principal thematics in the building sector and about the view on the future through their top priorities. The number of specialists which responded to the research were about 25%, a reasonable number. According to the participants, the most important arguments are energy efficiency, affordability, circular economy, internal market regulation and digitalisation. Most stakeholders prefer moving towards a life cycle approach, to an industry which focuses not only on the construction process but considers the whole life cycle of a building.

The respondents of the survey were requested to provide information on which thematic groups or forums are of interest to their organisation. The greatest number of respondents was interested in sustainable use of natural resources, with 65%. Then the stakeholders were asked to identify future priority topics. Survey respondents were asked to select up to three most important priorities for them or their organisation going forward.

The top priorities were the circular economy, energy efficiency/decarbonising the economy and better regulation of the internal market.

Thematic Interest Responses	Thematic Interest Average	Priorities for the future Responses	Priorities for the future Average
Sustainable use of natural resources	65%	Circular economy, resources and affordability	64%
Internal Market	48%	Energy efficiency, decarbonising the economy	62%
Stimulating investment	43%	Better regulation of the Internal Market	48%
High level forum	40%	Digitalisation of design, planning and management	34%
International competitiveness	31%	Labour skills, mobility of workers and/or service providers	14%
Skills and qualifications	30%	Fast diffusion of new products, technologies	13%
None of Above	7%	Jobs and growth	12%
Total respondents: 171		Digital single market, procedures, proof of compliance	10%
		Investment opportunities across borders	10%
		Internal trade, globalisation	7%
		Other	2%
		Total Respondents: 156	

Fig. 4 - Thematic interest and priorities for the future - EU report on construction

To understand the business and how to reach the principal targets for the future, it is required to look at how the market is developing and on the topic of the main investments. The main expenditure on innovation in the construction industry is the investment in research (31,2%) and the purchase of machinery, equipment and software (43,2%). Another important part of expenditure is represented by resources allocated to other innovative activities, such as the staff training, the feasibility study or studies on verification and testing (21,6%). In the end there are lower investments on the learning of expertise from other enterprises or institutions (1,5%) and on the technical or aesthetical design of new products and services (2,4%).



Fig. 5 - Investments by construction companies with at least 10 workers (2014-2016)

A survey of ANCE (Associazione Nazionale Costruttori Edili - National Association of Builders) in 2019 analysed the financial support received by construction companies with at least 10 employees, during the three-year period 2014-2016. From this study the 23,3% of these companies stated that they had benefits from public incentives to introduce product and process innovations. Almost 50% of this support comes from local authorities, 40% from central government and the remaining 10% from the European Union. The sector that most frequently uses public support is the industrial sector, with a share of beneficiary companies reaching 39,1%.

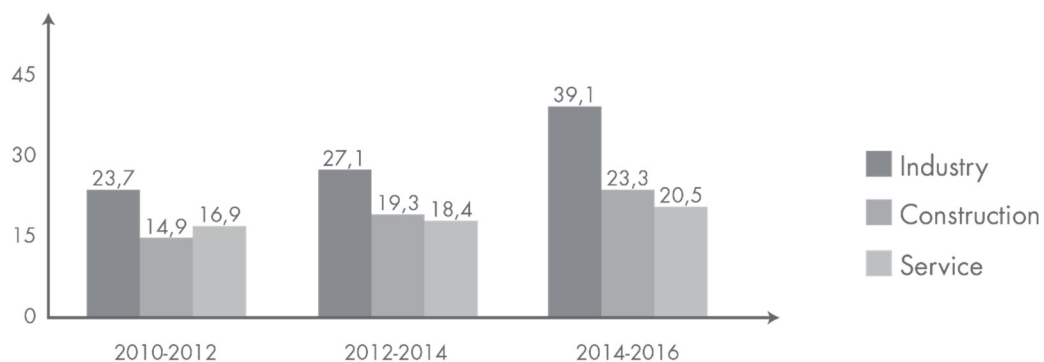


Fig. 6 - Construction companies with at least 10 workers which introduced innovations by public funding

From the comparison of the data of each year from 2014 to 2016 results that there has been a general economic increase in all sectors. Moreover, nowadays this trend is still growing and the financial support, since the beginning of COVID pandemic, is increasing rapidly, in particular over the digitalisation of the construction. This is due to new ways of working all around the world: global closure and distancing are leading to smart methods, with digital interconnection.

2.1.2. Built environment management:

The term built environment refers to the human-made surroundings that provide the setting for human activity, ranging in scale from buildings and parks or green space to neighbourhoods and cities. The built environment is a material, spatial, and cultural product of human labor that combines physical elements and energy in forms for living, working, and playing. Currently, built environments are typically used to describe the interdisciplinary field that addresses the design, construction, management.

Technology is playing a pivotal role in shaping the industries of today by augmenting processes, streamlining activities, and integrating innovations to propel the functioning of companies and organizations across a multitude of industries and help them achieve new heights. Building information modelling (BIM) is prominent practice. It involves illustration & pre-execution overview of physical and functional characteristics of places. BIM tools help the planner in making a future ready informed decision regarding a building or other built asset. The built environment through the use of BIM can improve in the various stage of work and planning.

Procurement:

From the need of a new construction work, are approximately defined the budget and the construction time, according to the owner request. After this first beginning phase, the procurement process starts. There is no set way to bid construction jobs, but there are different methods based on the lowest bid and on an accurate cost estimate. This phase can make the difference between success and total failure for a contractor. The final decision on the bid is made by analysing different factors, such as the price, the qualifications and the time to complete the project. The three traditional methods of bidding are:

- Design-Bid-Build;
- Design-Build;
- Construction Management;

Design bid build and Design build:

This is the traditional system of project delivery and the one which project owners are most familiar with. DBB is a linear process where there isn't overlap between tasks and one follows the completion of another. The owner selects an architect, which releases the documents to the general contractor or to a prequalified group to make their bid for the construction and the working methodology and schedule. This bid includes the other bids of the subcontractors, for each specific trade. The amount of the proposed bid is totally based on the design made by the architect, by the lowest bid possible. The design consultant team reports directly to the owner, which can define and control the design through the help of the architectural consultant.

The difference between the Design Bid Build and the Design Build is that in the second case the design and the construction aspects of the project are contracted with a single entity. This system is easier and consents to the owner to focus more on combining design, permits and construction schedules. The first design is moderately developed by an architect. Then the project starts by the development, from a general contractor or an architect/engineer, of the final design. For the owner, the Design Build minimizes the risk of the project and reduces the delivery schedule overlapping the design and construction phases. The problems with this system come from the difficulty to estimate the costs and the presence of unexpected situations that can raise the expenditures.

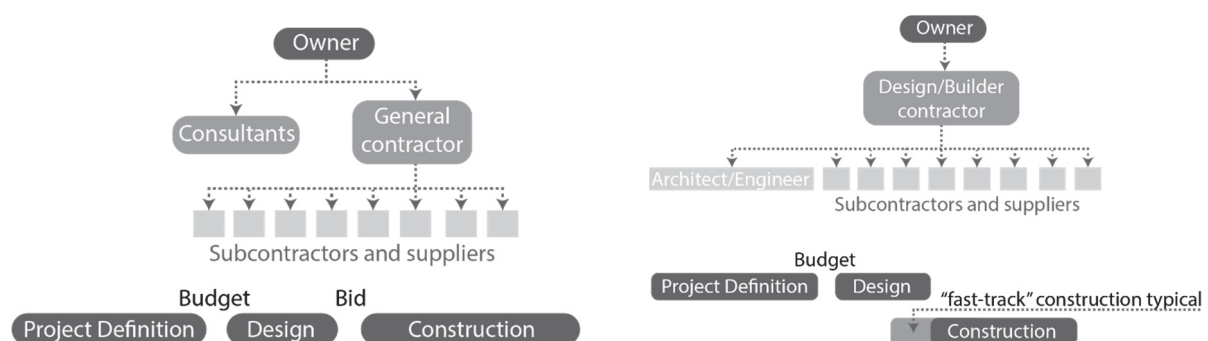


Fig. 7- Structure and schedule of the traditional Design Bid Build and Design Build delivery system

Construction management:

In the construction manager as constructor delivery system, the construction manager is hired to complete the design phase as a project coordinator and general contractor. The CM works directly with the architect or project team. Once the tender document is defined, the construction manager invites contractors or subcontractors to bid for the various works of the project.

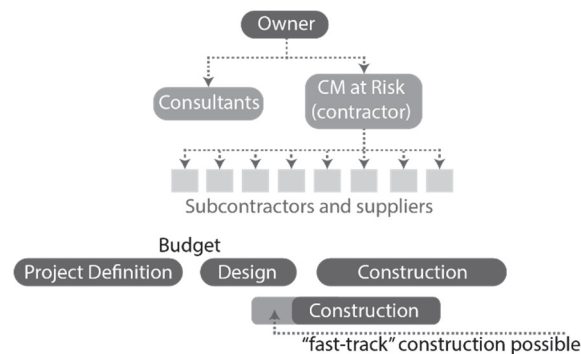


Fig. 8 - Structure and schedule of the traditional Construction Manager at risk system

Integrated project delivery:

Integrated Project Delivery (IPD) is an approach to reach a procurement that integrates people, systems, business structures and practices into a process based on collaboration between them. That optimizes the project results, increases value to the owner, reduces waste and maximizes efficiency through all phases of design, fabrication and construction. The IPD projects are distinguished by highly effective collaboration among the stakeholders.

The core of the Integrated Project Delivery is the interconnection among all members because of the use of new technological tools. The team is guided by principles of trust, transparent processes, open information sharing and shared risk and reward. The outcome is the opportunity to design, build and operate as efficiently as possible. The benefits of IPD comes from new technologies that, when utilized in conjunction with collaborative processes, make increases in productivity and decreases in field conflicts, waste and project schedules.

In practice, IPD differs from traditional models in two areas: team assembly and project phasing/execution. In an integrated project, the design decisions are as far as possible from a non-integrated project. They are more effective and less costly, often without the re-thinking of typical project phases.

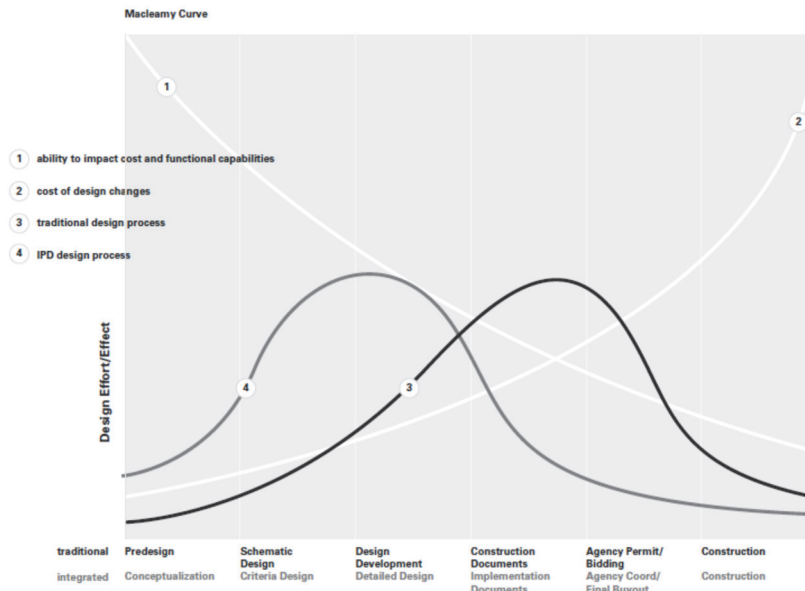


Fig. 9 - Differences between IPD project and traditional project

The design decision making is moved forward and is driven by two key concepts: the early integration of constructors, installers, fabricators and suppliers; the ability to model and simulate the project accurately using BIM tools. These concepts enable to complete the design to a much higher level of completion before the starting of the documentation phase.

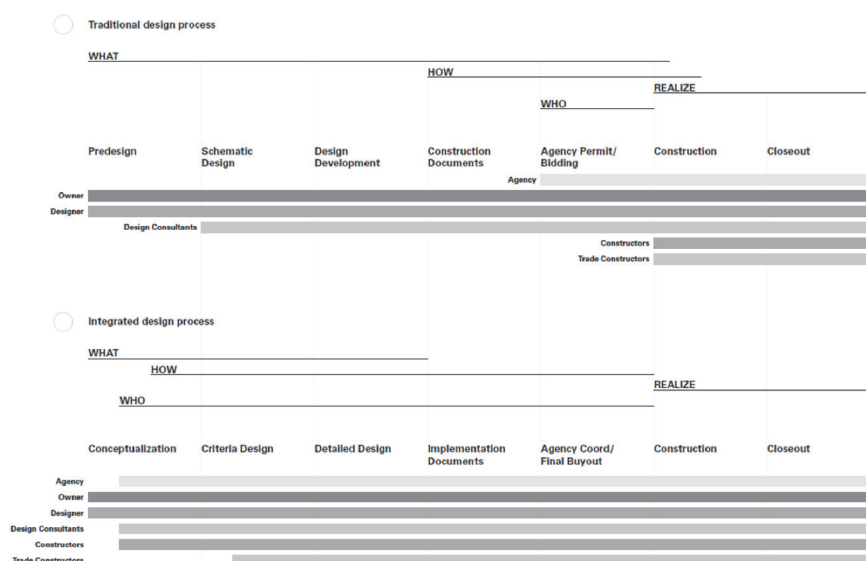


Fig. 10 - Delivering an Integrated Project

Construction:

Once contractors and other stakeholders have been appointed and designs are sufficiently advanced, work may commence on the project site. Typically, a construction site will include a secure perimeter to restrict unauthorized access, site access control points, office and storage areas for materials, machinery and equipment. The construction methodology or execution planning is provided in accordance with contract requirements. The works are based on the tender scheme program and are submitted initially after the contract award. The project control is required for the following documentation:

- *Shop drawing preparation;*
- *Material procurement;*
- *Arranging subcontractors;*
- *Material delivery;*

The program dates for these items derive from the overall project schedule.

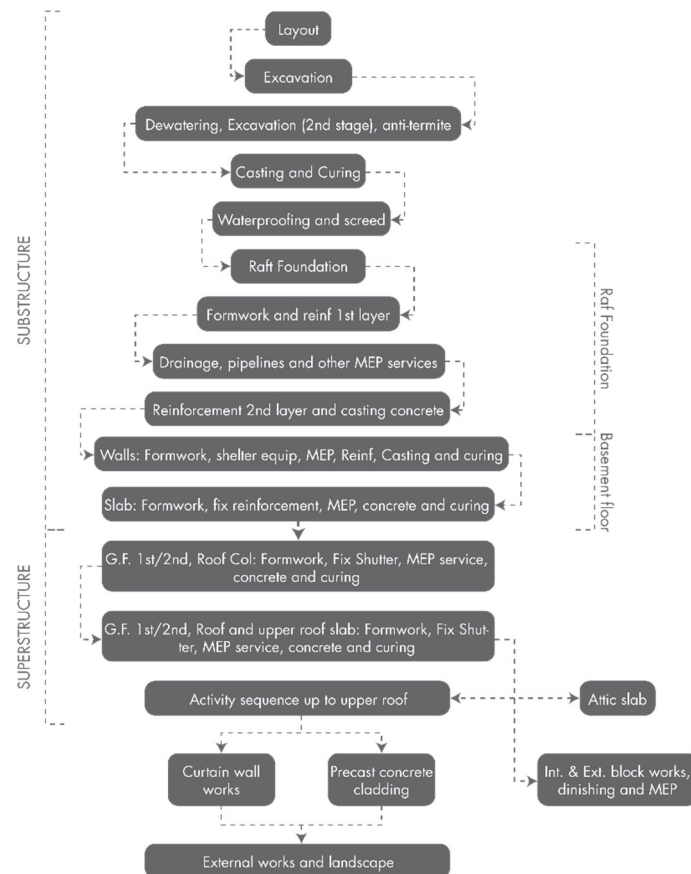


Fig. 11 - Construction methodology flow chart

On-site construction:

There are a few common examples of traditional construction techniques:

- *Brick and block*: it is the most common method used, especially in the construction of internal blockwork walls, surrounded by external walls of brick or stone;
- *Timber frame*: this is another common method in construction of houses, in which a rigid timber frame is used as the internal structure of the building. That method is usually adopted in small construction, while for larger structures it is difficult to build with.
- *Steel frame*: this method takes the same approach, using a steel frame for the internal structure of the building. It is most frequently used in the large scale constructions, for its absence of complications and for its working quickness.

The use of these methods brings some advantages such as a sturdy building which can be completely unique. However, there are even many issues. In fact the completion of the project becomes weather dependent, and any adverse weather can damage the work already completed. In on-site works, the builders have to follow a more linear method, which means it can take longer to finish and so cost more. The main problem is that the different worker groups can't do their labor at the same time, but they must follow a sequence of works, until the refinement and the works' end.

To contrast these issues, recent developments in computational design and digital fabrication with concrete enable the realization of freeform geometries that optimize the material use and the site management. 3D concrete extrusion printing (3DCP) is one of the new methods to build on-site with concrete. The main advantages is the shaping concrete without formwork and placing material only where functionally required. The new design tools open up opportunities for architects and engineers to create more sustainable and lean structures.

Prefabrication:

The off-site techniques take a very different approach to the construction of buildings. These methods involve a building being constructed in a context away from the building site itself. The different elements are assembled within the workshop and then are simply transported to the building site and put together in a matter of days. The first advantage that prefabrication brings is the speed in which a project can be completed. Prefabrication has long been recognized as a green production technology to minimize the adverse environmental impacts such as waste, noise, dust, and air pollution.

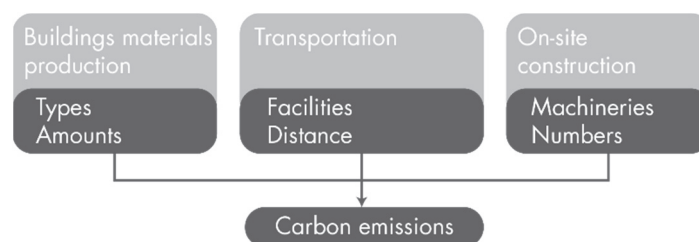


Fig. 12 - System boundary of life cycle assessment of carbon emissions of buildings

Construction waste means the solid garbage generated from construction activities, such as site clearance, excavation, construction, refurbishment, renovation and demolition. It Mainly contains waste construction materials.

Level	Description	Examples
0	Cast in-situ	Conventional construction technologies, using formwork and falsework, rebar and cast in premixed concrete
1	Component and subassembly	Components like doorsteps, lintels, and so on, to be formed as functional components such as doors and windows
2	Non-volumetric assembly	2-dimensional precast concrete wall panels, precast components with no usage space enclosed, e.g., precast concrete partition wall, precast lost form, semi-precast slab, non-structural prefabricated external wall
3	Volumetric assembly	Encompassing all 3D preassembled units enclosing usable space but do not constitute part of the building structure, e.g., volumetric precast bathroom, precast kitchen, precast water tank, precast refuse chute
4	Modular building	3D preassembled volumetric units forming part of or the complete building structure, like motel rooms, MiC

Fig. 13 - Taxonomy of different levels of prefabrication

At the beginning, the prefabrication was often used in the low-rise houses construction, but over the years its use has increased in high-rise building projects in metropolitan cities such as New York, Tokyo, Singapore, Hong Kong, and many other densely populated places.

The perfect material for prefabrication is the steel, with its strong and tensile strengths and ability for free extension. The manufacturing of the building out of the worksite, means that the labors are not affected by the weather and the building is assembled at a faster rate. With the increase in speed comes the decrease in overall cost, making buildings produced through off-site methods an extremely cost-effective expansion solution. Actually there are different levels of prefabrication adopted, ranging from full cast in situ to complete prefabrication.

Another application of the off-site construction is the modular construction. In this method, many modules are prefabricated and are assembled or integrated with onsite built structures such as steel frames, elevator shafts and stairwells. The modular prefabrication leads to minimizing project completion time and cost. It enhances productivity, increases quality and improves safety.

2.1.2.1. Lean Construction:

The construction industry is seen, by researchers, as a slowly developing industry that is suffering from low productivity and poor performance compared to other industries. It has been criticised for being inefficient, wasteful, a high-risk and low-profit industry. Most of those criticisms can be traced to the industry characteristics such as construction companies' high sensitivity to market conditions, lack of an industry-level strategic vision, low-entry barriers, competitive tendering mechanisms, small profit margins, short-term and temporary organisational configurations. The analysis of project plan failures indicates that normally only about 50% of the tasks on weekly work plans are completed by the end of the plan week and that constructors could mitigate most of the problems through active management of variability, starting with the structuring of the project (temporary production system) and continuing through its operation and improvement.

In the early 1990s, to improve the performance of the industry, under the term Lean Production System (LPS), some researchers developed a new production management method for the project management practices learning from the Japanese manufacturing, in particular the Toyota Production System (TPS).

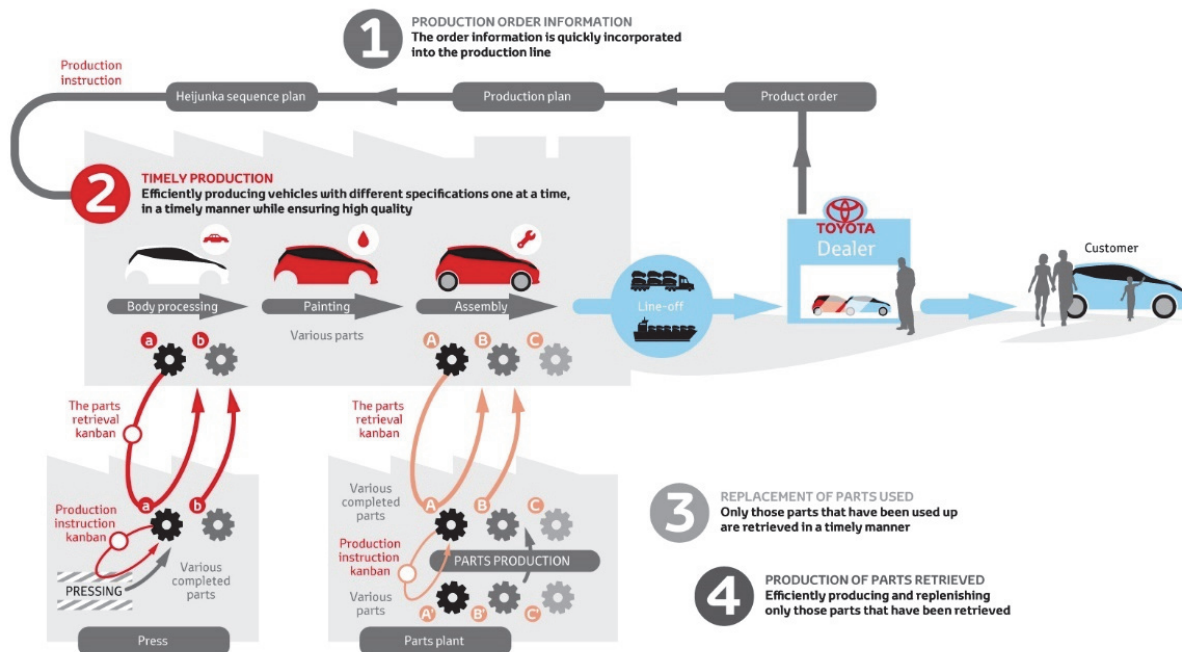


Fig. 14 - Toyota Production System (TPS)

With time, all the techniques and principles adapted into the construction industry and construction project delivery mechanism were called Lean Construction (LC). Lean found its way into the construction sector by Koskela (1992), which, with a series of studies, proposed a new efficiency improvement method with focus on cost and waste reduction. Lean Construction principles came into play after understanding the demerits of craft and mass production. It is all about reducing waste and maximizing the value, that is the relation between time cost, quality and function. Talking about wastes, there are eight types of waste identified: defects, overproduction, waiting, non-utilized talent, transportation, inventory, motion, extra-processing.

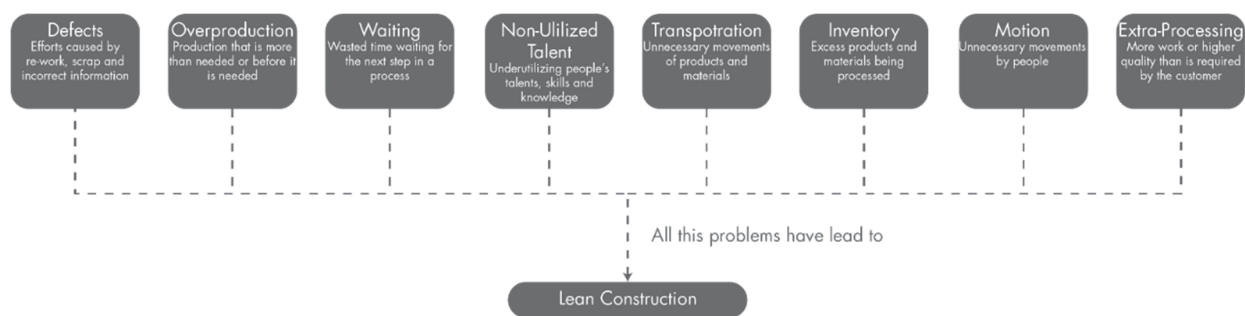


Fig. 15 - Wastes of construction industry which lead to Lean Construction

LC is the application of lean manufacturing principles and practices to the end-to-end design and construction process. This approach tries to manage and improve construction processes with minimum price and maximum value by considering the client needs, while it helps to achieve and maintain sustainability objectives across the entire construction supply chain. Unlike manufacturing, construction is based on the project production process. It presents a practice oriented development in construction management and construction projects by encouraging the reduction, through learnings from LPS, of some important problems and wastes of construction industry such as: fragmented supply chains, relationships between actors influenced by a culture of conflict, low-profit margin, frequent time and space conflicts in on-site production, low productivity and quality, slow-take up of innovation and change.

With the recent world climatic problems, which influence the environment and the buildings indeed, the new guideline of the construction sector is sustainability. This approach is developed under three different but complementary thematics: Environmental, Social and Economic. A sustainable construction looks to reduce the amount of wastes of the various production, but also to fulfil the subject involved (customer, employees, communities, etc.) and to reduce the total expenditure of the works, trying to finish just in time. To keep the complexity manageable, key actors are divided into supplier (responsible processing, logistics and distribution), developer (responsible for the planning and delivery), and customer (involved in design and occupancy). Nowadays the IPD type relational project procurement is revealed as the best suited technique to link the Lean Construction method to the construction project.

In IPD, main construction project organisations act as an integrated unit through inter-contracts among each other based on proportional profit and risk sharing, as a compensation and incentive mechanism. However, the reluctance of the use of LC in macro industry is due to the fact that IPD is subject to various barriers:

- *Cultural*: the unwillingness of the industry to change its traditional supply and procurement methods;
- *Financial*: issues associated with selecting compensation and incentive structures commensurate to the unique characteristics of project suppliers;
- *Legal*: liability and insurance issues;
- *Technological*: ownership, liability and interoperability concerns in the integrated use of technology to achieve collaboration;

However the Lean Construction is applied in the small and medium-sized enterprises (SMEs). The SMEs represent 99% of all businesses in the EU and their importance in construction is increasing, particularly in developed economies, where many large contractors prefer not to retain permanent staff and outsource construction activities to smaller companies, acting more like project management or project integrating organisations. However, SMEs are more prone to variations in the economy, therefore, they do not have spare resources to invest in innovation. The progress and development of construction is encouraged by big enterprises which research new methods to reduce the expenditure of the works. Some of the major works of big companies are developed by the synergy between Lean Construction methodologies and the use of the BIM, which fulfils and completes some LC principles. The use of BIM reduces variation, in fact the ability to manage information integrity, including design model, and the automated generations of report reduces the wastes of re-work and waiting for information. This affects the economic impact on construction. Also BIM reduces the cycle times, cutting it from entry process to completion and shortening the amount of work in the various stages. This is relevant in design management, construction planning and control on-site. Furthermore, BIM enables visualization, simulation, and analysis of both construction products and processes. Visualization greatly helps clients understanding the design of a building, and requirements capture is improved. BIM helps align the various project

team members of the project, removing much of the waste that results from inconsistent designs across disciplines. Designers can simulate and analyse building performance to improve functional planning. For contractors and their suppliers, visualizing the construction process supports better planning and production control. Finally, and perhaps most obviously, where used effectively, BIM improves information flows, modular construction and increased prefabrication of building parts and assemblies.

<u>Principal Area</u>	<u>Principle</u>
<u>Flow process</u>	<u>Reduce variability</u> Get quality right the first time (reduce product variability) Improve upstream flow variability (reduce production variability) <u>Reduce cycle times</u> Reduce production cycle durations Reduce inventory <u>Reduce batch sizes (strive for single-piece flow)</u> <u>Increase flexibility</u> Reduce changeover times Use multiskilled teams <u>Select an appropriate production control approach</u> Use pull systems Level the production <u>Standardize</u> <u>Institute continuous improvement</u> <u>Use visual management</u> Visualize production methods Visualize production process <u>Design the production system for flow and value</u> Simplify Use parallel processing Use only reliable technology Ensure the capability of the production system
<u>Value generation process</u>	<u>Ensure comprehensive requirements capture</u> <u>Focus on concept selection</u> <u>Ensure requirement flow down</u> <u>Verify and validate</u>
<u>Problem-solving</u>	<u>Don and see for yourself</u> <u>Decide by consensus, consider all options</u>
<u>Developing partners</u>	<u>Cultivate an extended network of partners</u>

Fig. 16 - Lean Construction principles

Commissioning:

The building commissioning (Cx) is a process for ensuring efficient building operation that can be applied to new construction and existing buildings. It is the method intended to verify and document that all the construction systems of a building work are made as intended to achieve the owner's project requirement (OPR) and as designed by the planners. There are different typologies of commissioning based on a particular nomenclature:

- Cx: generic commissioning;
- EBCx: existing building commissioning;
- MBCx: monitoring-based commissioning, a sub-process of EBCx;
- NCCx: new construction commissioning;

At the beginning, commissioning referred to the testing of the heating, ventilation and air conditioning (HVAC) systems of a building. Nowadays it includes energy and water conservation, occupant comfort, life-safety, system criticality and technology improvements. The service method can vary from owner to owner and project to project, but the scope is the same, i.e. the development of owner's project requirement. For new construction the process begins with periodic site observation during the construction phase and continues through inspections, testing, balancing, acceptance, training and an agreed-on warranty period near the completion of the structure. It therefore encompasses all the necessary planning, delivery, verification and risk management of critical functions performed in, or by, facilities. Cx also achieves a higher energy efficiency, improved environmental health and occupant safety. It basically confirms that all the systems are efficient and cost effective.

The commissioning is proposed to deliver preventive and predictive maintenance plans, operating manuals, and training procedures.



Fig. 17 - General scope for building commissioning and the major systems that typically need it

Maintenance:

To ensure that the buildings and other assets retain a good appearance and operate at optimum efficiency the main process to follow is the maintenance of the construction and its elements. Inadequate maintenance can lead to decay, degradation and reduced performance. Also the bad maintenance of the building can affect health and threaten the safety of users, occupants and others in vicinity. Depending on the design, the quality of materials and of workmanship, the function and the location, the buildings can deteriorate at different rates and need different types of attention.

The quality of the design and of the workmanship can minimise the level of maintenance required. Indeed, the maintenance can help to maintain the structural stability and safety, prevent unnecessary damages, optimise the performance, reduce emissions of the building, etc.

This process should be organised through a program of cyclical maintenance. At the first point it includes daily routines, works upwards to periodic programs of weekly, monthly, annual and so on routines. At the quinquennial point the stakeholders are involved in the inspection for structural and other serious damages.

As said, there are different types of maintenance:

- *Planned maintenance*
- *Preventive maintenance*
- *Corrective maintenance*
- *Front-line maintenance*
- *Proactive maintenance*
- Reliability centred maintenance
- Scheduled maintenance

The Building Owner's Manual (or Operation and Maintenance Manual), contains the information required for the operation, maintenance, decommissioning and demolition of a building. It is prepared by the contractor and defined during the preliminary section of the tender, containing the requirements regarding structural, mechanical, electrical and plumbing services. When the building's services have changed, in new buildings

and also in existing buildings, the building log book is required to facilitate the Facility Management. FM is concerned with the management of the facilities in the built environment, delivering operational objectives and maintaining a safe and efficient environment.

2.1.2.2. How the proposed methodology can improve the built environment management:

Through the developed methodology, which will be explained in the next chapter, the entire built management and construction industry can improve. In fact it can help the contractors during the procurement stage, with a new interactive way of visualization, entering in an advanced level of IPD, where all the parts are involved in the process. It should optimize the construction process by introducing a different type of plan output, by the use of Extended Reality (VR, AR and MR), facilitating the elements pose, improving the construction site security or optimizing the computation of time and costs of the works. Also, this technique can be applied in the prefabrication, with the easier pose of the different panels in the 3D geometry, recreating accurate visualization of the joints. In the commissioning phase it is useful to verify the correct work execution and the right component placement, by the comparison of the project and the final product images. This comparison can be placed inside an archive, which registers all the changes applied in the examined building and can be used for the maintenance or the demolition of the building.

2.2. Critical issues

The management of the built environment, compared to other industries, like manufacturing or industrial, has a slower process for the development of a project or its production. This is affected by the gradual improvement and procurement of the new changes and technologies refined with the time. In fact the major problem of this sector is the lock in the traditional work phases. While, nowadays, the research on new types of materials or building methods is making many profits, with more sustainable and prolific typologies of constructions, the research and the application of new tools for the work process is very sluggish, and its results are difficult to be applied into the construction context. This is due to the inadequate preparation of the subjects involved in the project, from the planners to the constructors, as well as the amount of expenditures required for the initial step of the beginning prototypes and methodologies proposed.

The optimization of the working process of the construction industry is far from being really efficient, creating sometimes additional costs or even the failure of all the projects, leaving unfinished and dilapidated structures. The first step of this study was the research of arguments, documentation and essays to analyse the main issues that can influence this world. The result of this first research found out several primary problems which will be discussed below.

2.2.1. Data required at the beginning project stage:

One of the main issues that already appears in the early stages of the project is the considerable time and expense required to generate the building construction plan. In 2D-based communication the amount of information required to develop the feasibility studies, cost estimates, scheduled design, structural design, energy-use analysis etc. is enormous and slows down the beginning stages of planning, including a considerable number of re-workings on the changes and outline schedule. All this elaboration of information and delays are one reason for increasing costs in the construction world, and the presence of unforeseen events produces unnecessary waste of time.

In large projects, like civil-engineering constructions (bridges, dams, viaducts, maritime works, energy installations...) or strategic buildings (airports, railway stations, skyscrapers, office buildings...), that are major works for the site cities and communities, the total of subjects involved is considerable: over hundreds of designers, engineers and managers. In those cases the time for the coordination of the 2D-based works is impressive and raises the work-related expenses.

Unlike the 2D-based project, in the BIM projects, the data management is easier and the interconnection among the stakeholders makes an efficient workflow. But, like for the traditional method, also for BIM the amount of data acquired in the preliminary phases of the project is extremely high and normally the time for its acquisition and management is limited. This problem resulted in a slow start-up process, mistakes or missing information and waste of unnecessary time.

2.2.2. Data as only geometry:

Surveying is the only method to acquire information from an existing structure or from a new construction site. As just said, the amount of data required is huge, and, for big working sites, it is arduous to take that amount of data. Nowadays, there are different techniques to make a surveying, starting from a traditional laser distance measurer and trilateration, to laser scanning and photogrammetric tools.

The photogrammetric method is faster and more accurate compared to other methods, in fact, the creation of a point cloud and the photographic documentation, can help to recreate geometries with a high level of accuracy. The problem of the existing methods of surveying is the use of the acquired data only for the geometries losing the possibility to make smart this information and use it for the development of the project design. With this working method is required another process of manually importation of the data during the design, modelling for example the facilities or other detailed elements. Sometimes, the modelling is unnecessary or unrequired, wasting a lot of work and time during the preliminary stages of a project.

2.2.3. First modelling phase with high level of detail:

During the first phases of a project, the level of detail required for the models is unknown. This consideration allows the planners to develop models and designs that contain a lot of information and data. The modelling of all the geometries and the integration with their properties require time and this can be a problem if in future the project should change and so the model. In fact, the eventual changes need to be re-worked, increasing the costs of the project. Also, in the primary stages, what information is useful for the development of the design is unknown, and it is necessary to retard as possible the modelling. That can't happen because of the urgent necessity of a model and lead to inaccurate or incomplete design.

2.2.4. Missing informations:

The short time required for the design production and the building engineering sometimes leads the project planners to quick drawings with a lack of information. At the beginning, during the research by the builder, the final set of drawings and specifications must contain sufficient detail to facilitate the construction bids, but at the same time the initial stage of planning can't afford that level of detail required. This problem through errors and omissions often leads to disputes with the contractor, extended times for re-working on changes and reallocated extra costs. Another issue with the contractors or subcontractors happens when the shop drawings (which must be the most detailed representation to use for fabrication) are inaccurate, incomplete or based on older designs, which could make additional significant cost efforts.

2.2.5. Re-working on the project:

Another reason for an increase of time is the re-working of the building design and engineering. That could happen because of different reasons: request of changes from the client; errors found in the planning; unmet demands of laws by structural design, energy-use analysis, fire-fighting plan, etc.

After the identification of the problem, the re-working comes from the implementation of requests of modification, corrective actions, preventive actions and correction of defects. Later these changes can be fulfilled and accepted or elaborated again, increasing time and costs through another re-work. During the beginning of the project the costs of the changes are extremely low as opposed to the stakeholder's influence that is high. But with time, the costs raise rapidly while the influence of stakeholders decreases. This inequality includes the expensive works in the terminal phase of building where the planner's control is lower and there are few solutions to the problems.

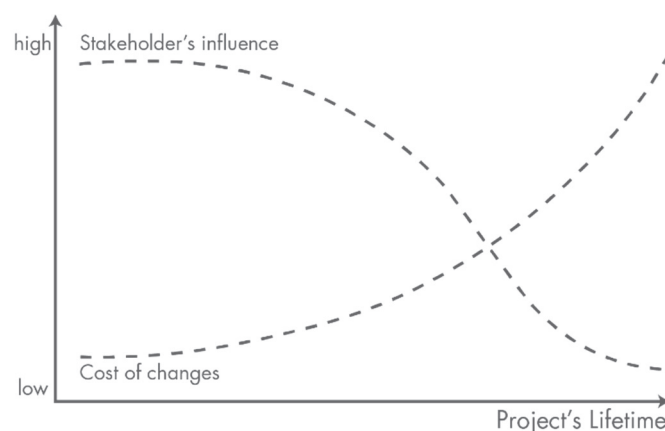


Fig. 18 - Influence of change costs during project's lifetime

2.2.6. Errors due to 2D design:

Before the beginning of the design, site analysis, site surveying and geotechnical investigations are required. The construction normally cannot start until planning permission has been granted, and may require preparatory work to ensure relevant infrastructure has been upgraded before building work can commence. After this first stage, the design of the structure starts. Depending on the product service, some design stages may be irrelevant, ignored in real-world situations in order to save time and reduce cost. Typical stages of the design process include: pre-production design; design during production; post-production design; re-design. In addition to the architectural drawings, it also includes the structural, the facility and other engineering drawings.

The conceptual design is the first phase of the 2D-based planning. It is followed by reviews and iterations (re-works) to fix the design. The schematic design phase starts when all the re-works on the conceptual design are performed and accepted by the owner. After his approval, the design team can proceed to the detailed design phase. The architects start by developing the design concept and then generate information deliverables like preliminary massing and orientations of the project. These deliverables are stored as documents, and after the architectural design ends, are passed on the structural/civil engineers. Then, they proceed with the development of their own concept design and the production of information deliverables. During all these phases, the MEP (Mechanical, Electrical and Plumbing) engineers wait to receive the data deliverables from the architects and the other engineers, to start developing their project. After the finalization of the preliminary project design, by each planner involved, the necessary adjustments should be performed, sharing the documentations in iterative feedback loops, until the owner's approval.

Many problems of the traditional 2D CAD design are created by the waiting of the different participants for each other's design completion. Also the data deliverables are stored before they can be exchanged between the various teams. That could make the data obsolete and create wastes. The iterative loops and re-works create limited communication and information sharing. The data tends to go back and forth between

the various stakeholders in several loops before the design deliverables can exit the loop through the approval of the owner. Since the deliverables are in 2D CAD, any adjustment has to be reflected in all other documentations.

Also in 2D-based models the amount of work required makes it very difficult to draw in an accurate way. This outline model most of the times excludes the out-site fabrication and construction by forcing the planners to define an on-site building system that often is costlier, less safe and with minor quality control. The difficult interpretation of 2D causes inconsistency, inaccuracy and uncertainty in design, providing errors during the construction phase that need to be resolved by the project team through changes that implies time and costs increase. Because of all of the information provided on paper or on electronic files, the project manager finds it more difficult to deliver all the relevant information to builders first and facility management teams later. Also for the builders, it is difficult to understand the 2D papers provided by the project team, often creating misunderstandings and errors in the construction, which are usually very relevant and significantly increase the expenditure.

2.2.7. Timing of information learning:

The majority of construction projects are still conducted traditionally with the use of 2D drawings, reports, schedules and photo logs, making the process complicated and inefficient. This is time wasting, inclined to error, costly, and remains a significant barrier to effective building operation and maintenance.

In a recent research by Arizona State University, *Jad Chalhouh and Steven K. Ayer* [3] analysed the traditional construction method compared to a new method with mixed reality. In this case study was required to a number of industry professionals (engineers, managers and electricians), divided in two groups, to assemble an electrical conduit, one group using paper printed design and the other one using a MR visor. The different use of each approach between the two groups has emphasized the timing of information learning: the traditional method group required about 3 times the time used by the other group.

The conclusion of this study is the evaluation of the waste of time required for the information learning, this involves learning. This results in augmented costs of the construction process.

Activities durations for different visualization methods				
Activity	Visualization method (time in seconds)		Difference (Paper plans - MR)	Percentage - value
	Mixed Reality	Paper Plans		
Looking at information	64	191	127	0.00478

Fig. 19 - Arizona State University study on information learning by paper plans and MR

For an architect or engineer, preparing the intervention on-site could be arduous, in fact they have to evaluate the climate changes on the works that with concrete or wood materials can make the good success of placement and operating; long times with bad weather. Recurrent bad weather prolongs the working schedule which results in additional costs. Both planners and builders influence the construction process, particularly in the on-site fabrications where the timing of materials and facilities placement is actually relevant. Referring again to *Chalhoub and Ayer* study.

They observed much time is needed for the placement and the assembling of the electrical conduit by the paper plans group, while for the Mixed Reality group the working process was really fast. The importance of the Arizona State University research is the analysis of the waste of time during the information learning, the founding of the right pieces for placement, the positioning and the assembling by the traditional method of construction. All these operations can be optimized, reducing also the critical increase of the building costs, by the use of new technologies like Mixed Reality and the creation of twin models.

Activities durations for different visualization methods				
Activity	Visualization method (time in seconds)		Difference (Paper plans - MR)	Percentage - value
	Mixed Reality	Paper Plans		
Placement and Positioning	5	85	80	<0.000001
Assemble conduit	277	504	227	0.000081

Fig. 20 - Arizona State University study on material placement by paper plans and MR

2.2.8. Information managing and storing:

After the structure building, the next stage is the maintenance of the construction. This phase requires the information of all the processes and the working achieved on the structure during all its life cycle. The problem in the traditional construction process is the research of needed information because of the paper based model of output, also the storage of the amount of the project sheets is also problematic. The building changes over time are major problems. Indeed, the storage of information most often gets lost and it is hard to find the timeline of layer structure of achievements.

2.3.Digitalisation

The construction sector and its activities strongly affect the economic, environmental and social development. Construction is a horizontal sector, serving many industries and services. This sector faces numerous challenges related to competitiveness, labor shortage, resource efficiency and especially productivity. Construction suffers from low financial returns and has been slow to take up the process and technology innovations that could help it, with respect to both profitability and performance. Traditionally this sector has focused on making improvements, but nowadays it is more difficult than in the past. Projects are even larger and more complex. The growing demand for environmentally sensitive construction leads the traditional practices to change, and, often, there is a shortage of skilled workers and supervisory staff. These are deep issues that require new ways of thinking and working.

Today, digitalisation has become a popular concept around the world, by its ability to create efficiency in operations and provide new opportunities. Industries such as banking, manufacturing and retailing have all come to understand the benefit of digitalisation and have keyed into the future by using it as a new approach for ensuring competitive gain and efficiency. While these other industries have adopted the use of this development, the construction industry is yet to fully accept the delivery of its services.

This failure to use the inherent benefit of digitalisation has significantly affected the industry, especially in developing countries, as no major transformation is evident within their construction sector. There is a need to change using new technologies like BIM, to fully implement it in all facets of its activities. The European Union Commission recognises the digitalisation of the construction sector as a potential game changer, which could contribute significantly to sustainable development. It is estimated that the full-scale digitalisation in non-residential buildings could lead to annual cost savings of 0.6 - 1.0 trillion € (13% to 21%) in the engineering and construction phases and 0.3 - 0.4 trillion € (10% to 17%) in the operations phases. The EU has promoted several policies and initiatives aiming to foster digitalisation in the construction sector.

These include the “Strategy for sustainable competitiveness of the construction sector and its enterprises”, the “EU BIM task Group” and the “EU Digital Construction Platform”. In EU Member States, the construction industry has adopted digital innovations, with the use of BIM as the main method. The use of digital technology, leads to many benefits, for example: the inclusion among the subjects involved in procuring construction projects; the improvement in process quality; the increased responsiveness and productivity; expansion in market; the facilitation of outlines of schedule in construction procedure; less re-workings; etc.

There are three main challenges for construction digitalisation:

- *Technical*: include issues, interoperability, scaling up data, information management from single asset to networks of assets, data accuracy, development of automated data description and analysis tools.
- *Governance*: include negotiating security and access to information.
- *Social*: include reluctance to invest time or money in digital transformation or bridging digital skills gaps.

The digitalisation of the construction can be applied to different building and civil labors. For example, technology and photogrammetry could be used in higher-definition surveying and geolocation, through the use of 3D laser scanning with drones, which gives geographic information systems and improves surveying speed and accuracy.

Also, it could increase the digital collaboration and mobility, through the interconnection of the subjects involved by the managing of the deliverables and the archiving of the project's data. The most important development of digitalisation could be the Internet of Things and advanced analytics. The management of the vast amounts of data through sensors and wireless technologies could speed up the whole project, creating an intelligent platform for the workers. It could be realised through smart machinery, equipment, materials and structures that can improve the quality, the energy efficiency and the safety.

2.3.1. Building Information Modelling:

Industry 4.0, digitalisation, smart building, virtual reality: these are terms that are also entering into the common use of a traditionalist sector such as construction. The Building Information Modelling is the most recent stage of a revolutionary path that has profoundly transformed in the last thirty years the world of design in the construction industry in all its various forms and skills: architectural, engineering, management, etc.

BIM involves a new way of approaching the conception, execution and maintenance of the work. This new approach considers and manages in a unified manner the architectural, structural and engineering projects' characteristics and properties, including materials, components and systems. It is useful for the planning of the construction phase, execution time and costs and maintenance works. The information is considered as part of a single process extended along the entire life cycle of the product, that prevents and reduces errors or inconsistencies, and also optimizes the executive verification and control process. The BIM methodology adoption and development, involves a redefinition and expansion of the "dimension" concept in projects. According to the National Institute of Building Science (NIBS), Building Information Modelling is by its very nature connected, in addition to 3D modelling, to construction times, defined as 4D, and to the management of construction costs, defined as 5D; these first three dimensions are also accompanied by phase 6D, inherent to the project environmental sustainability characteristics, and phase 7D, relating to Facility

Management (FM). If 3D modelling allows the creation of intelligent parametric objects that also permits the instant modification of the project, the 4D dimensions makes possible to view the activities related to the realization of the work, generating Gantt time diagrams for the control of the construction stages. The 5D dimension, on the other hand, is aimed at controlling the costs of the work: in fact, from the work, it is possible to obtain schedules and metric calculations to plan and control the costs of the project. With the 6D it is possible to analyse the performance of the building right from the first design phase, optimizing its overall energy efficiency. Finally, with 7D, the project enters the Facility Management dimension: in this context, the BIM approach makes it possible to use the data and information, developed during all the phases, in order to guarantee the product management over time and undertake the necessary maintenance actions. Each phase of the development, execution and management of the project draws evident advantages from the adoption of the BIM approach compared to traditional methods of project management, in terms of operational flow productivity and precision. In the design phase, in particular, the use of BIM allows the creation of virtual models that improve and expand the data management and the information quality, allowing designers to work in a collaborative way, on shared technical choices, with an immediate identification and resolution of project inconsistencies. The BIM model also allows to carry out simulations or precise calculations of materials, automatically generate component schedules, perform advanced calculations related to different aspects of the project (lighting, energy requirements, acoustic performance, etc.). Overall, the high degree of precision, the information detail and the consequent improvement in the efficiency of all stages of the process is able to generate important added values, increasing the clients competitiveness, design firms and manufacturing companies, and ultimately constituting a decisive factor of competitiveness on the market.



Fig. 21 - BIM dimension

2.3.1.1. Information and communication technology

From 2D and 3D assisted design to parametric design, this innovation has led to a profound change of perspective in the way of conceiving the work in all its phases, from concept to execution and subsequent management. BIM through its tools and applications is capable to manage all the information, from the design of the individual elements to the calculation, from time management to the verification of technical and financial information, in a sort of “ecosystem” capable of hosting, relating and updating in real time all the data and information necessary for the entire life cycle of the constructions. In this perspective, BIM modelling incorporates not only information relating to the building geometric characteristics, but also all data relating to resources (material, economic, human and temporal) necessary for the work realization. Sharing of information, interoperability, digital standards, Common Data Environment (CDE): these are some of the most important conceptual bricks on which the development of this new methodology represents the future for the whole construction world. Compared to traditional methods, the advantages offered by BIM are many, first of all in terms of optimization of operational flows and, consequently, of productivity. In fact, BIM is not limited to expanding the database of the data contained in the three-dimensional models of the project and the possibilities of sharing them; these advantages also have important repercussions in terms of time and cost optimization. Another impact is the complete elimination of errors, inconsistencies and interferences, thanks to real time updating of all project tables and documents. A further important aspect of BIM innovative approach is the high integration between the design phase and the executive phase, through interactive analysis scenarios between the 3D models processed. For the economic aspects, it is possible, for example, to view the cost and analyse prices and costs, generate budget and site WBS views. The last dimension of BIM is the management of the completed work: the availability of a complete final model in all its parts that gives a marked efficiency in the field of facility management activities.

2.3.1.2. Level of Detail

Within the BIM approach, the Level Of Detail (LOD) has the task of precisely defining the level of depth of the various information contained within the model. In this perspective, the LODs represent a defined point of reference that allows all those involved in the project to specify and articulate the construction of a BIM model with a high degree of clarity and reliability of its contents. In particular, the AIA's standard BIM protocol, "G202-2013, Building Information Modelling Protocol", defines the contents and degree of details of the various LODs.

According to this document, the degree of development can be obtained through the elaboration of a building or infrastructure model and it has been divided into 5 levels:

- LOD 100: Conceptual representation;
- LOD 200: Generic models and quantity indication;
- LOD 300 - 350: Executive design;
- LOD 400: Construction design;
- LOD 500: As built;

In accordance with this framework, all drawings and documents relating to the project are automatically generated with a degree of detail in accordance with the LOD of the project itself.

According to the Italian legislation, in particular the UNI11337-4:2017, the definition of LODs is slightly different, but the principles are the same of the AIA's definition:

- LOD A: the elements are represented graphically through a symbolic geometric system taken as a reference with no constraint on geometry. Quantitative and qualitative characteristics are indicative;
- LOD B: the elements are graphically virtualized as a generic geometric system. Qualitative and quantitative characteristics are approximate;
- LOD C: the elements are graphically virtualized as a defined geometric system. The qualitative and quantitative characteristics are defined generically in accordance with the limits of the current regulations and technical standards of reference;

- LOD D: the elements are graphically virtualized as a detailed geometric system. The qualitative and quantitative characteristics are specific to a defined plurality of similar products. Interface to other building-specific systems is defined, including approximate manoeuvring and maintenance encumbrances;
- LOD E: the elements are graphically virtualized as a specific geometric system. Quantitative and qualitative characteristics are specific to a single manufacturing system related to the defined product. The level of detail related to manufacturing, assembly and installation is defined, including specific handling and maintenance dimensions;
- LOD F: the objects express the on-site verified virtualization of the specific production system executed/constructed. The quantitative and qualitative characteristics are those specific to the individual production system of the product laid and installed. The management, maintenance and replacement interventions, to be carried out throughout the life cycle of the work, are defined for each individual product;
- LOD G: the objects express the updated virtualization of the actual state of an entity in a defined time. The management, maintenance and/or repair and replacement operations to be carried out throughout the life cycle of the work are defined for each individual product.

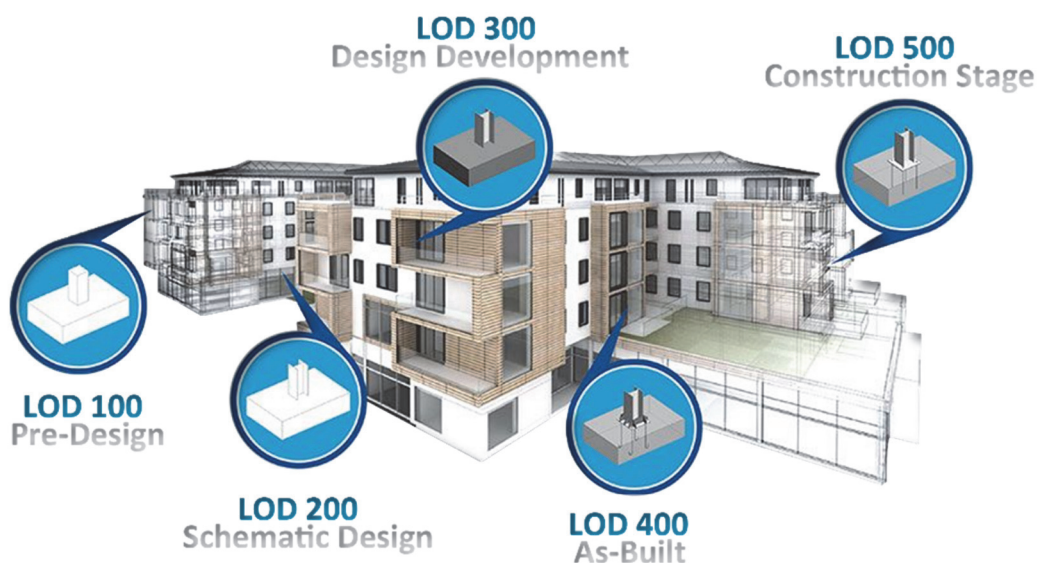


Fig. 22 - Definition of Level of Detail

2.3.1.3. Industry Foundation Classes

Industry Foundation Classes (IFC) is an industry-developed product data model for the design and full lifecycle representation of buildings, based on ISO standard (ISO 16739). It has broad support from most software companies, in fact, the Industry Foundation Classes is the most commonly used data-model in AEC. It is a schema developed to define an extensible set of consistent data representations of building information for exchange between AEC software applications. IFC is designed to address all building information, over the whole life cycle. Because IFC is defined as an extensible data model and is object-based, the elements can be elaborated and specialized by sub-typing to make any number of sub-entities. At the top level of the IFC data model are the domain-specific extensions of these object and relation entities, which are based on Structural Elements and Structural Analysis Extensions, Architectural, Electrical, HVAC, and Building Control Element Extensions. All IFC models provide a general building spatial structure for the layout and accessing of building elements. IFC organizes all object information into the hierarchy of Project -> Site -> Building -> BuildingStorey -> Space. Each higher-level spatial structure is an aggregation of lower-level ones, plus any elements that span the lower-level classes. Because of the IFC hierarchical object subtyping structure, the objects used in exchanges are nested within a deep sub-entity definition tree. All physical objects, process objects, actors, and other basic constructs are abstractly represented similarly. The *IfcObject* level provides links to properties of the element, based on its type (defined lower down in the hierarchy tree). *IfcProduct* defines the location of the element and its shape. *IfcElement* carries the relationship of this element with others. There are many types of assemblies, P-sets, and features that can support structural, mechanical, and other system elements. Analysis models, load data, and product performance parameters can also be represented in some areas.

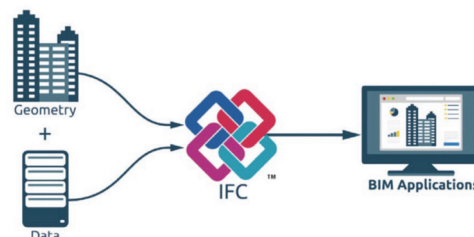


Fig. 23 - IFC input scheme

2.3.1.4. BIM common data environment

The concept of interoperability is deeply rooted in the Building Information Modelling (BIM) methodology. In the Informatic Technology (IT) field, interoperability indicates the ability of a system to exchange data and information with other systems or programs, allowing a dialogue between software and different applications characterized by high reliability and minimization of errors. Transposed to BIM, interoperability consists in the possibility of exchanging the data, contained in the initial design model, between different software and application platforms. While the traditional software, dedicated to the management and processing of data, lacked the ability to integrate each other, the transversality of the BIM approach necessarily requires maximum accessibility of information to all subjects involved. The key to this accessibility is IFC. Complementary element to the BIM, the "Data Sharing Environment" is called ACDat in the UNI 11337-5 standard or CDE (acronym for Common Data Environment) in the British BS PAS 1192 standards. The CDE is explicitly mentioned in the recent Italian BIM Decree as a platform for the archiving, sharing and management of project data. It represents one central element of the digitalization process in construction sector. From the definition contained in the English legislation, the CDE is divided into four areas (Work in Progress, Shared, Published Documentation and Archive). The specific characteristics and properties of the CDE are taken up and defined by the unified Italian reference standard, the UNI 11337-5, which has qualified the Data Sharing Environment as the container for all information related to the works. In this virtual environment, data and models, as well as all the project relevant information, are deposited, processed, reviewed, shared and published, so the flow of operations is synchronized according to predefined rules.

The National Building Information Modelling Standard (NBIMS) categorizes the Building Information Model (BIM) three ways:

- as a product;
- as an IT based deliverable, and a collaborative process;
- as a facility lifecycle management requirement;

Another way to characterize BIM is to define a levelled progression maturity of the information technology application in construction which also expresses the process degrees of collaboration:

- *BIM Level 0*: 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. 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, where all parts 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 parts. 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).
- *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 parts 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."

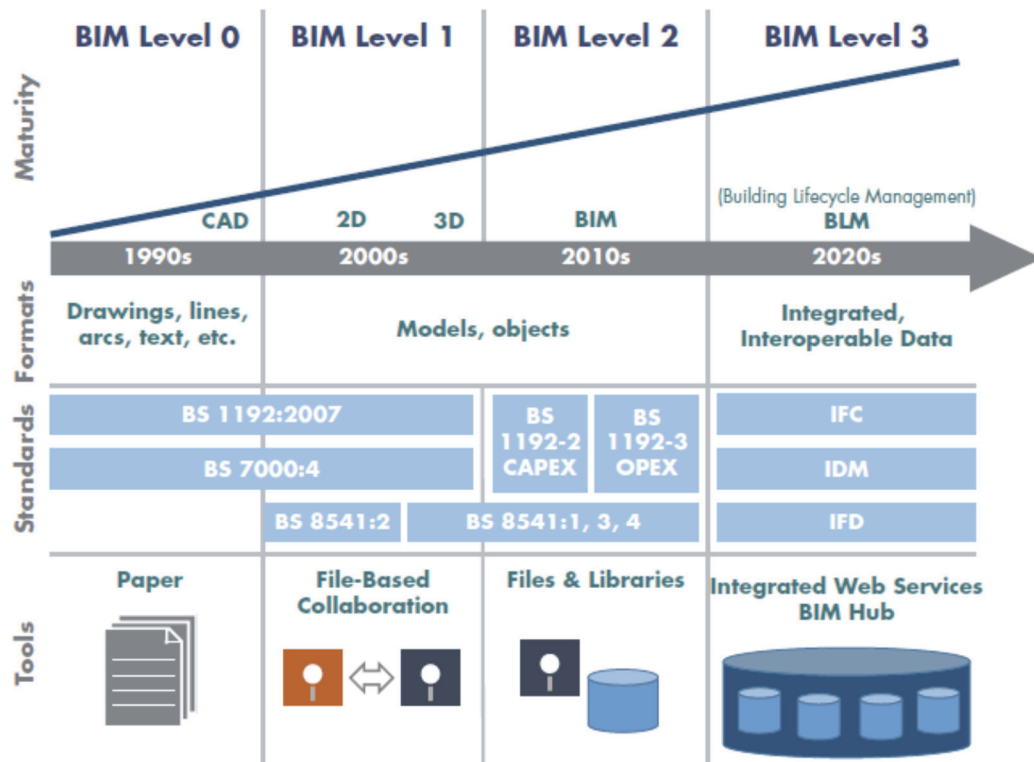


Fig. 24 - The BIM maturity model by Mark Bew and Mervyn Richards

2.3.1.5. BIM processes and tools

With the introduction of 3D modelling, the advanced geometries can describe a building model through its contents or its capabilities. This has changed the modelling process by overlapping the traditional CAD digital files, which consists in vectors, lines and layer identification, with additional information within the model geometry. Construction models are characterized by building components which are represented by objects that carry computable graphic and data attributes to identify them. The components include consistent and nonredundant data that describes how they behave, needed for analyses and work processes. For the first run study of a construction process, the Virtual Design and Construction (VDC) is used as a building information modelling to focus on the production process. These types of studies are standard practices in lean manufacturing and lean construction. With the VDC the planners test all the processes (including facilities, work process, supply chains...) in a virtual way before executing works in the field to construct the building. This is done to identify and remove constraints, improving project performance and the resulting facilities.

The BIM software are developed in the following hierarchy:

- *BIM tools*: an information sender, receiver and processor, used in association with BIM platforms;
- *BIM platform*: core information generator with functions to maintain the integrity of a model based on the parametric and object-based modelling capability;
- *BIM environment*: : A set of BIM applications that are interfaced to support multiple information and process pipelines in a project, an organization, or a local construction sector. BIM environments encompass the various BIM tools, platforms, servers, libraries, and work flows within the project or the organization;

The most known BIM platform is Revit, introduced by Autodesk in 2002. It provides an easy-use interface with drag-over hints for each operation and smart cursor. It offers a different editing layer, from 2D drawings to 3D interface for the direct modelling of the building. Revit supports hierarchical relations of parameters. Indeed has the largest set of associated applications, linked through IFC exchange format. It supports different types of formats, including DWG, DXF, DGN, SAT, IFC, gbXML and ODBC (Open DataBase Connectivity).

2.3.1.6. Benefits

Each development, execution and management phase of the project, has evident advantages from the adoption of the BIM approach compared to traditional methods of project management, in terms of operational flows, productivity and precision. The expansion of the database in the three-dimensional model and the possibility of sharing, entails, in one hand, important repercussions in terms of time and cost optimization, and on the other hand, a strong reduction or elimination of inconsistencies, duplications and interference thanks to the real-time updating of all the project tables according to the variations made and, consequently, to errors and subsequent corrections. In the design phase, in particular, the use of BIM allows the creation of virtual models that improve and expand the data management and the information quality, allowing designers to work with collaborative networks, through shared technical choices, leading to immediate identification and resolution of project inconsistencies.

The BIM model also allows to carry out simulations or precise calculations of materials, to automatically generate component schedules, to perform advanced calculations related to different aspects of the project (lighting, energy requirements, acoustic performance, etc.), to generate renderings and 3D animations. In the execution phase, BIM allows to overcome the inefficiencies typical of traditional methods by creating a real and effective integration between the planning and executive phases. Overall, the high degree of precision, the information detail and the consequent improvement in the efficiency of all stages of the process is able to generate important added values, increasing the competitiveness of clients, design firms and construction companies.

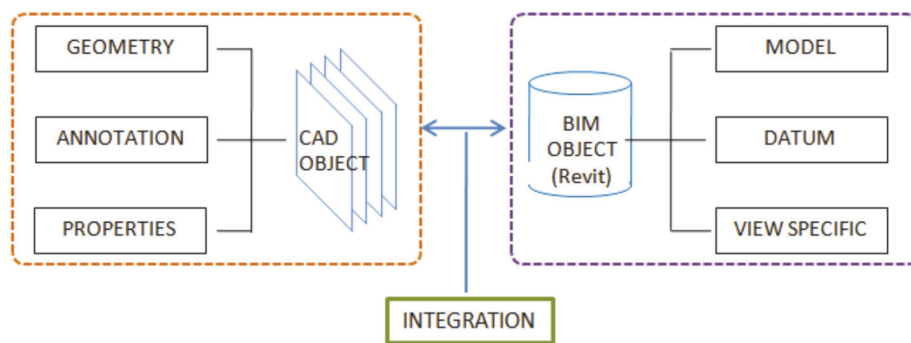


Fig. 25 - BIM integration of CAD properties

2.3.2. Extended Reality (XR):

The term Extended Reality refers to all real and virtual combined environments and human machine interactions generated by computer technology and wearables. XR includes Virtual Reality, Augmented Reality and Mixed Reality.

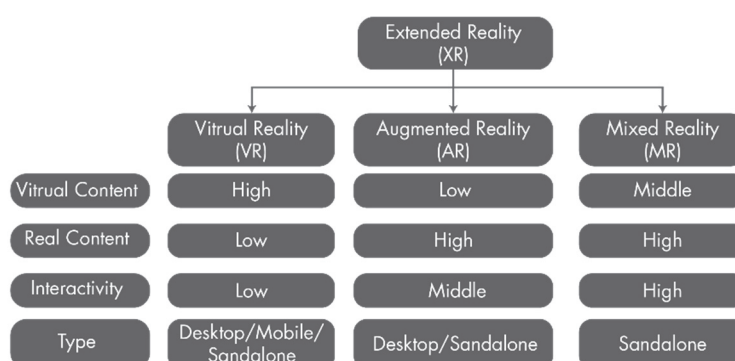


Fig. 26 - Comparison of VR, AR, and MR wearable technologies

Extended Reality provides a large number of levels in the Virtuality from partially sensor inputs to Immersive Virtuality. This helps the AEC industry to realise more efficient projects and develop all the phases of the construction process under more supervised works.

Virtual Reality excludes the real world, creating a virtual content and environment, which immerse the user, simulating his physical presence in that environment. This happens with the use of realistic images generated by different softwares and devices. VR can be used in architecture and engineering for the first visualization of the project, which enables a better understanding of complex designs, identifying its issues. Virtual Reality remains a digital experience, while Augmented Reality combines real and digital into one immersive environment. By the use of cameras and advanced sensors AR combines the surrounding with digital elements generated in real time. The combination of digital and real helps the stakeholders to work in a more efficient, accurate and confident way. The computer generated content is often viewable from economic devices like smartphones or tablets, which provide a very limited viewing experience.

There are four types of Augmented Reality:

- Marker-based AR (like QR codes);
- Location-based AR (like GPS);
- Projection-based AR;
- Superimposition-based AR (like the placement of virtual furnitures in real environment);

One of the major innovations of AR is the ability for users to make changes to the building's models directly on the field site. The workers can display interior and exterior views of a structure and make any modifications to the virtual plans while keeping one view intact. For example the users would be able to remove and relocate walls or components or modify the layout using only a few taps on their devices. Also the Augmented Reality can allow users to virtually see the building's progress against its schedule, even producing an additional level of project management. This technology provides the tools for construction companies to plan a project from start to finish, ensuring accuracy, preventing re-work and saving building costs.

Despite its potential, AR is still not used as much as possible, because of safety and comfort of users, who have to wear it for long working hours. Also the equipment is often susceptible to adverse weather conditions and it functions only with a solid internet connection and static environment. These are all factors that aren't always present on job sites.

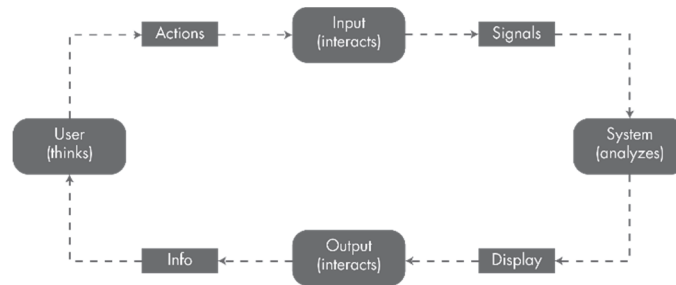


Fig. 27 - 3D user interacts

In addition to AR could be used the Mixed Reality (MR), which combines the best aspects of VR and AR. Mixed Reality is, as the name says, a mix between the real world environment and a computer-generated environment. This technology provides a new level of interactivity, but, at the same time, this category is somehow not well defined, creating problems with the VR and AR devices.

The only tools developed are prototypes like Microsoft and Trimble Hololens which allows the users to see the real world and the digital twin which overlays the first one. The potential applications of MR in the AEC industry are numerous, especially the overlapping or interaction of virtual and physical context on-site.

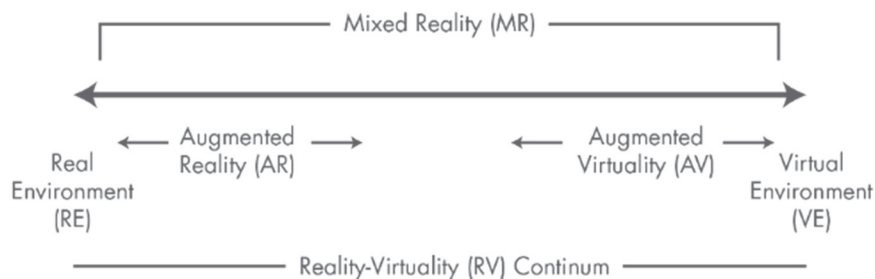


Fig. 28 - Reality - Virtuality continuum

2.3.3. Twin model:

A digital twin is the combination of a computational model and a real-world system, designed to monitor, control and optimize its functionality. It is a virtual representation in real-time of a physical object or process, and while it could appear to be an exact replica, however, digital twins are not necessarily realistic representation, but relevant abstraction of the physical asset. They can help with the management of assets by keeping records of inventory processes, historical data and additional equipment.

The digital twins have three main elements: a physical product, a digital match and the connection between them, which is the exchange of data, information, and knowledge.

Digital twins have the following characteristics:

- Connectivity;
- Homogenization;
- Reprogrammable and smart;
- Digital traces;

2.3.4. Game Engine

A game engine (GE) refers to a collection of modules of simulation code that develops the game's behaviour and environment. It influences the game graphics, configuration files, the inputs, the outputs, like 3D rendering, and the game physics and dynamics. The structure of GEs is based on three vital components of a game: Game tools, Game Utility and Game content. Tools refer to all the mechanisms used to develop a game, such as camera editor, material editor, configuration files and game map. The Game content refers to all related features in any game, like graphics file, audio file, and network components, which allow the connection and the data access between multiple users. Utility components define all needed data types, message formats, and required files.

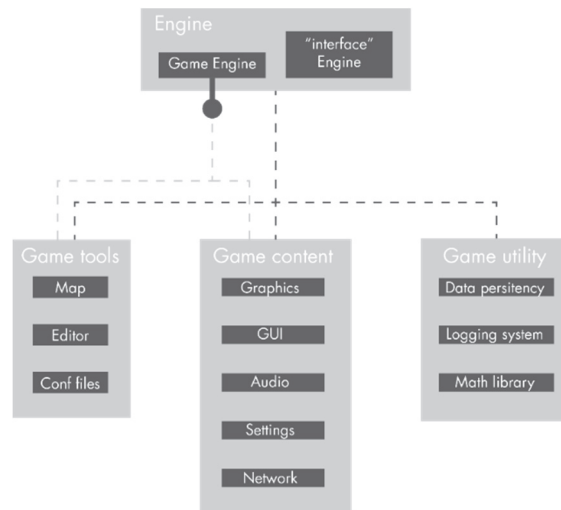


Fig. 29 - Game Engine component

In large-scale construction projects, the process of monitoring the implementation of every single part of buildings and reflecting them on the BIM models can become highly labour intensive and error-prone, due to the vast amount of data produced in the form of schedules, reports and photo logs. Today, information management in the construction industry has become one of the biggest problem and challenge. For a building, a huge number and variety of information is required. The solution should be the cloud database systems, which can manage huge amounts of data and share them with interconnected stakeholders. These systems are the base of today GEs, which have the ability to connect gamers all around the world and share data and information between them.

In the AEC industry the game engines offer a technological platform used for the performing of feasibility studies, design, performance analysis, generation of data, etc. GEs provide an excellent platform for virtual environments and coupled with the models created through BIM platforms, can be used as integration and implementation platform, but also as 3D rendering engine and as a tool for developing Virtual Reality and Augmented Reality applications. For a long time, VR and AR have been used for design and construction prototyping, while nowadays, they are entering in the planning, construction, management and maintenance worlds. The possible exchange of IFC data between different platforms, without loss of information, and the integration with coding languages, has transformed the game engine into one of the most useful and important tools for the AEC industry. It could be the future of this business for the coming years.

2.4. Surveying

Building surveying is the procedure of purchasing information, such as the construction typology, the materials used, the geometries, the condition of the structure, the level of deterioration etc. From this information, it is possible the planning of the future works or interventions that can be actuated in the construction. The surveying is useful also for the individuation of the changes of any type applied in the beginning building and the production of an archive that explains all the works over its lifetime.

2.4.1. Geometric surveying:

The geometric survey has the aim to build a discrete model of the building, through the detection of the 3D space position of some significant points of the structure. Depending on the tools and procedures used, there are different metric surveying methods:

- *Direct surveying*: carried out by the operator with the help of simple measurement tools, such as the metric distance measurer, plumb bob, etc. The direct surveying is used for the detection of plans and sections;
- *Indirect surveying*: carried out with cameras and tools, which allow to extract information from all the frames to directly build a geometric model of the object;

Direct surveying

The construction of a discrete geometric building model requires the use of a coordinated system of vertical and horizontal directions. The vertical direction is first established by the use of gravity, then it can be found horizontal, that is orthogonal to the vertical. This process is easy and should be made through the use of plumb bob, which helps also to take correct horizontal measurements in relation to the vertical direction. For the horizontal direction it is useful the spirit level, that indicates the orthogonality to the vertical direction and the parallelism to the floor. The main tool for the distance measurement is the laser distance measurer, which is an ultrasonic distance meter with

a laser pointer. Once measured all the building distances, the first step is the sketching of the ambient plans and sections with the measured dimensions.

To determine the mutual position of the significant number of points of the building it is necessary to define a reference system that connects the measure phase with the sketch and design phase. The reference system is defined by tracking a polygon or a broken line (open or closed), that is used as the basis of the trilateration operation. In fact, for direct surveying, the principal method of measurement is the trilateration that guarantees the quality of the result, allowing the detection through the subdivision in triangles of spaces that can even be complex. The triangle is a useful figure in surveying, because it is non-deformable and therefore it can be drawn only knowing the length of the three sides (trilateration).

2.4.2. Photogrammetry

The other method to obtain the geometric model of the building is through indirect methods like photogrammetry. Photogrammetry is the science of acquiring information through the process of recording, measuring and interpreting photographic images. Photogrammetric surveying is used for high precision surveys, to receive a large amount of information, for large surveying or in presence of considerable complexity of architectural forms and for inaccessible buildings. It allows the detection of the measure and the representation of structures and the simultaneous computation of several points, without having physical contact with them. There are different types of photogrammetry:

- *Architectural*: characterized by a distance between the sensor and the observed object at most of a few dozen meters;
- *Aerial*: realized through the use of aerial photographic equipment flying above the observed territory. It goes from a minimum of 300 meters to a maximum of 20,000 meters;
- *Satellite*: made by satellites for the study of territorial resources;
- *UAV photogrammetry*: the unmanned aerial vehicle (UAV), or drone, is used for non-large areas and can support architectural photogrammetry for the surveying of buildings and infrastructures;

Photogrammetry differs from the direct methodology because it consents to survey objects without the physical contact with them, takes simultaneously an enormous number of different points and the measures are taken in a second time, not in the surveying moment. It is faster, economical and precise.

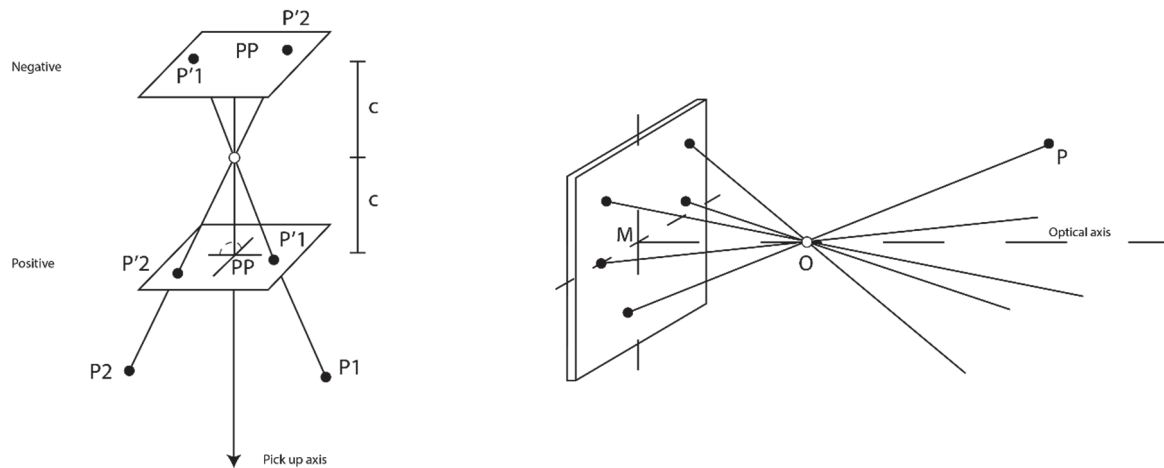


Fig. 30 - Photogrammetry principles

The collinearity equations are the principal analytical foundation of the photogrammetry and will be used in the following chapter to obtain the camera pose estimation. The photogrammetric application resolves the basic problem of relating the three-dimensional object space with the two-dimensional image space in a univocal way matching discrete points in the two systems of quantities. Therefore, there are three types of quantities identified:

- The 3D coordinates (X, Y, Z) of the object;
- The 2D (x, y) of the image;
- The values of the orientation parameters G (camera parameters);

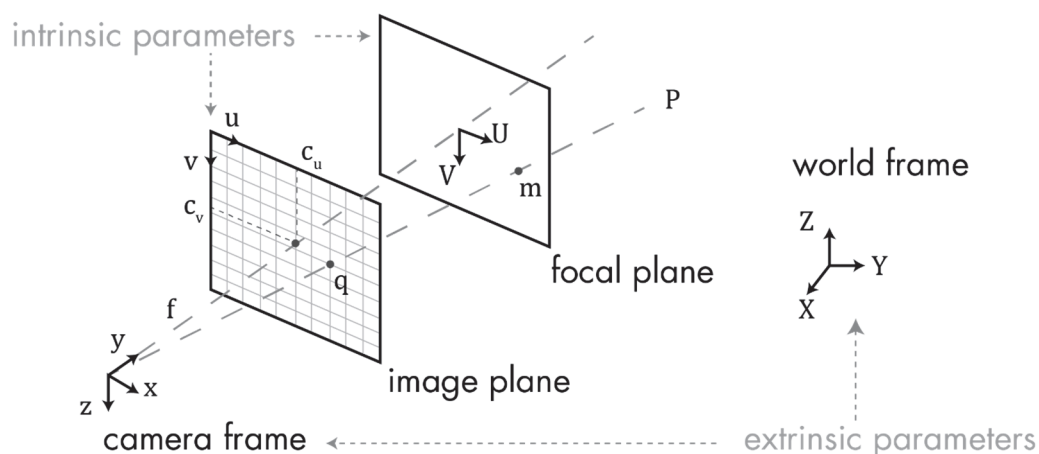


Fig. 31 - Camera stenopeic model

The intrinsic parameters are:

- The focal distance f ;
- Coordinates of perspective center (c_u, c_v) ;
- Distortion (errors of the target);

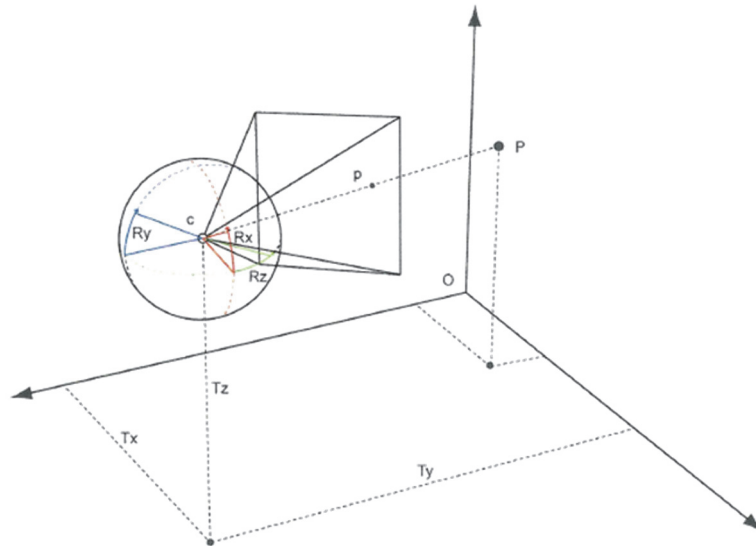


Fig. 32 - Camera extrinsic parameters

The extrinsic parameters are the camera position (T_x, T_y, T_z) and the camera orientation (R_x, R_y, R_z) . Through the combination of the internal parameters of the camera and the external world's parameters it is possible the geometrical reconstruction of the building, recreating a cloud point, which is measurable and scalable. This is a time-expensive method that requires a huge number of photos to recreate only a few rooms point cloud, but nowadays, with laser scanning and other specific tools, the reconstruction of the 3D geometries is more immediate.



Fig. 33 - Examples of laser scanner or mobile mapping tool

In the proposed methodology, a high number of equirectangular pictures are required to obtain the required information in the 3D model. The equirectangular panoramic photography is a photographic technique that allows the creation of pictures, which cover an angle of 180° in vertical and 360° in horizontal. The spherical images can be produced by a series of photoshoots or through specific cameras that automatically produce the 360° images.

2.4.2.1. Cameras

There are different typologies of cameras:

- Metric camera
- Semi-metric camera
- Non metric camera

In an ideal optical system exist two principal planes H and H' , the intersection between these planes and the optical axis (OA) defines the nodal points of the camera.

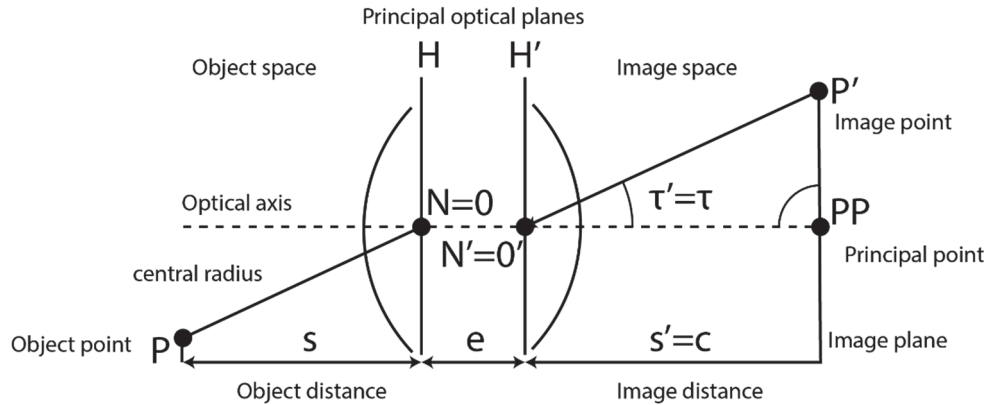


Fig. 34 - Camera ideal optical system

The camera lens is a system developed through assembling different lenses where the diaphragm is not central. His behaviour differs from the ideal optical system and produces different distortions.

If the panoramic image is produced with a normal camera, the first important thing to consider is the nodal point of the camera, which corresponds to the perspective center of the camera lens. Indeed, the camera needs to rotate around this point to obtain a perfect assembled image.

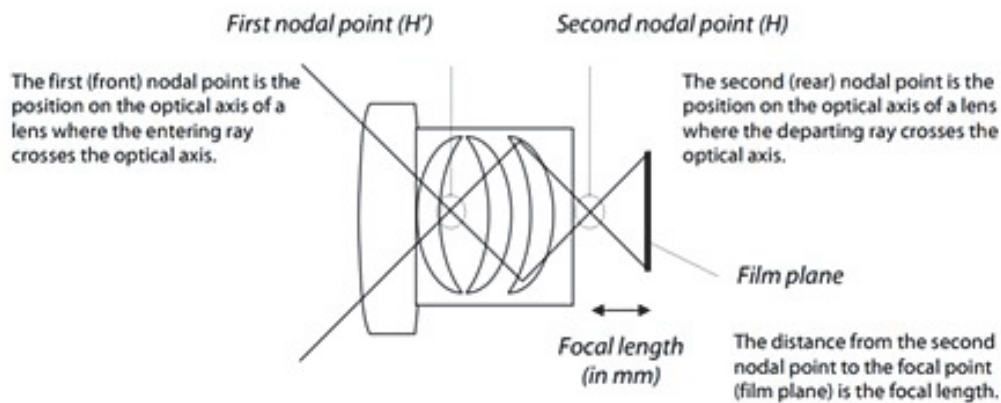


Fig. 35 - Camera real optical system

The pictures must be overlapped about 25% - 40% to obtain a perfect result with high quality and precision. The photos need to be taken with an homogenic sunlight, to not overcome different illumination in the various parts.

The equirectangular panoramic photography can be time-wasting and inaccurate if produced with a composition of images, so is more efficient and faster to develop it with a specific 360° camera. Cameras with a 360° panoramic view are tools to extend the FOV of common eyes and to simulate the process of observing the surrounding world. Differently from standard cameras, a scene of 360° cannot be projected on a single plane, the panoramic picture is formed by projecting the 3D world on a sphere from the central point. A 360° camera captures two images or video files from dual lenses with a 180-degree field of view and automatically stitches them together in-camera.

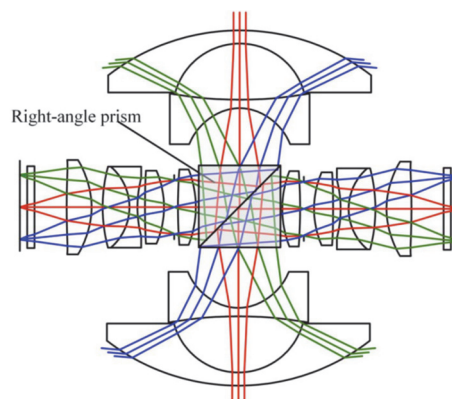


Fig. 36 - layout of the compact panoramic system with two imaging channels

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Methodology

The proposed methodology is about working on the built environment, but it could be applied, in a different way, also for the management of new buildings, by the construction works or safety of the workers control, the inside furniture design, the working stage control...

It starts with a rapid geometric surveying and detailed photographic documentation. In that way it is possible to recreate the basic geometric environment and through the pictures obtain a high level of information inside it. Once recreated the 3D - BIM model, with the use of a game engine, it is possible to make a navigation of data inside its geometries, through the use of the equirectangular photography. The importation of the IFC model helps to acquire the information from the model, while the images make a real-time rendered environment, which can be implemented with additional information added by the user. The scope of this research is the creation of a new professional method of working, speeding up the whole work and surveying process, with the achieving the pose estimation of the camera and the creation of an interactive system of data navigation. The conclusion is the creation of a historical archive of the developments of the building during the time.

3.1. Surveying

This approach starts with a low detailed geometric surveying. It could be done with the classic trilateration method, through a metric laser measurer or by the creation of a point cloud. The problem with the standard surveying models is that the combination of point clouds and photography doesn't always give the optimal solution. An example of this statement is the point cloud obtained through the photogrammetric surveying inside the construction department case study.

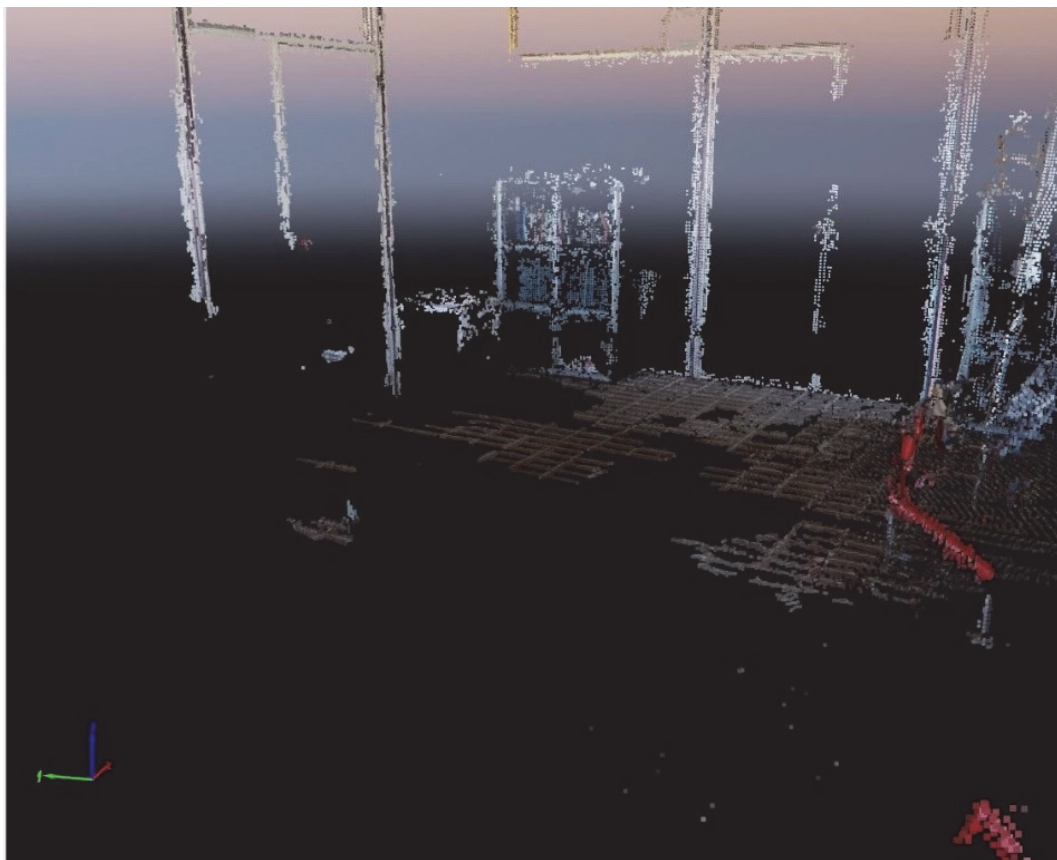


Fig. 37 - Point cloud from photogrammetric surveying

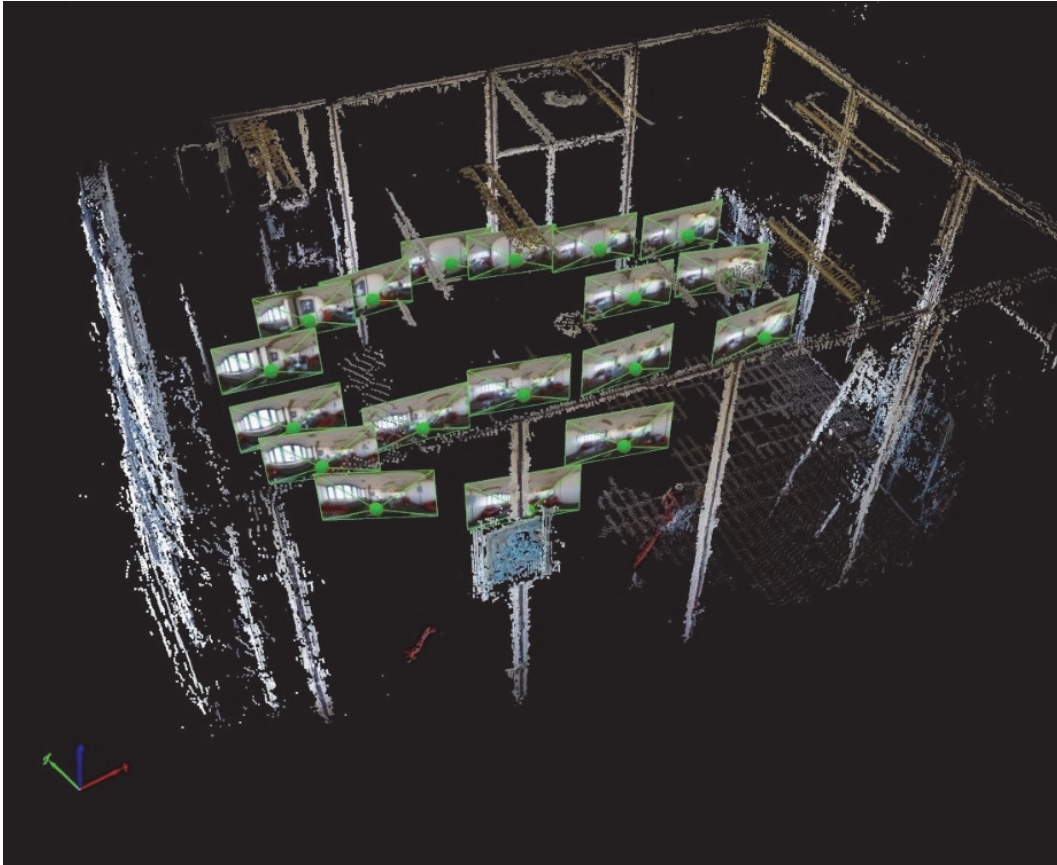


Fig. 38 - Point cloud from photogrammetric surveying



Fig. 39 - Geometric model from photogrammetric surveying

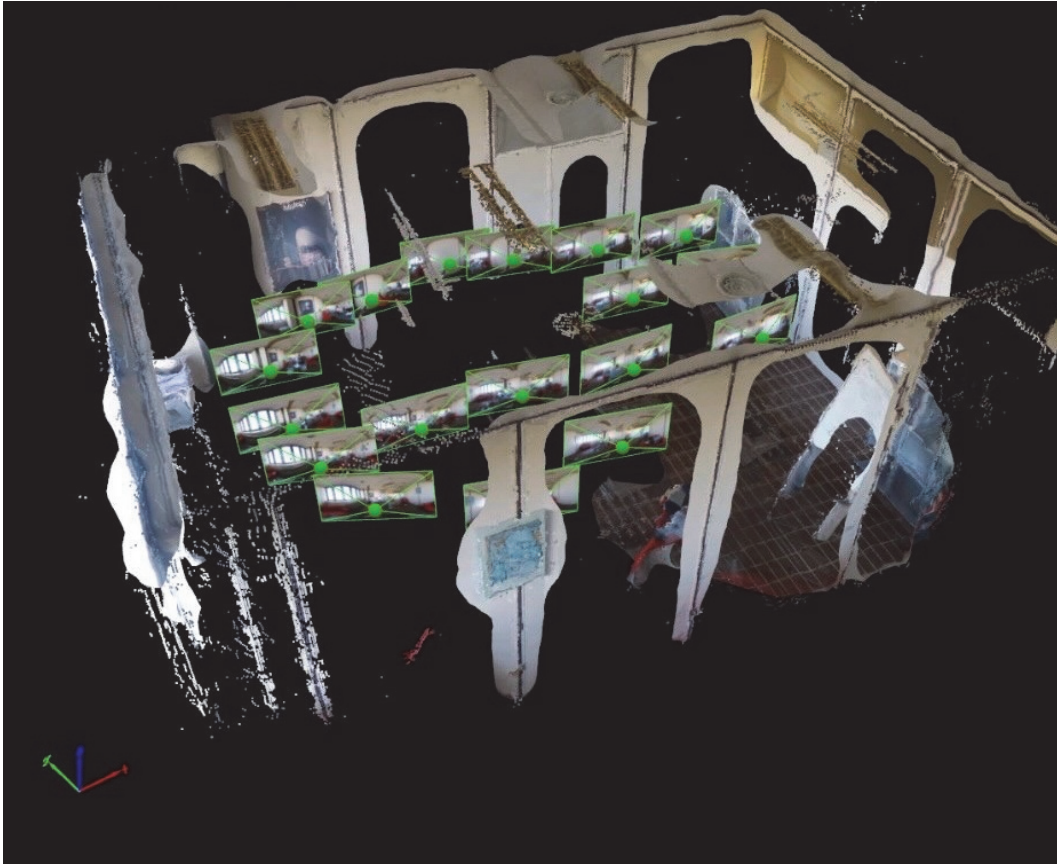


Fig. 40 - Geometric model from photogrammetric surveying

It's shown how the photographic surveying isn't optimal with the white elements, not representing in this case the room walls. The point cloud obtained by overlapping the different images has all void spaces where the walls should be. So it is required to develop a new method, which allows to clearly represent all the elements and where it is possible to obtain different typologies of informations, not only geometrical.

It is propounded to make a geometric survey using a direct point cloud tool, like GeoSLAM, and then make an accurate photographic documentation using the equirectangular pictures. It's recommended to have a large number of images of the ambients, to have an optimal visualization of the spaces. For example in the system development in Chapter IV are made two photos in the bigger environments and one in the smaller.

3.2. BIM modelling

With all the required data obtained, the next step of the proposed methodology is the design of a BIM model, with the definition of the basic properties of the elements. The analysed environment is reconstructed into a BIM software in 3D, with a Level of Definition 200:

“The model element is graphically represented within the model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the model element.”

Or for the Italian legislation at LOD C.

“The elements are graphically virtualized as a defined geometric system. The qualitative and quantitative characteristics are defined generically in accordance with the limits of the current regulations and technical standards of reference.”

Basically, the 3D model must contain the principal structure of the building, such as the structural system, flooring, walls, windows, false ceilings, etc.

That means that the BIM model represents the primary geometric system which, in the following phases, will be compared with the pictures for the alignment between 2D image space and 3D world space. After the alignment, the BIM model could be modified and implemented with the MEP elements or other details to have an as-built model, comparable with the photographs like a rendered model.

3.3. Camera pose estimation and image alignment

The proposed method is summarized by:

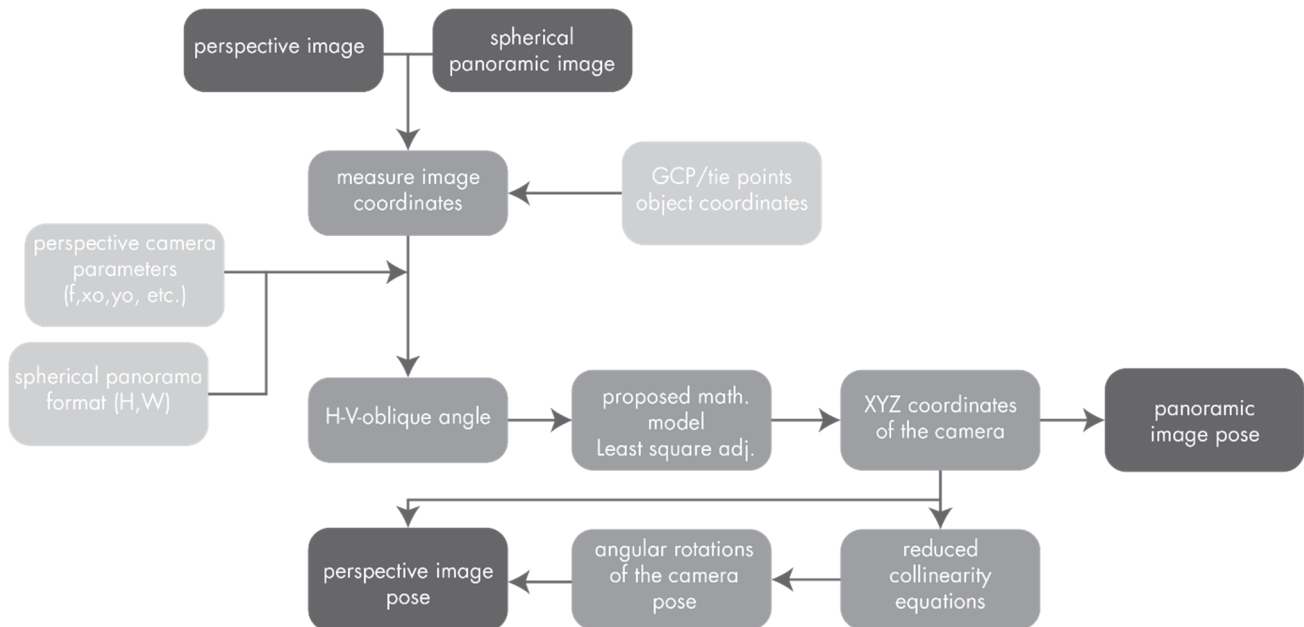


Fig. 41 - Oblique angular-based resection workflow

This scheme summarizes the subsequent, more detailed, analytical system of mapping the 2D equirectangular panoramic images, the measurement of these, their comparison with the world geometrical system, and the process of camera pose estimation and image alignment. In fact the main purpose of this research is the computation of the 3D coordinates of the camera, where the image was taken and the alignment of the picture with the developed BIM model. In that way it is possible to measure and annotate the photographic navigation through the use of the 3D model, and to implement this model with new detailed elements positioned with the help of the images.

3.3.1. Mapping 2D equirectangular photo into 3D space:

360° panoramas allow recording a 360° view of the place being photographed, which is used as an important source of Virtual Reality (VR) media. The most immersive way to view 360° panoramas is to use a dedicated head mounted display (HMD).

The equirectangular projection is a simple map projection that transforms planar coordinates into spherical coordinates. The reverse projection transforms from the sphere back onto the plane. The spherical model use these definitions:

- λ is the longitude of the location to project also called "yaw";
- φ is the latitude of the location to project also called "pitch";
- φ_1 are the standard parallels where the scale of the projection is true;
- φ_0 is the central parallel of the map;
- λ_0 is the central meridian of the map;
- x is the horizontal coordinate of the projection location on the map;
- y is the vertical coordinate of the projected location on the map;
- R is the radius of the sphere;

The longitude and the latitude are defined in terms of radians.

For the forward projection:

$$\begin{aligned}x &= R(\lambda - \lambda_0) \cos \varphi_1 \\y &= R(\varphi - \varphi_0)\end{aligned}$$

For the reverse projection:

$$\lambda = \frac{x}{R \cos \varphi_1} + \lambda_0$$

$$\varphi = \frac{y}{R} + \varphi_0$$

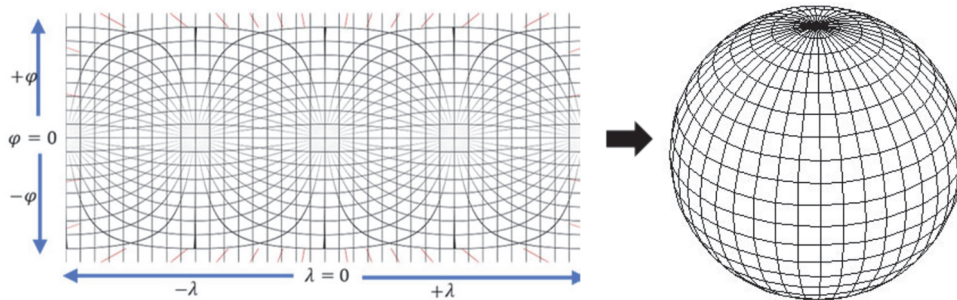


Fig. 42 - Points projected from 2D panorama equirectangular image to 3D space

To project the 2D coordinate of a pixel $P (x_p, y_p)$ in an equirectangular image ($width = W$, $height = H$) to its 3D spherical coordinate (x, y, z) , first is calculated its longitude and latitude coordinates (λ, φ) on the sphere by:

$$\lambda = ((x_p + 0.5) / W - 0.5) * 2 * \pi$$

$$\varphi = (0.5 - (y_p + 0.5) / H) * \pi$$

Then, is calculated its 3D coordinates on a unit sphere, where is set the 3D point $(1, 0, 0)$ as the original point, and set its longitude and latitude to 0. The 3D coordinates can be calculated as:

$$x = \cos \varphi \cos \lambda$$

$$y = \cos \varphi \sin \lambda$$

$$z = \sin \varphi$$

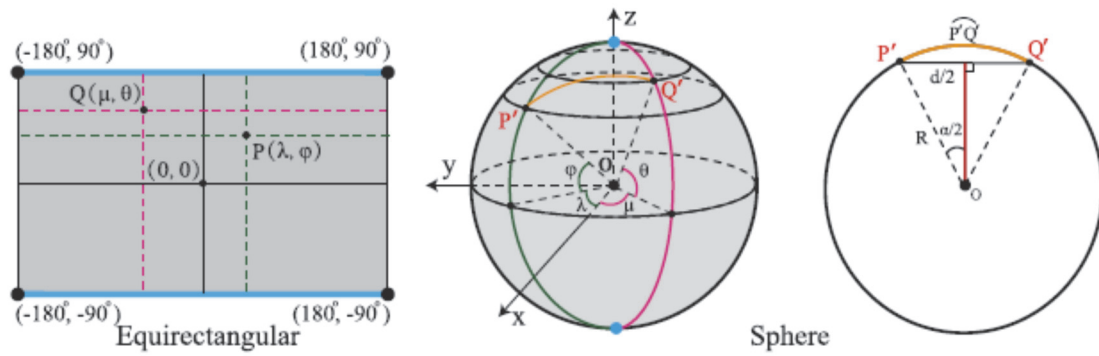


Fig. 43 - Transformation of equirectangular coordinates into spherical coordinates

In equirectangular image mapping, the selected image has a 2:1 ratio where the width is exactly twice the height. This is logical, since it covers 360° horizontally and 180° vertically and allows the viewer to look in every direction, including the zenith and nadir. Every point in the equirectangular panorama has a latitude (vertical angle) and longitude (horizontal angle) coordinates, the horizontal and vertical angles are used to solve the pose of the equirectangular panorama by space resection.

After the importation of the panoramic 360° images of the ambient that will be represented, the first step for the equirectangular mapping is the creation of a Sphere in the 3D Game Object Hierarchy.

For the representation of 3D objects are used the meshes, approximating surfaces with a collection of triangles. This works fine when all lines are straight, but becomes

troublesome when curves are involved. The default sphere mesh, known also as a UV sphere, is basically a rectangular grid wrapped around a sphere and compressed into a single point at the poles. This kind of sphere is the most used, but for the equirectangular mapping, the high concentration of triangles at the pole, creates many distortions of the view. An alternative mesh solution is with the platonic solids, which are more symmetrical than a UV sphere. In the three-dimensional space, a platonic solid is a regular, convex polyhedron. It is constructed by congruent (identical in shape and size), regular (all angles equal and all sides equal), polygonal faces with the same number of faces meeting at each vertex.

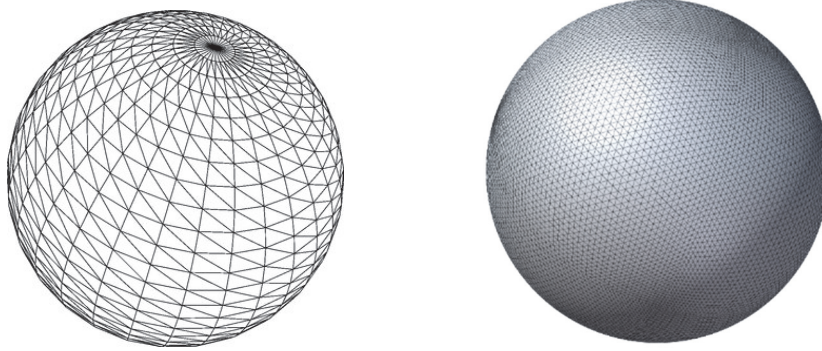


Fig. 44 - Uv sphere mesh vs polyhedric octahedron mesh

3.3.2. Collinearity equations:

The collinearity equations are based on two equations, used in photogrammetry and computer vision, to relate a plane picture (2D) to objects coordinates (3D). The equations recreate the object from the central projection. Collinearity is considered as the standard mathematical model in photogrammetry and machine vision to compute the image orientation within the bundle adjustment. The bundle adjustment is the problem of simultaneously refining the 3D coordinates describing the scene geometry, the parameters of relative motion, and the optical characteristics of the camera employed to acquire the images. The collinearity concept is based on assuming the object point, its image coordinates, and the camera lens are collinear, all located on a straight line.

$$\xi = \xi_0 - c \frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$\eta = \eta_0 - c \frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

A minimum of three reference points or ground control points (GCPs) are required to solve the resection problem. Basically, collinearity equations are nonlinear and commonly solved by starting from a proper array of initial pose values which are decisive in the solution. Different methods are introduced in the field of photogrammetry and machine vision to solve the nonlinearity in the collinearity model and to efficiently solve with a minimum number of control points. From a machine vision perspective, the camera pose is commonly solved as the perspective n-point (P-n-P) problem and this direct solution approach is mainly developed with three points (P-3-P) or four points (P-4-P) methods. However, the P-n-P direct methods result in various solutions and the correct solution one should be determined.

Furthermore, these methods are limited to a specific number of reference points ($n=3, 4$, or 5) and do not consider the redundancy in observations which is supposed to strengthen the solution from a statistical viewpoint.

Another common approach is the direct linear transformation (DLT) and it is based on the projective relations between the image and the object space by estimating the so-called projection matrix. A minimum of five reference points is fundamental to solve the system of DLT equations in a direct linear solution. The camera orientation approaches are either nonlinear solutions and dependent on the proper initial values or linear, non-rigorous solutions which cannot handle statistically the redundant observations. Furthermore, these methods are sensitive to the poor spatial distribution of the points and the camera interior orientation is also required. Particularly, bad distribution is present when the points are placed on or close to a straight line. Similarly, DLT can result in a weak conditioned system of equations if all reference points are positioned on a common plane.

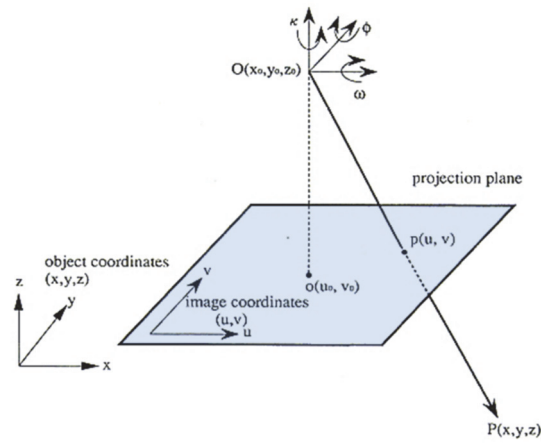


Fig. 45 - Collinearity equations principle

3.3.3. Perspective-n-Point problem:

The Perspective-n-Point problem originated from camera calibration has the purpose to determine the position and orientation of the camera with respect to a scene object from n correspondent points. It is applied in many important fields, such as computer vision, automation, image analysis, photogrammetry, robotics, etc.

The problem was summarized by Fischler and Bolles [35]:

"Given the relative spatial locations of n control points, and given the angle to every pair of control points from an additional point called the Center of Perspective (CP), find the lengths of the line segments joining CP to each of the control points."

The study of the P-n-P problem mainly consists of two aspects:

- Design fast and stable algorithms that can be used to find all or some of the solutions of the P-n-P problem;
- Give a classification for the solutions of the P-n-P problem, i.e., give the conditions under which the problem has one, two, three or four solutions;

There are many results for the first problem but the second is still open. The smallest subset of the P-n-P problem is the P-3-P that yields a finite number of solutions. The P3P problem is the most basic case of the P-n-P problems. All other P-n-P ($n > 3$) problems include the P-3-P problem as a special case. The Perspective Three Point (P-3-P) problem aims at using the observations of three given points (control points) in physical space from a single view to determine the pose (position and orientation) of the camera being used. It is a long-standing and fundamental problem in the field of computer vision, with

new insights into its properties and improved solutions continuing to be discovered. The P3P problem was first introduced and solved in 1841 by Grunert, who noticed that this problem typically does not lead to a unique mathematical solution, but leads to four distinct solutions, any of which could be the pose of the camera. Since then, the P3P problem has been extensively studied, and numerous camera pose estimation problems have been derived from this basic issue, including the P4P [37].

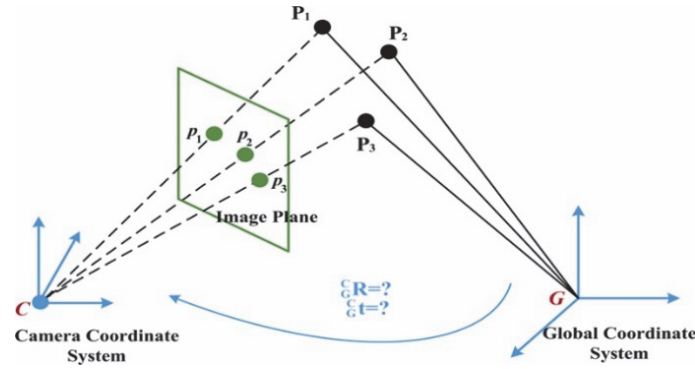


Fig. 46 - The P-3-P problem

For the P-4-P problem, if the four control points are not coplanar, the maximum number of positive solutions under the distance-based definition is 5; if the four control points are not coplanar, the maximum number of admissible solutions is 4. In the Fig. x it is shown that both the configurations (A, B, C, D) and (A', B', C', D') satisfy the distance-based definition, where O is the optical center, a, b, c, d are four image points. However, it is impossible to transform the first configuration into the second by a rotation and a translation since (A, B, C, D) is the reflection of configuration (A', B', C', D') respect to plane (ABC) , i.e., the two configuration cannot be solutions of the same P-4-P problem.

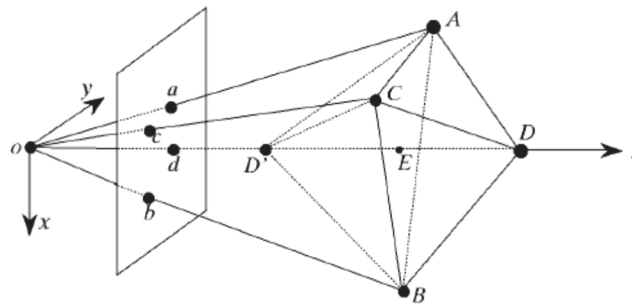


Fig. 47 - The P-4-P problem

3.3.4. Camera oblique angle:

The scope of this methodology is the development of a mathematical model for perspective and equirectangular panoramic image orientation determination, which considers the redundancy in observations and the correction of improper initial values. This is made through the introduction of a solution with geometric stability and reliability which converges to a global solution even with improper initial values. The developed model is based on using angular conditions represented by oblique angles instead of using horizontal and vertical angles. Spherical trigonometry laws will be used to derive the oblique angles while vector geometry will be applied to develop the mathematical model that relates: the derived angles, the camera unknown orientation parameters, and the coordinates of the object points. The mobile mapping system accuracy improvement, through the realignment of the trajectories, will help in speeding up all the surveying works, improving faster data elaborations.

Given a spherical triangle ABC with two known vertical angles (β_1, β_2) and one known horizontal angle (θ), the inclined angle γ may be computed from the cosine rule (Murray 1908).

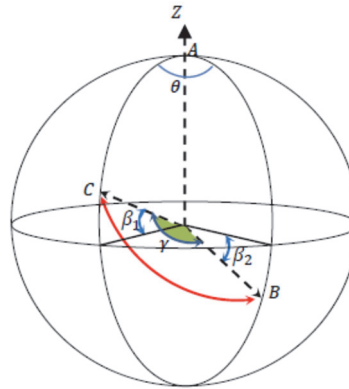


Fig. 48 - Oblique angle γ

The cosine rule can be used to solve the spherical triangle ABC and to compute the inclined angle γ .

$$\cos(\gamma) = \cos(\theta)\cos(\beta_1)\cos(\beta_2) + \sin(\beta_1)\sin(\beta_2)$$

Three points are necessary to define the inclined angle in the orientation problem and a minimum of three oblique angles is necessary to define the object space coordinates of the camera and the same applies for the image triangulation problem.

The inclined angles are defined by knowing the horizontal and vertical angles to the target point. These angles are indirectly observed by knowing the image coordinates.

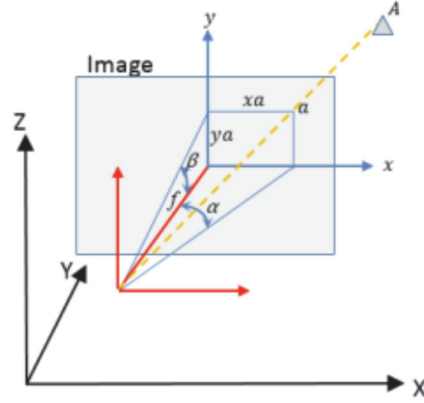


Fig. 49 - Horizontal and Vertical angles (α , β) by using observed image coordinates

The computation begins with estimating the oblique angles and knowing the two control points (i and j) coordinates. For perspective images, this is possible by using the observed image coordinates referenced to the principle point of both control points as follows:

$$\vartheta_i = \tan^{-1} * \frac{x_i}{f}$$

$$\vartheta_j = \tan^{-1} * \frac{x_j}{f}$$

$$\vartheta = |\vartheta_i - \vartheta_j|$$

$$\beta_i = \tan^{-1} * \frac{y_i}{\sqrt{(x_i)^2 + f^2}}$$

$$\beta_j = \tan^{-1} * \frac{y_j}{\sqrt{(x_j)^2 + f^2}}$$

With:

x_i, y_i, x_j, y_j : observed image coordinates of the points i and j ;

f : camera focal length;

For the equirectangular images the horizontal and two vertical angles (ϑ , β_i , β_j) are computed by:

$$\vartheta = \text{pixel}^\circ * (\text{col}_j - \text{col}_i)$$

$$\beta_{i,j} = \text{pixel}^\circ * \left(\frac{\text{image height}}{2} - \text{row}_{i,j} \right)$$

With:

col_i, col_j : x-coordinates in pixels for the control points i and j ;

row_i, row_j : y-coordinates in pixels for the control points i and j ;

$pixel^\circ$: pixel size in degrees;

With these data computed, it is possible to obtain the oblique angle γ . The maximum number of oblique angles, is given by:

$$Max.no, of oblique angles = \frac{(n^2 - n)}{2}$$

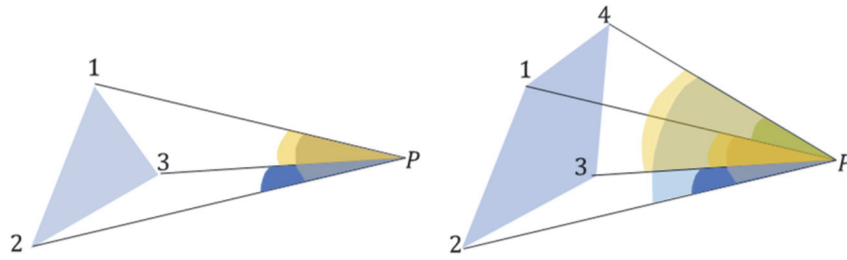


Fig. 50 - The composed oblique angles related to three and four observed control points

The high redundancy of the observed oblique angles makes strength the stability of the solution and the convergence to an optimal minimum. The oblique angles can be derived using the approximate camera 3D coordinates applying the vector dot product:

$$\cos\gamma = \frac{dx_i dx_j + dy_i dy_j + dz_i dz_j}{L_i L_j}$$

With:

$dx_{i,j}, dy_{i,j}, dz_{i,j}$: the difference in coordinates the viewing camera P and points i and j ;

$L_{i,j}$: spatial distances between the camera and the observed control points i and j .

The previous equation can be reformulated to further compute the partial derivatives $(\frac{\partial F}{\partial X_p}, \frac{\partial F}{\partial Y_p}, \frac{\partial F}{\partial Z_p})$ to the unknown coordinates of the camera (X_p, Y_p, Z_p) as follows:

$$F = L_i L_j \cos \gamma - (dx_i dx_j + dy_i dy_j + dz_i dz_j)$$

$$\frac{\partial F}{\partial X_p} = X_i - 2X_p + X_j + \frac{\cos \gamma (X_p - X_j) L_i}{L_j}$$

$$\frac{\partial F}{\partial Y_p} = Y_i - 2Y_p + Y_j + \frac{\cos \gamma (Y_p - Y_j) L_i}{L_j}$$

$$\frac{\partial F}{\partial Z_p} = Z_i - 2Z_p + Z_j + \frac{\cos \gamma (Z_p - Z_j) L_i}{L_j}$$

The partial derivatives of the previous equation are necessary to solve the nonlinearity of the observation equations system.

3.3.5. Vector Δ and Covariance Matrix Σ :

The solution of the oblique angles equations will be applied by least squares adjustment using either Gauss-Newton technique or Levenberg Marquardt:

$$\Delta = (B^t Q_e^{-1} B)^{-1} B^t Q_e^{-1} F$$

The covariance matrix is:

$$\Sigma = \sigma_o^2 (B^t Q_e^{-1} B)^{-1}$$

Where:

Δ : vector of corrections to the camera coordinates $(\delta_{X_p}, \delta_{Y_p}, \delta_{Z_p})$;

B : matrix of partial derivatives to the camera coordinates X_p, Y_p, Z_p ;

$$B = [\frac{\partial F}{\partial X_p}, \frac{\partial F}{\partial Y_p}, \frac{\partial F}{\partial Z_p}]$$

Q_e : cofactor weight matrix of the observations;

Σ : covariance matrix of the camera coordinates;

3.3.6. Image alignment:

The alignment between two sets of corresponding 3D point data is computed by finding optimal rotation and translation. This problem, as stated before, requires a minimum of three points to be solved. Through the least squares method it is possible to obtain the optimal solution of the pose estimation. The method of least squares is a standard approach to approximate the solution of overmined systems by minimizing the sum of the squares of the residuals made in the result of every single equation. It is done with a series of iterations, solving the right coordinates.

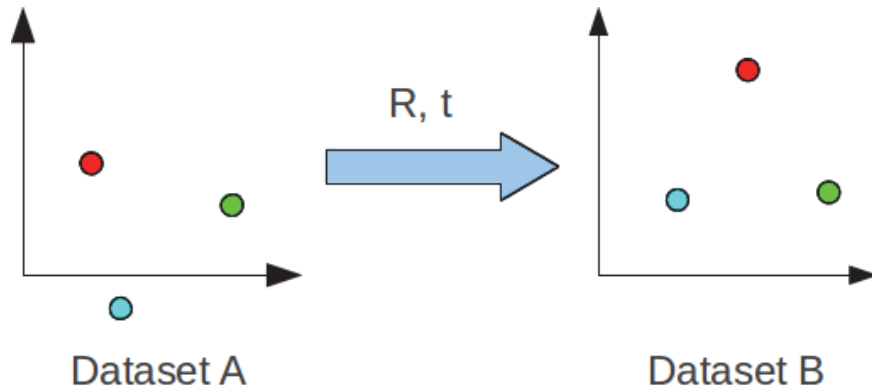


Fig. 51 - Comparison between two dataset of corresponding 3D points

In the previous image the R is the rotation matrix and t the translation vector. To make the alignment between the two datasets, the transformation required is the Euclidean or Rigid transform, which preserves the shape and size.

The Euclidean isometry is a geometric transformation of the space, that includes the rotations and translations (roto-translations), and preserves the distance between every pair of points. A rigid transformation is defined as:

$$T(v) = R * v + t$$

In this case the rigid transformation expression is defined as:

$$B = R * A + t$$

Where A and B are the matrix [4x4] of the 3D points with known correspondences.

The first step is finding the centroids:

$$centroid_A = \frac{1}{N} \sum_{i=1}^N A^i$$

$$centroid_B = \frac{1}{N} \sum_{i=1}^N B^i$$

With A^i and B^i vectors $[3 \times 1]$ $[[x, y, z]]$.

To find the optimal rotation, the best way is using the Kabsch algorithm, that minimizes the Root-mean-square deviation (RMSD) between two paired sets of points. The RMSD is a measure of the differences (errors) between values predicted by a model or an estimator and the values observed. To find the rotation matrix, the Kabsch algorithm uses the Singular Value Decomposition (SVD). The SVD is a factorization or decomposition of a matrix into three other matrices:

$$SVD(M) = [U, S, V]$$

$$M = U * S * V^T$$

Where:

$M = \text{factorization } m * n \text{ matrix}$

$U = m * m \text{ complex unitary matrix}$

$S = m * n \text{ complex unitary matrix}$

$V = n * n \text{ complex unitary matrix}$

First is required to re-centre both dataset so that both the centroids are at the origin.

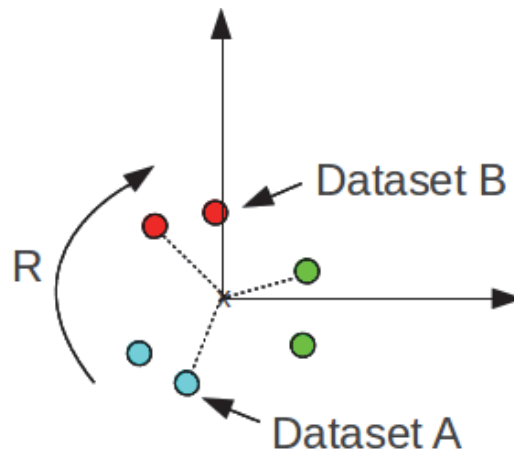


Fig. 52 - Re-centre of the datasets

This removes the translation component. This step is done with the finding of the camera pose estimation, which, in mathematical terms, is the translation vector. Using the covariance matrix Σ it is possible to resolve the image rotation problem.

$$\Sigma = (A - centroid_A)(B - centroid_B)^T$$

$$SVD(\Sigma) = [U, S, V]$$

$$R = VU^T$$

The result is a $[3 \times 3]$ matrix, but for this case study the optimal rotation matrix need to be expressed in terms of quaternions, which are a four dimensional structure based on complex numbers expressed in form of:

$$q = a + bi + cj + dk$$

With a, b, c, d real numbers and i, j, k unit-vectors pointing along the three spatial axis. In this situation, the set of quaternions is made by a 4-dimensional vector space:

$$[w, x, y, z]$$

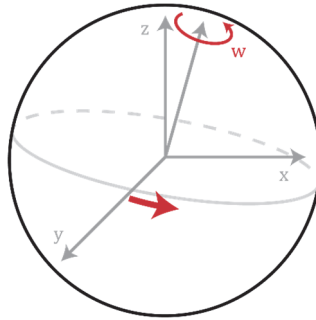


Fig. 53 - Quaternion vectors

3.3.6. MATLAB Function Code:

```
% input
% point: [x,y,z] n*3 object points
% oblique angles and % Tx,Ty,Tz: initial value of the unknown position
% output: adjusted Tx,Ty,Tz

clc,clear,close all
%%% given GCPs
point=[4x4];
%%% initial coordinates
Tx;Ty;Tz;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Oblique=[1x6]*pi/180;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% resection of oblique angles %%%%%%%%%%%%%%%
[Tx1,Ty1,Tz1] =threeD_resection_oblique(point,Oblique, Tx, Ty, Tz);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% adjusted coordinates %%%%%%%%%%%%%%%

T= [Tx1 Ty1 Tz1];
disp('Camera Position');
disp(T);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure(1)
for i=1:size(point,1)
    plot3([Tx point(i,1)], [Ty point(i,2)], [Tz
point(i,3)], 'k', 'linewidth',3);hold on
    plot3([ point(i,1)], [point(i,2)], [point(i,3)], '^r', 'markersize',
8, 'markerfacecolor', 'r');hold on
    text(point(i,1), point(i,2), point(i,3), num2str(i), 'fontsize',12);
end
axis image
grid on
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [Tx,Ty,Tz] = threeD_resection_oblique(point,oblique,Tx,Ty,Tz)
ii=0;D=[1;1;1];
X=point(:,1); Y=point(:,2); Z=point(:,3);DD=[0;0;0];
while max(abs(D)) >.00001
    ii=ii+1;
```

```

for i=1:size(X,1)
    dx(i,1) = (Tx - X(i,1));
    dy(i,1) = (Ty - Y(i,1));
    dz(i,1) = (Tz - Z(i,1));
    lp(i,1) = ((Tx - X(i,1))^2+(Ty - Y(i,1))^2 + (Tz - Z(i,1))^2)^(1/2);
end
kk=0;
for i=1:size(X,1)-1
    for j=i+1:size(X,1)
        kk=kk+1;
        C(kk,1)= cos(oblique(kk));
        ax(kk,1) =X(i,1)-2*Tx+X(j,1)+(((C(kk,1))*(2*Tx-
2*X(i,1))*lp(j,1))/(2*lp(i,1)))+(((C(kk,1))*(2*Tx-
2*X(j,1))*lp(i,1))/(2*lp(j,1)));
        ay(kk,1) =Y(i,1)-2*Ty+Y(j,1)+(((C(kk,1))*(2*Ty-
2*Y(i,1))*lp(j,1))/(2*lp(i,1)))+(((C(kk,1))*(2*Ty-
2*Y(j,1))*lp(i,1))/(2*lp(j,1)));
        aaz(kk,1) =Z(i,1)-2*Tz+Z(j,1)+(((C(kk,1))*(2*Tz-
2*Z(i,1))*lp(j,1))/(2*lp(i,1)))+(((C(kk,1))*(2*Tz-
2*Z(j,1))*lp(i,1))/(2*lp(j,1)));
        F(kk,1) = lp(i,1)*lp(j,1) *C(kk,1) -
((dx(i,1)*dx(j,1))+(dy(i,1)*dy(j,1))+(dz(i,1)*dz(j,1)));
    end
end

%% LS adjustment
b= [ax ay aaz];
N=inv(b'*b);
T=b'*-F;
D=N*T;
% update coordinates
Tx=Tx+D(1,1);
Ty=Ty+D(2,1);
Tz=Tz+D(3,1);
%%%%%%%%%%%%%%
DD=[ DD,D];
end

V=b*D-F; % residuals
sigma=(V'*V)/(size(b,1)-size(b,2));
vcov=diag(sigma*N);

```

```

SS=sqrt(vcov);
disp('std. dev. ');
disp (SS);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
DD(:,1)=[];D=DD;
figure(2)
subplot(1,3,1)
plot((1:size(D,2)), D(1,:), '-ro', 'Markerfacecolor','r', 'LineWidth',2),hold
on
title('CONVERGENCE OF X-COORDINATES')
xlabel('NUMBER OF ITERATIONS')
ylabel('CORRECTIONS')
grid on
legend('X')
set(gca,'xtick',1:1:ii)
axis tight
subplot(1,3,2)
plot((1:size(D,2)), D(2,:), '-b^', 'Markerfacecolor','b', 'LineWidth',2),hold
on
title('CONVERGENCE OF Y-COORDINATES')
xlabel('NUMBER OF ITERATIONS')
ylabel('CORRECTIONS')
grid on
legend('Y')
set(gca,'xtick',1:1:ii)
axis tight
subplot(1,3,3)
plot((1:size(D,2)), D(3,:), '-ms', 'Markerfacecolor','k', 'LineWidth',2),hold
on
title('CONVERGENCE OF Z-COORDINATES')
xlabel('NUMBER OF ITERATIONS')
ylabel('CORRECTIONS')
legend('Z')
set(gca,'xtick',1:1:ii)
grid on
axis tight

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end

```

This is an iterative procedure that finds the right camera pose estimation, based on a statistical method. In fact, a series of iterations are needed to calculate the exact pose estimation of the camera and the rotation. Sometimes, if the beginning position of the camera is a lot different from the correct one, the result could be mathematically correct, but not realistic and useful for the case study.

3.4. Game Engine

In this case study the digital twin is an important tool to measure the built environment. In fact, with the developed methodology, starting from the real building and through the previously explained surveying techniques, it is possible to acquire in a short time huge amounts of data and information. From the geometry and the images, the elements identification and properties can be reconstructed, and exporting these data it is possible to create an historical digital building twin and an archive of all the works. From the archive the building should be re-designed, re-planned, or simply maintained, developing a new circular process of relation between real environment and digital twin.

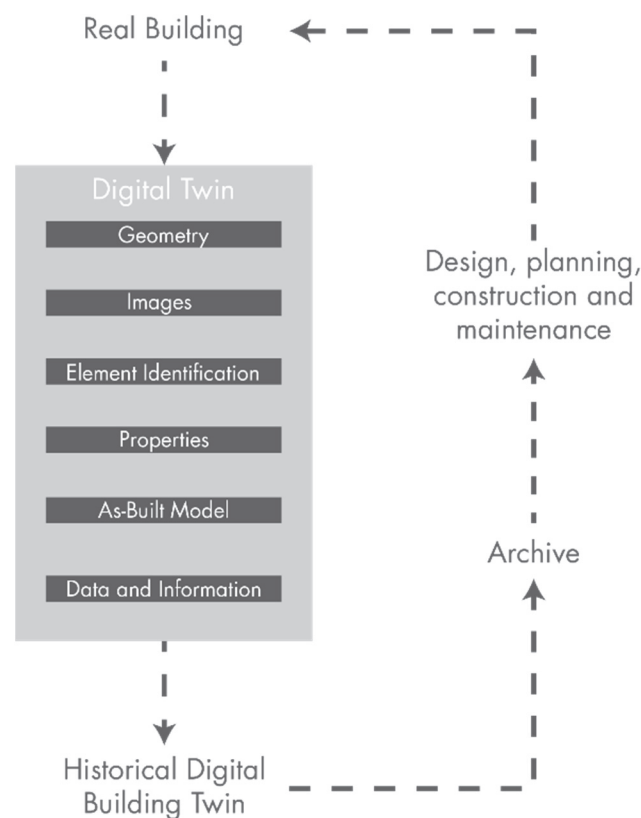


Fig. 54 - Digital twin elements and interaction with real-built environment

3.4.1. Unity 3D:

Unity 3D Game Engine is a game development engine which includes a rendering motor and a set of tools for rapid workflows between designers and programmers. Unity work with C# multi-paradigm programming language, with the characteristics of portability, typing (supports strongly typed variable declarations), metaprogramming (ability to treat other programs as their data), methods and functions, supporting of properties, namespace, memory access, functional programming, etc.

It is a multiplatform application which can be run on both Microsoft Windows and Apple MacOS computers, and also in different typologies of devices. Another crucial aspect of Unity is the networking, i.e. the computer sharing information among two or more devices. At the same time, the customers can work on the same project, modifying and creating objects and scenes, which should be immediately seen by others.

This game engine is the most used by creators, for its simple interface, the free version and because of the large amount of data that could contain. Because of this last condition, it is ideal for the coordination and collaboration with BIM platforms, by importing models and creating realistic augmented models and environments. Working with BIM means importing the geometries, but also all the data and information contained into the elements and its properties.

3.4.2. Alignment:

The first scheduled step inside Unity 3D is the importation of the IFC BIM model and the equirectangular images. Then is possible the creation of a Shader and materials, which can be applied to the polyhedric spheres recreating the various surroundings of the building. Once constructed the scene and approximately positioned the spheres as the photoshoot points, it is possible to compare the photographic environment with the geometric environment. The sphere sizes are irrelevant for the equirectangular projections because of collinearity equations. The alignment is implemented transforming the MATLAB function code into a C# code, where it is possible to select the control point into the images and into the 3D space.

After the points selection the camera pose estimation is determined through the covariance matrix and the sphere rotations with the Kabsch algorithm.

C# Alignment Function Code:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using TMPro;
using MathNet.Numerics.LinearAlgebra;
using MathNet.Numerics.LinearAlgebra.Double;

public class PointerManager : MonoBehaviour
{
    RaycastHit hit;
    Ray ray;

    Vector3 pictureDir = Vector3.forward;
    Vector3 modelPoint = Vector3.zero;

    bool spaceIsPressed = false;
    bool pictureOn = true;
    bool collinearityGoinOn = false;
    bool escapable = false;
    Transform InitialCameraTransform;
    Transform InitialImageTransform;

    public new Camera camera;
    public TextMeshProUGUI hitCoordinates;
    public TextMeshProUGUI hitIfcElement;
    public GameObject pictures;
    public GameObject myPict;

    public List<Vector3> imageDirections = new List<Vector3>();
    public List<Vector3> modelDirections = new List<Vector3>();
    public List<Vector3> modelPoints = new List<Vector3>();
    public List<GameObject> imageMarkers = new List<GameObject>();
    public List<GameObject> modelMarkers = new List<GameObject>();

    Color imageLabelColor = new Color(1.0f, 0.0f, 0.0f, 1.0f);
    Color modelLabelColor = new Color(1.0f, 0.0f, 0.0f, 1.0f);
```



```

void Update()
{
    foreach (Transform child in pictures.transform)
    {
        if (child.gameObject.activeSelf) myPict = child.gameObject;
        camera.transform.position = myPict.transform.position;

        if (Input.GetKeyDown("space")) spaceIsPressed = true;
        if (Input.GetKeyDown("left shift")) togglePictures();
        if (Input.GetKeyDown("escape")) clearLastCollinearity();
    }

}

void FixedUpdate()
{
    RaycastHit hit, invHit;
    ray = camera.ScreenPointToRay(Input.mousePosition);
    if (Physics.Raycast(ray, out hit))

    {
        hitCoordinates.text = "x: " + hit.point.x.ToString("F3") + ", y: "
+ hit.point.z.ToString("F3") + ", z: " + hit.point.y.ToString("F3");
        hitIfcElement.text = hit.transform.name;

        if (spaceIsPressed)
        {
            if (pictureOn)
            {
                if (!collinearityGoinOn)
                {
                    collinearityGoinOn = true;
                    pictureDir = ray.direction;
                    Debug.Log("pict direction: " +
ray.direction.ToString("F6"));

                    Ray invRay = new Ray(hit.point, -ray.direction);
                    if (Physics.Raycast(invRay, out invHit))
                    {
                        GameObject pictSphere =
GameObject.CreatePrimitive(PrimitiveType.Sphere);
                        pictSphere.transform.position = invHit.point;
                        pictSphere.transform.localScale *= 0.008f;

                        pictSphere.GetComponent<Renderer>().material.SetColor("_Color",
imageLabelColor);

                        GameObject t = new GameObject();
                        t.transform.position = invRay.direction * 0.3f;

```

```

        TextMeshPro markerText =
t.AddComponent<TextMeshPro>();
        Vector2 s = new Vector2(0.0f, 0.0f);
        t.GetComponent<RectTransform>().sizeDelta = s;
        markerText.text = (imageMarkers.Count +
1).ToString();

        markerText.fontSize = 40;
        markerText.color = imageLabelColor;
        markerText.transform.localPosition +=
invRay.direction * 0.3f;
markerText.transform.SetParent(pictSphere.transform, false);
        markerText.transform.LookAt(invHit.point);
        imageMarkers.Add(pictSphere);
        addImageCollinearity();
        escapable = true;}}}}
    else
    {    if (collinearityGoinOn)

        {    modelPoint = hit.point;
            Debug.Log("model point: " +
modelPoint.ToString("F6"));

            Ray invRay = new Ray(hit.point, -ray.direction);
            if (Physics.Raycast(invRay, out invHit))

                {    GameObject modelSphere =
GameObject.CreatePrimitive(PrimitiveType.Sphere);
                    modelSphere.transform.position = hit.point;
                    modelSphere.transform.localScale *= 0.02f;

modelSphere.GetComponent<Renderer>().material.SetColor("_Color",
modelLabelColor);

                    GameObject t = new GameObject();
                    t.transform.position = invRay.direction * 0.3f;
                    TextMeshPro markerText =
t.AddComponent<TextMeshPro>();
                    Vector2 s = new Vector2(0.0f, 0.0f);
                    t.GetComponent<RectTransform>().sizeDelta = s;
                    markerText.text = (modelMarkers.Count +
1).ToString();

```

```

        markerText.fontSize = 50;
        markerText.color = modelLabelColor;
        markerText.transform.localPosition +=
invRay.direction * 5;
markerText.transform.SetParent(modelSphere.transform, false);
        markerText.transform.LookAt(2 * hit.point -
camera.transform.position);

        modelMarkers.Add(modelSphere);
        addModelCollinearity();
        escapable = true;
        collinearityGoinOn = false;}}}

        spaceIsPressed = false;}}}
else
{
    hitCoordinates.text = "";
    hitIfcElement.text = "";}}}

void saveInitialState()
{
    InitialCameraTransform.position = camera.transform.position;
    InitialImageTransform.rotation = myPict.transform.rotation;
    InitialImageTransform.position = myPict.transform.position;
    Debug.Log(InitialCameraTransform.position);
    Debug.Log(InitialImageTransform.rotation);
    Debug.Log(InitialImageTransform.position);}

void acceptResection()
{
    saveResection();
    imageDirections.Clear();
    modelDirections.Clear();
    modelPoints.Clear();
    clearMarkerList(modelMarkers, -1);
    clearMarkerList(imageMarkers, -1);
    collinearityGoinOn = false;
    spaceIsPressed = false;
    Debug.Log("Resection Saved");}

public void clearResection()
{
    imageDirections.Clear();

```

```

modelDirections.Clear();
modelPoints.Clear();
clearMarkerList(modelMarkers, -1);
clearMarkerList(imageMarkers, -1);
collinearityGoinOn = false;
spaceIsPressed = false;
Debug.Log("Resection Cleared");}

public void clearMarkerList(List<GameObject> mList, int position)
{
    GameObject go;
    if (position < 0)
    {
        for (int i = mList.Count - 1; i >= 0; i--)
        {
            go = mList[i];
            mList.RemoveAt(i);
            foreach (Transform child in go.transform)
            {GameObject.Destroy(child.gameObject);}
            Destroy(go);}}
    else
    {
        go = mList[position];
        mList.RemoveAt(position);
        foreach (Transform child in go.transform)
        {GameObject.Destroy(child.gameObject);}
        Destroy(go);}}

public void clearLastCollinearity()
{
    if (escapable)
    {
        if (pictureOn)
        {
            clearMarkerList(imageMarkers, imageMarkers.Count - 1);
            imageDirections.RemoveAt(imageDirections.Count - 1);
            collinearityGoinOn = false;}
        else
        {
            clearMarkerList(modelMarkers, modelMarkers.Count - 1);
            modelPoints.RemoveAt(modelPoints.Count - 1);
            collinearityGoinOn = true;}
        escapable = false;}}

public void addImageCollinearity()
{imageDirections.Add(pictureDir); }
public void addModelCollinearity()
{modelPoints.Add(modelPoint); }

```

```

void togglePictures()
{
    foreach (GameObject go in imageMarkers)
        go.SetActive(!go.activeSelf);

    myPict.SetActive(!myPict.activeSelf);
    pictureOn = !pictureOn;
    spaceIsPressed = false;}

public void Resection()
{
    float maxError = 0.00001f;
    Vector3 startPosition = myPict.transform.position;
    Vector3 T = new Vector3(startPosition.x, startPosition.y,
startPosition.z);
    Vector3 R = new Vector3(0.0f, 0.0f, 0.0f);

    int obliqueAngleNum;
    obliqueAngleNum = (imageDirections.Count * imageDirections.Count -
imageDirections.Count) / 2;
    Matrix<float> pointArray =
Matrix<float>.Build.Dense(modelPoints.Count, 3);
    Vector<float> obliqueAngleVector =
Vector<float>.Build.Dense(obliqueAngleNum);
    for (int i = 0; i < modelPoints.Count; i++)
    {
        pointArray[i, 0] = modelPoints[i].x;
        pointArray[i, 1] = modelPoints[i].y;
        pointArray[i, 2] = modelPoints[i].z;
        //Debug.Log(pointArray[i, 0] + " " + pointArray[i, 1] + " " +
pointArray[i, 2]);}

    int k = 0;
    for (int i = 0; i < imageDirections.Count - 1; i++)
    {
        for (int j = i + 1; j < imageDirections.Count; j++)
        {
            obliqueAngleVector[k] = Vector3.Angle(imageDirections[j],
imageDirections[i]);
            //Debug.Log("obliqueAngle[" + (k).ToString() + "]" +
obliqueAngleVector[k]);
            ++k;}}
    Vector3[] d = new Vector3[modelPoints.Count];

```

```

Vector3[] a = new Vector3[obliqueAngleNum];

float[] VectorOne = { 1.0f, 1.0f, 1.0f };
Vector<float> D = Vector<float>.Build.Dense(VectorOne);
Vector<float> C = Vector<float>.Build.Dense(obliqueAngleNum);
Vector<float> F = Vector<float>.Build.Dense(obliqueAngleNum);
Matrix<float> b = Matrix<float>.Build.Dense(obliqueAngleNum, 3);
Matrix<float> N = Matrix<float>.Build.Dense(3, 3);
Vector<float> TT = Vector<float>.Build.Dense(3);
Vector<float> V = Vector<float>.Build.Dense(obliqueAngleNum);
Vector<float> vcov = Vector<float>.Build.Dense(3);
Vector<float> SS = Vector<float>.Build.Dense(3);

Matrix<float> imageDir = Matrix<float>.Build.Dense(3,
modelPoints.Count);
Matrix<float> retImageDir = Matrix<float>.Build.Dense(3,
modelPoints.Count);
Matrix<float> globalErr = Matrix<float>.Build.Dense(3,
modelPoints.Count);
Matrix<float> modelDir = Matrix<float>.Build.Dense(3,
modelPoints.Count);
Vector<float> imageCentroid = Vector<float>.Build.Dense(3);
Vector<float> modelCentroid = Vector<float>.Build.Dense(3);

Matrix<float> H = Matrix<float>.Build.Dense(3, 3);
Matrix<float> Rot = Matrix<float>.Build.Dense(3, 3);

float sigma;

int iterations = 0;
int maxIterations = 100;
while (D.AbsoluteMaximum() > maxError && iterations <
maxIterations)
{
    for (int i = 0; i < modelPoints.Count; i++)
    {
        d[i] = T - modelPoints[i];
        //Debug.Log(d[i].magnitude);}
        int kk = 0;
        for (int i = 0; i < modelPoints.Count - 1; i++)
        {
            for (int j = i + 1; j < modelPoints.Count; j++)

```

```

        { C[kk] = Mathf.Cos(obliqueAngleVector[kk] * Mathf.PI /
180);

        a[kk].x = modelPoints[i].x - 2 * T.x + modelPoints[j].x
+ ((C[kk] * (2 * T.x - 2 * modelPoints[i].x) * d[j].magnitude) / (2 *
d[i].magnitude)) + ((C[kk] * (2 * T.x - 2 * modelPoints[j].x) *
d[i].magnitude) / (2 * d[j].magnitude));

        a[kk].y = modelPoints[i].y - 2 * T.y + modelPoints[j].y
+ ((C[kk] * (2 * T.y - 2 * modelPoints[i].y) * d[j].magnitude) / (2 *
d[i].magnitude)) + ((C[kk] * (2 * T.y - 2 * modelPoints[j].y) *
d[i].magnitude) / (2 * d[j].magnitude));

        a[kk].z = modelPoints[i].z - 2 * T.z + modelPoints[j].z
+ ((C[kk] * (2 * T.z - 2 * modelPoints[i].z) * d[j].magnitude) / (2 *
d[i].magnitude)) + ((C[kk] * (2 * T.z - 2 * modelPoints[j].z) *
d[i].magnitude) / (2 * d[j].magnitude));

        F[kk] = d[i].magnitude * d[j].magnitude * C[kk] -
(d[i].x * d[j].x + d[i].y * d[j].y + d[i].z * d[j].z);
        //Debug.Log(kk.ToString() + "
"+obliqueAngleVector[kk].ToString() + " " + C[kk].ToString());
        //Debug.Log(a[kk].x);
        ++kk;}}

    for (int i = 0; i < obliqueAngleNum; i++)
    {b[i, 0] = a[i].x; b[i, 1] = a[i].y; b[i, 2] = a[i].z;}
    N = b.TransposeThisAndMultiply(b).Inverse();
    TT = b.TransposeThisAndMultiply(-F);
    D = N.Multiply(TT);
    T.x = T.x + D[0]; T.y = T.y + D[1]; T.z = T.z + D[2];
    ++iterations;}

    V = b.Multiply(D).Subtract(F);
    sigma = (V[1] * V[1] + V[2] * V[2] + V[3] * V[3]) / (b.RowCount -
b.ColumnCount);
    vcov = N.Diagonal().Multiply(sigma);
    //Debug.Log("vcov " + vcov[0].ToString("F4") + ", " +
vcov[1].ToString("F4") + ", " + vcov[2].ToString("F4"));
    //Debug.Log("sigma " + sigma.ToString("F4"));
    SS[0] = Mathf.Pow(vcov[0], 0.5f); SS[1] = Mathf.Pow(vcov[1], 0.5f);
    SS[2] = Mathf.Pow(vcov[2], 0.5f);

    Debug.Log("iterations: " + iterations.ToString() + ", Center: " +
T.ToString("F4"));

```

```

        Debug.Log("std. dev. " + SS[0].ToString("F4") + ", " +
SS[1].ToString("F4") + ", " + SS[2].ToString("F4"));

        camera.transform.position = T;
        myPict.transform.position = T;

        for (int i = 0; i < modelPoints.Count; i++)
        {Vector3 ModelDir = -(camera.transform.position -
modelPoints[i]).normalized;
            modelDirections.Add(ModelDir);
            Debug.Log("direction [" + i + "]");
            Debug.Log("image: " + imageDirections[i].ToString("F6"));
            Debug.Log("model: " + modelDirections[i].ToString("F6"));}

        for (int i = 0; i < modelPoints.Count; i++)
        {    imageDir[0, i] = imageDirections[i].x; imageDir[1, i] =
imageDirections[i].y; imageDir[2, i] = imageDirections[i].z;
            modelDir[0, i] = modelDirections[i].x; modelDir[1, i] =
modelDirections[i].y; modelDir[2, i] = modelDirections[i].z;
        }

        for (int i = 0; i < modelPoints.Count; i++)
        {    imageCentroid[0] += imageDir[0, i] / modelPoints.Count;
imageCentroid[1] += imageDir[1, i] / modelPoints.Count; imageCentroid[2] +=
imageDir[2, i] / modelPoints.Count;
            modelCentroid[0] += modelDir[0, i] / modelPoints.Count;
modelCentroid[1] += modelDir[1, i] / modelPoints.Count; modelCentroid[2] +=
modelDir[2, i] / modelPoints.Count;}

        for (int i = 0; i < modelPoints.Count; i++)
        {    imageDir[0, i] -= imageCentroid[0]; imageDir[1, i] -=
imageCentroid[1]; imageDir[2, i] -= imageCentroid[2];
            modelDir[0, i] -= modelCentroid[0]; modelDir[1, i] -=
modelCentroid[1]; modelDir[2, i] -= modelCentroid[2];}

        H = imageDir.TransposeAndMultiply(modelDir);

        var SVD = H.Svd(true);
        Rot = SVD.U.Multiply(SVD.VT).Transpose();

```



```

        retImageDir = Rot.Multiply(imageDir);
        globalErr = retImageDir.Subtract(modelDir);
        Vector3 axialGlobalErr = new Vector3();
        for (int i = 0; i < modelPoints.Count; i++)
        {
            axialGlobalErr.x += Mathf.Abs(globalErr[0, i]) /
modelPoints.Count; axialGlobalErr.y += Mathf.Abs(globalErr[1, i]) /
modelPoints.Count; axialGlobalErr.z += Mathf.Abs(globalErr[2, i]) /
modelPoints.Count;}

        float qw = Mathf.Sqrt(Mathf.Max(0, 1.0f + Rot[0, 0] + Rot[1, 1] +
Rot[2, 2])) / 2.0f;
        float qx = Mathf.Sqrt(Mathf.Max(0, 1.0f + Rot[0, 0] - Rot[1, 1] -
Rot[2, 2])) / 2.0f;
        float qy = Mathf.Sqrt(Mathf.Max(0, 1.0f - Rot[0, 0] + Rot[1, 1] -
Rot[2, 2])) / 2.0f;
        float qz = Mathf.Sqrt(Mathf.Max(0, 1.0f - Rot[0, 0] - Rot[1, 1] +
Rot[2, 2])) / 2.0f;

        Quaternion Q = new Quaternion(copySign(qx, Rot[2, 1] - Rot[1, 2]),
copySign(qy, Rot[0, 2] - Rot[2, 0]), copySign(qz, Rot[1, 0] - Rot[0, 1]),
qw);

        Debug.Log("Center:  " + T.ToString("F4"));
        Debug.Log("std. dev. " + SS[0].ToString("F4") + ", " +
SS[1].ToString("F4") + ", " + SS[2].ToString("F4"));

        Debug.Log("EULER " + Q.eulerAngles.ToString("F4"));
        Debug.Log("Mean Axial Errors: " + axialGlobalErr.ToString("F4"));

        myPict.transform.rotation = Q;
        acceptResection();}

float copySign(float magnitude, float sign)
{
    if (sign > 0)
    {return Mathf.Abs(magnitude);}
    else
    {return -Mathf.Abs(magnitude);}
}
}
}

```

3.4.3. Properties visualization, modelling and measurement:

With the alignment of all the environments is possible the comparison of the two models (i.e. photographic and geometric). That allows the visualization of the BIM properties directly from the equirectangular images, through the selection of the IFC elements.

It is also possible to directly measure the images by the physical model in the background. The measurement is developed by the difference of the two position vectors in the space, finding the vector distance. The points are selected in Unity adding the "Mesh Collider" property to the objects, which simulate the physical component of the walls or of the other elements, hitting them with the mouse.

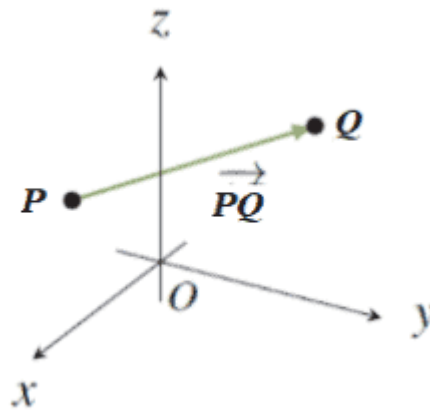


Fig. 55 - Distance vector between two points in the space

$$\overrightarrow{PQ} = \vec{Q} - \vec{P} = \begin{pmatrix} x_Q & x_P \\ y_Q & y_P \\ z_Q & z_P \end{pmatrix}$$

Creating prefab elements inside the Unity Asset panel it is possible to insert them in the scene by the instantiate command. The objects can be placed in a certain point of the environment and then translated or rotated. This procedure is the final step to enrich the BIM model with the detailed MEP elements.

The translation is computed with the vector distance between the start position point and the destination point. For the rotation it is required the Euclidean rotation matrix. It could be decomposed into the three dimension space rotation axis.

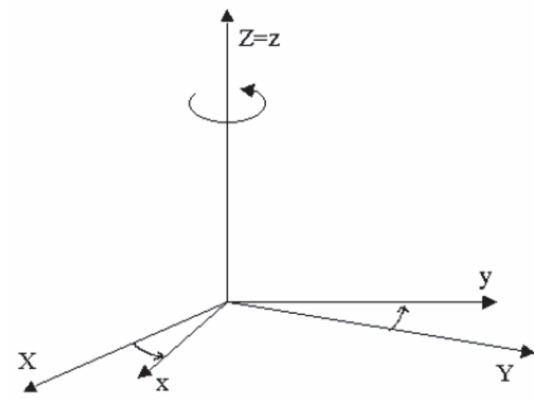


Fig. 56 - Decomposition of the 3D space rotation in the three dimension

the decomposed angles are:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}$$

$$R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

With the obtained angles it is possible to rotate in the space the placed objects.

3.5. Bibliography

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- [37] *Z.Y. Hu, F.C. Wu*: A note on the Number of Solutions of the Noncoplanar P-4-P Problem - 2002
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< http://nghiaho.com/?page_id=671>
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3.6. Source of illustrations

Fig. 41 - Oblique angular-based resection workflow: [32] B. Alsadik: Robust resection model for aligning the mobile mapping system trajectories at degraded and denied urban environments - 2020

Fig. 42 - Points projected from 2D panorama equirectangular image to 3D space: [32] B. Alsadik: Robust resection model for aligning the mobile mapping system trajectories at degraded and denied urban environments - 2020

Fig. 43 - Transformation of equirectangular coordinates into spherical coordinates: [33] Y.Zhang, F.L. Zhang, Y.K. Lai, Z. Zhu: Efficient propagation of sparse edits on 360° panoramas - 2021

Fig. 45 - Collinearity equations principle: [32] B. Alsadik: Robust resection model for aligning the mobile mapping system trajectories at degraded and denied urban environments - 2020

Fig. 46 - The P-3-P problem: [36] Q. Yu, G. Xu, W. Dong, Z. Wang: Solving the perspective-three-point problem with linear combinations: An accurate and efficient method - 2021

Fig. 47 - The P-4-P problem: [37] Z.Y. Hu, F.C. Wu: A note on the Number of Solutions of the Noncoplanar P-4-P Problem - 2002

Fig. 48 - Oblique angle γ : [32] B. Alsadik: Robust resection model for aligning the mobile mapping system trajectories at degraded and denied urban environments - 2020

Fig. 49 - Horizontal and Vertical angles (α, β) by using observed image coordinates: [38] B. Alsadik: A modified method for image triangulation using inclined angles - 2016

Fig. 50 - The composed oblique angles related to three and four observed control points: [32] B. Alsadik: Robust resection model for aligning the mobile mapping system trajectories at degraded and denied urban environments - 2020

Fig. 51 - Comparison between two dataset of corresponding 3D points: [39] Nghia Ho: Finding optimal rotation and translation between corresponding 3D points - < http://nghiaho.com/?page_id=671 >

Fig. 52 - Re-centre of the datasets: [39] Nghia Ho: Finding optimal rotation and translation between corresponding 3D points - < http://nghiaho.com/?page_id=671 >

System development

The suggested methodology was tried inside the Polytechnic University of Marche (UNIVPM), into the Construction department of DICEA (Dipartimento di Ingegneria Civile, Edile e Architettura). The environment includes the entrance hall, outside the department, the waiting area inside, one technical room, one meeting room, two rooms dedicated to thesis students, one storage and eight offices.

The principal structure is realised with concrete prefab elements, while the partition walls are based on plaster and glass components mounted on metallic substructures. All the lighting, venting and sound elements are mounted over the suspended ceilings.

4.1. Surveying and modelling process

The analysis and tests on the case study started with the surveying process. The idea was to make the 3D model as detailed as possible, because of the opportunity to compare the traditional methodology with the proposed. As a consequence of this choice, it was defined to model in LOD 500, developing an as-built 3D environment where it is possible to analyse and see all the facility elements.

4.1.1. Geometric surveying:

The geometric surveying was developed in two different way:

- through the traditional method of trilateration with the help of a metric laser measurer;
- with the ZEB Horizon GeoSLAM tool, recreating a detailed point cloud of the ambient. The SLAM (simultaneous location and mapping) technology is the computational problem of constructing or updating map of an unknown environment while simultaneously keeping track of an agent's location with it;

The initial purpose was to enclose the error amount inside 1.5 cm, containing, in that way, the possible future deviations between the photographic environment and the 3D virtual environment. The precision review was made through the juxtaposition of the reconstructed geometrical model and the point cloud obtained.

The point cloud was taken immediately in minutes, through the navigation of the different rooms by an operator with the GeoSLAM tool. The exported point cloud was detailed and doesn't need much rework, only to clean the external points. Comparing the two configurations, it is possible to assert that the geometric surveying was made with accuracy, because of the small level of errors found.



Fig. 57 - GeoSLAM tool



Fig. 58 - Flooring point cloud plant

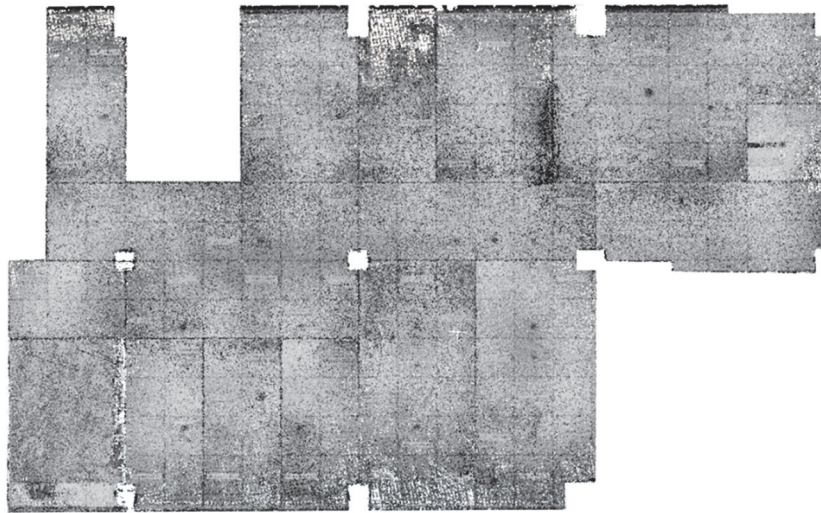


Fig. 59 - Ceiling point cloud plant

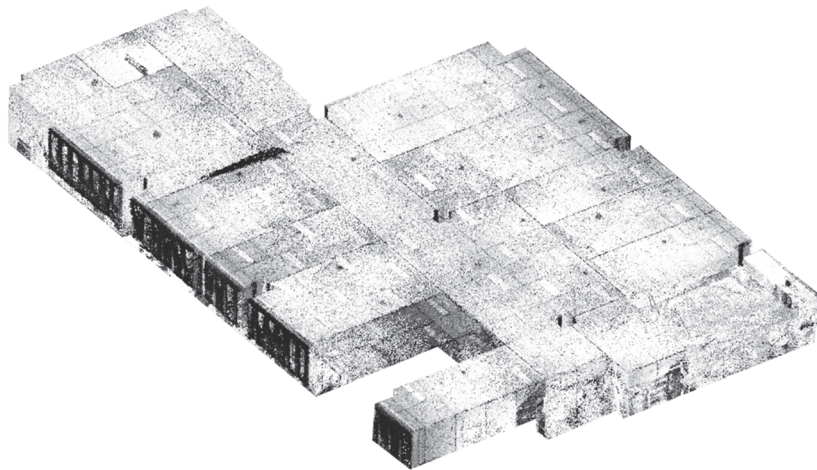


Fig. 60 - Point cloud view

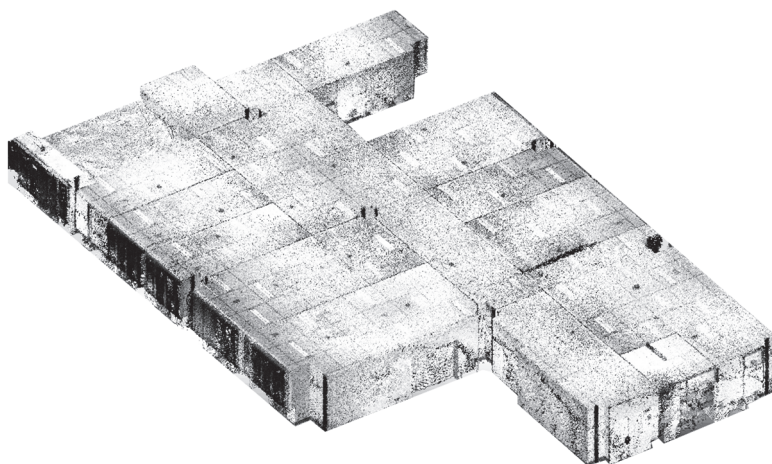


Fig. 61 - Point cloud view

4.1.2. Photographic surveying:

Ricoh Theta 360° panoramic camera was used to produce the photographic surveying, which was developed taking 2 photos in the bigger rooms and one in the smaller. There were a total of 23 images taken.



Fig. 62 - Photographic surveying map and Ricoh Theta Z1



Photo 1 - Entrance 1



Photo 2 - Entrance 2



Photo 3 - Waiting area 1



Photo 4 - Waiting area 2



Photo 5 - Waiting area 3

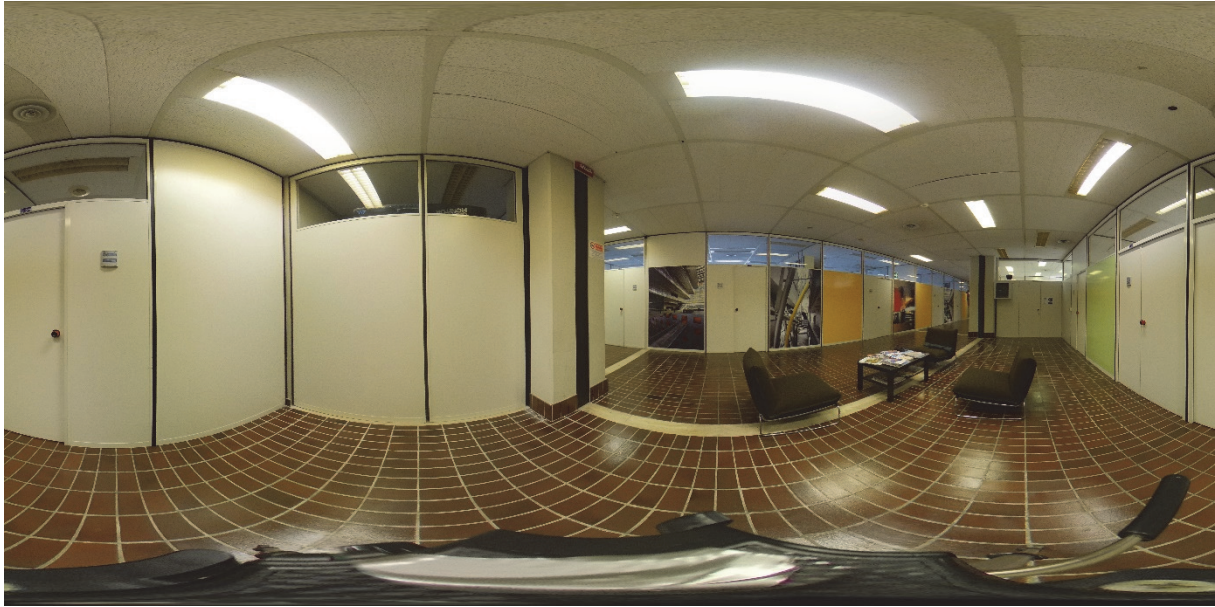


Photo 6 - Waiting area 4

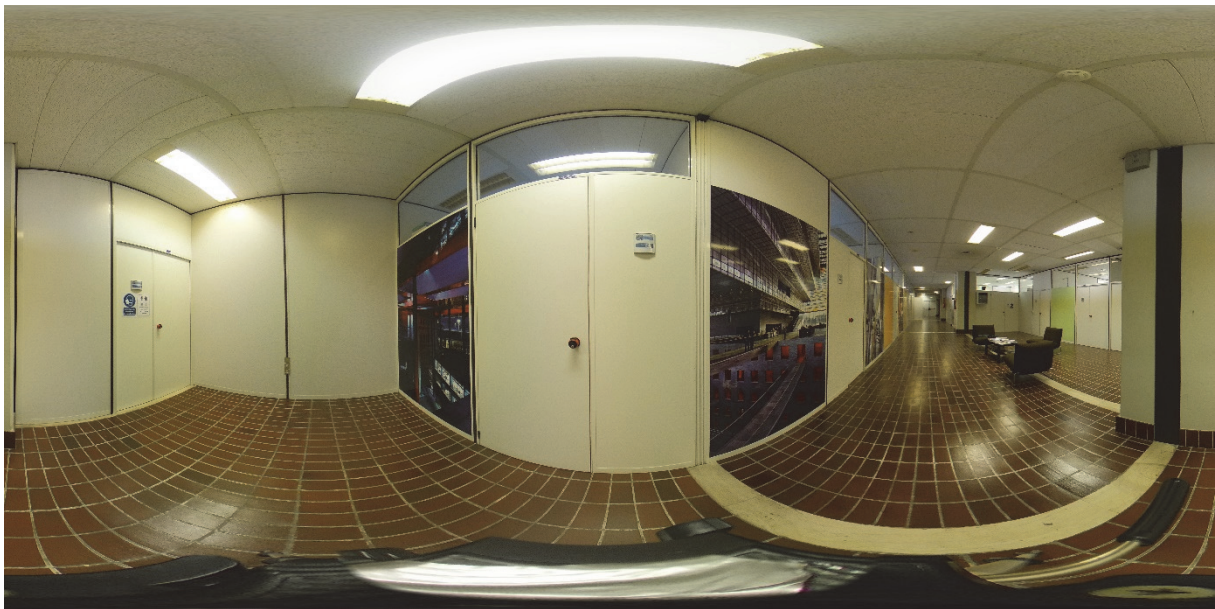


Photo 7 - Waiting area 5



Photo 8 - Technical room



Photo 9 - Conference room 1



Photo 10 - Conference room 2



Photo 11 - Office 1



Photo 12 - Office 2



Photo 13 - Office 3



Photo 14 - Office 4



Photo 15 - Office 5



Photo 16 - Study room 1

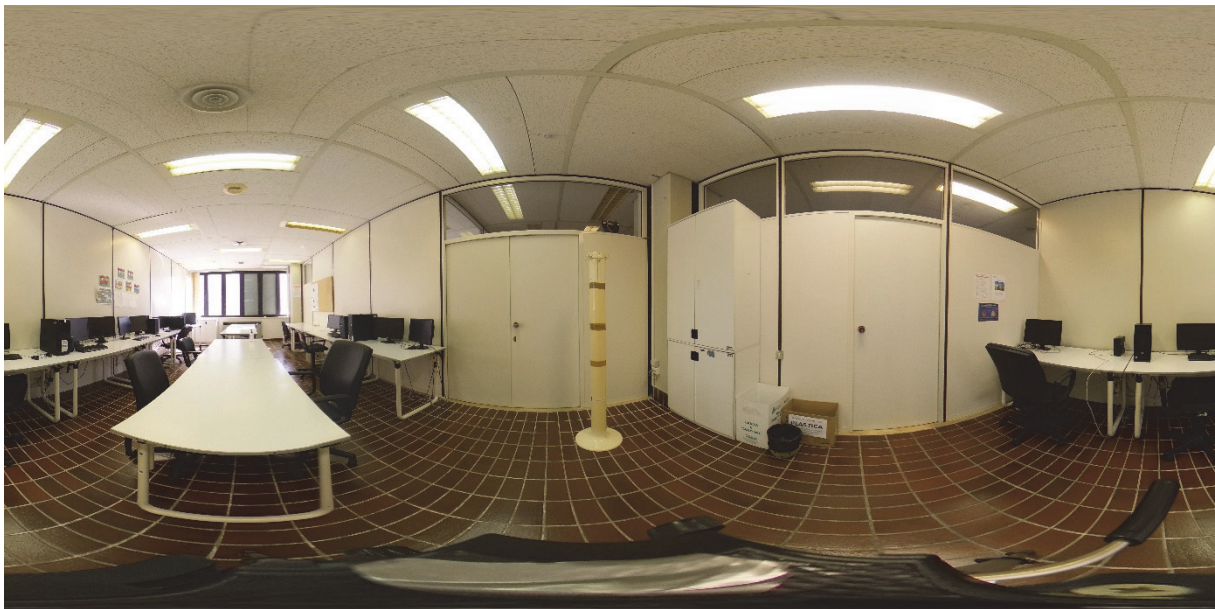


Photo 17 - Study room 2



Photo 18 - Study room 3



Photo 19 - Office 6



Photo 20 - Office 7



Photo 21 - Office 8



Photo 22 - Storing 1



Photo 23 - Storing 2

4.1.3. BIM modelling:

As said before, the BIM model was developed in LOD 500 with Revit. The high level of detail required is due to the possible comparison with the scene, to verify the errors or omission of elements. The detail elements imported inside the model were the subsequent:

- lightings;
- audio systems;
- venting systems (suction and emission);
- fire alarm systems;
- internet repeaters;
- radiators;
- fire protection systems;
- light switches;
- electrical outlet;

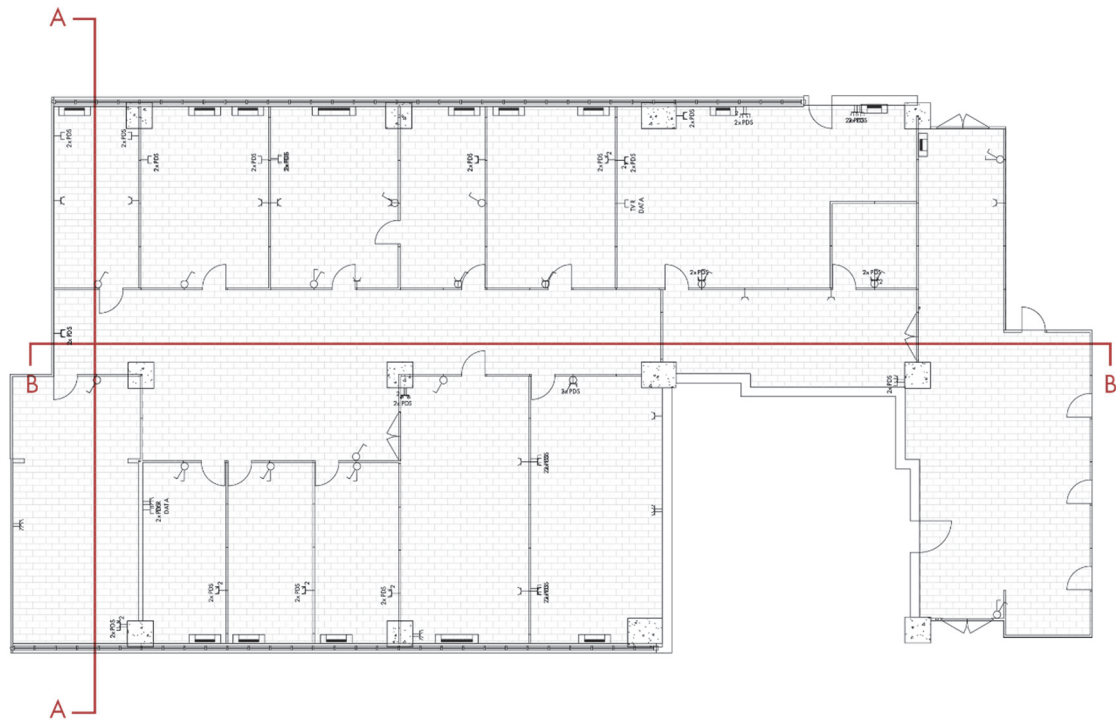


Fig. 63 - Flooring plan

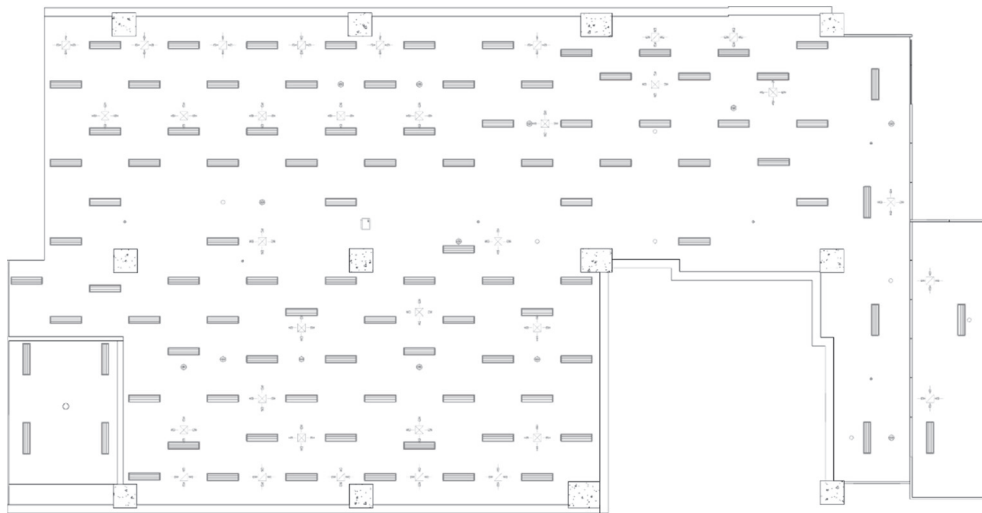


Fig. 64 - Ceiling plan

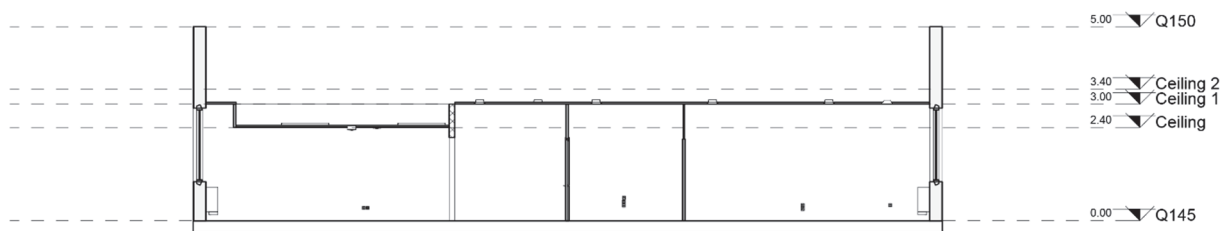


Fig. 65 - Section A-A

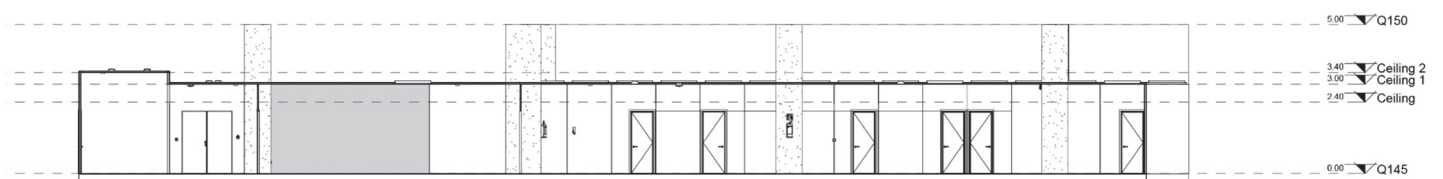


Fig. 66 - Section B-B

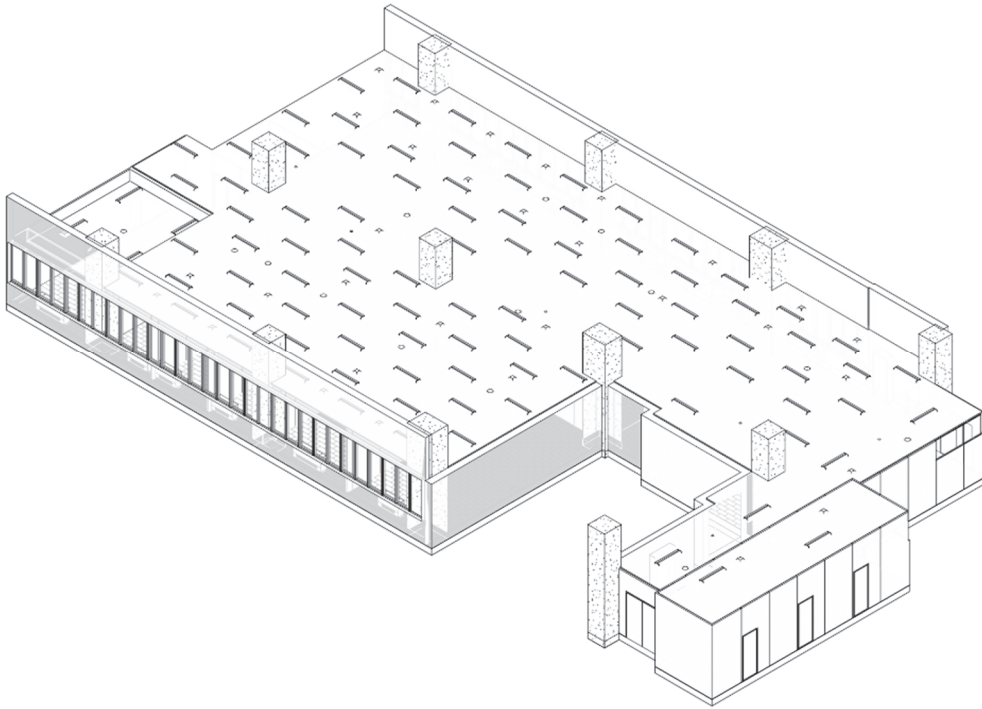


Fig. 67 - 3D model view

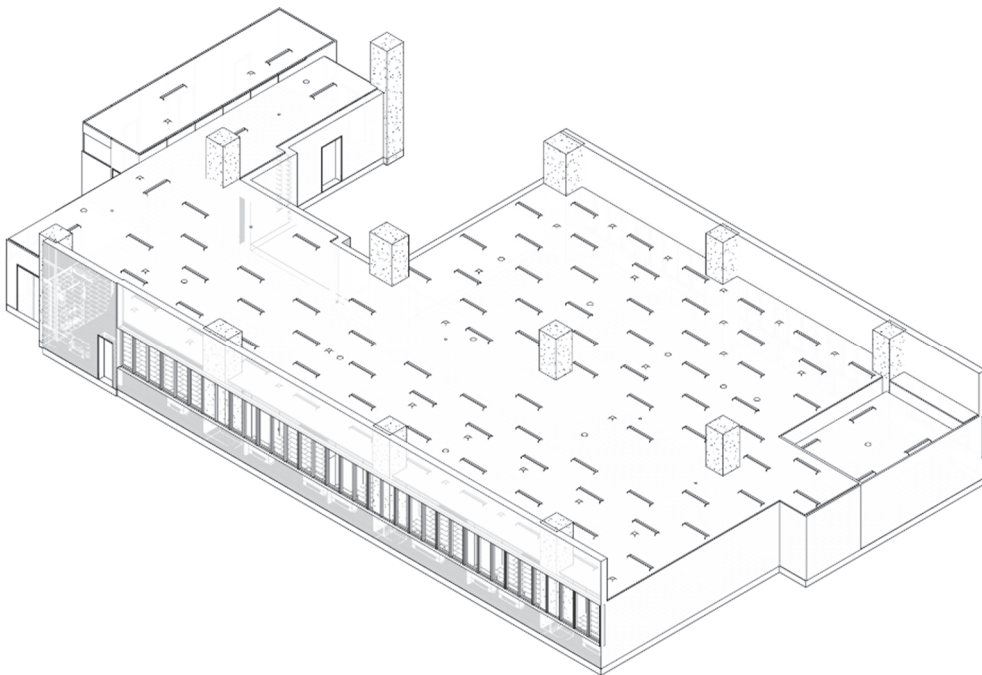


Fig. 68 - 3D model view

4.2. Virtual Reality process

After the modelling of the 3D BIM environment, the subsequent stages of work are developed and implemented in Unity 3D Game Engine. It was chosen because of the game engine diffusion, the free version, the opportunity to exchange different format files and the simplicity of inside working.

4.2.1. Importation in Unity 3D Game Engine:

To import the IFC model was developed a new Unity scene, which allows the insertion of the geometry and the connected properties of the elements. The Mesh Collider component was applied inside the 3D geometries to recreate a physical geometry that can be hit with the mouse.

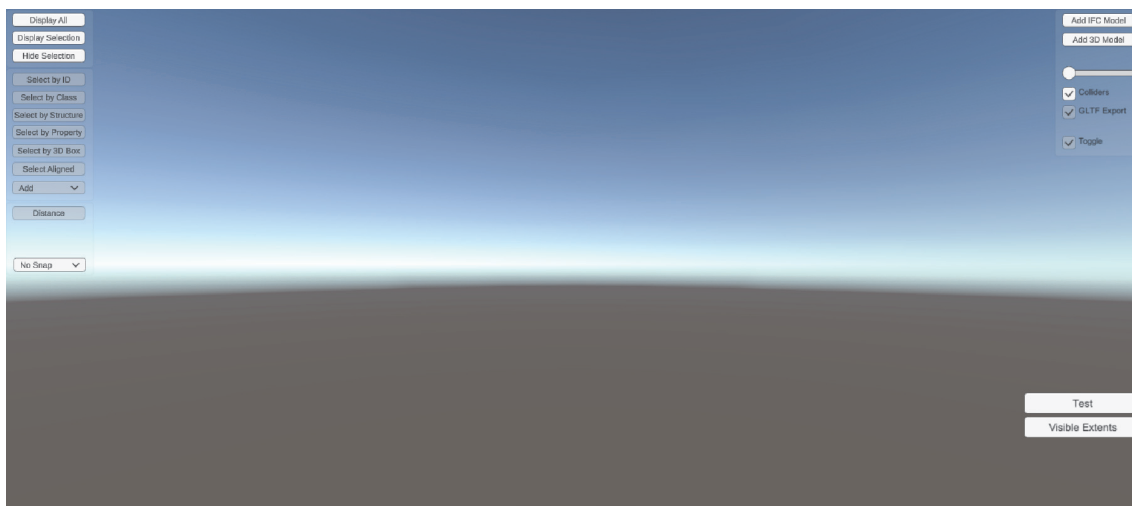


Fig. 69 - Unity 3D IFC importer viewport

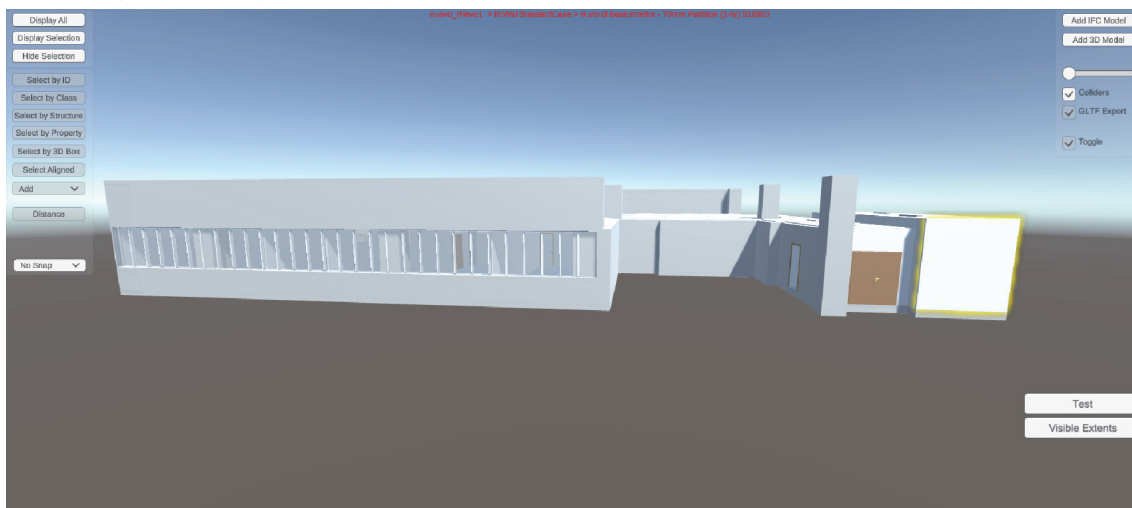


Fig. 70 - Model importation and properties viewport

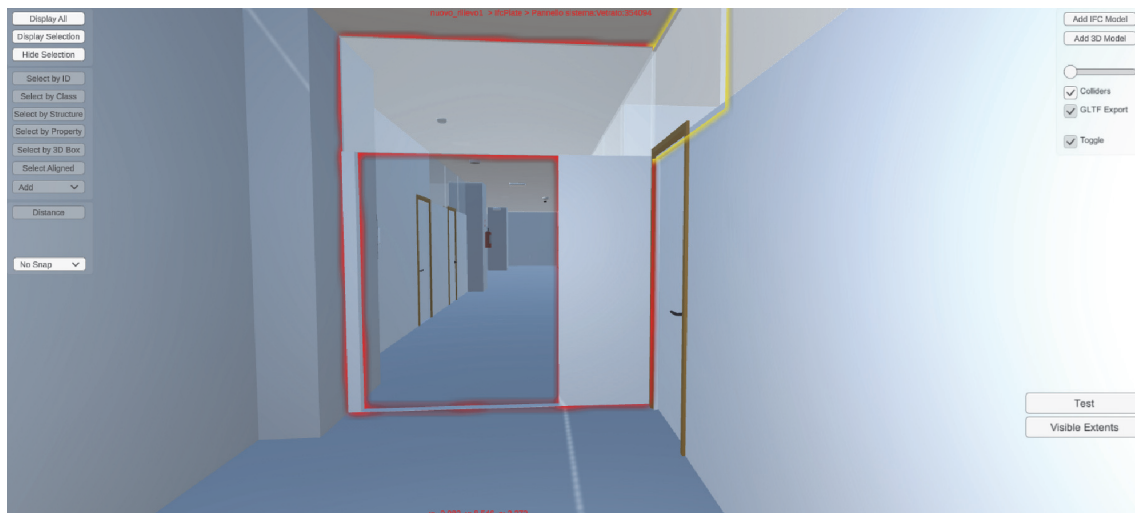


Fig. 71 - Model inside view

4.2.2. Creation of 3D space photo:

After the 3D environment setting, the next stage was the creation of a navigation system, which supports the comparison between geometry and photography. First, the polyhedric elements that contain the camera and the equirectangular images were imported. It was selected the Octahedron Sphere for the spheres mesh, because of the highest mesh subdivisions (16519 vertices and 32768 triangles), which allows to recreate regular and not distorted pictures.

OctahedronSphere Code:

```
using UnityEditor;
using UnityEngine;

public class OctahedronSphereWizard : ScriptableWizard
{
    [MenuItem("Assets/Create/Octahedron Sphere")]
    private static void CreateWizard()
    {
        ScriptableWizard.DisplayWizard<OctahedronSphereWizard>("Create
Octahedron Sphere");
    }

    [Range(0, 6)]
    public int level = 6;
    public float radius = 1f;
```

```

private void OnWizardCreate()
{
    string path = EditorUtility.SaveFilePanelInProject(
        "Save Octahedron Sphere",
        "Octahedron Sphere",
        "asset",
        "Specify where to save the mesh.");
    if (path.Length > 0)
    {
        Mesh mesh = OctahedronSphereCreator.Create(level, radius);
        MeshUtility.Optimize(mesh);
        AssetDatabase.CreateAsset(mesh, path);
        Selection.activeObject = mesh;
    }
}
}

```

With the creation of the meshes is required to create a material and apply it to the equirectangular photos. To make this possible a Shader code is needed.

In computer graphics a shader is a type of computer program used to calculate rendering effects with a high degree of flexibility. Most of the shaders are coded for a graphic processing unit (GPU), in fact are used to program the GPU's rendering pipeline with geometry transforming and pixel-shading functions. The position and the color of all pixels and textures can be altered using algorithms defined with shaders.

In this case the utilized shader was the Unlit Shader, which is applied without the need of external light. In fact, the textures used are the pictures taken with the environmental light of the case study. To invert the shader into the inside of the sphere is used the property of *"Cull"* applied with the *"front"* mode.

Inverted Unlit Shader Code:

```
Shader "Custom/Equirectangular" {
    Properties{
        _Color("Main Color", Color) = (1,1,1,1)
        _MainTex("Diffuse (RGB) Alpha (A)", 2D) = "white" {}
    }

    SubShader{
        Pass {
            Tags {"LightMode" = "Always"
            }
            LOD 200
            Cull Front

CGPROGRAM

            #pragma vertex vert
            #pragma fragment frag
            #pragma fragmentoption ARB_precision_hint_fastest
            #pragma glsl
            #pragma target 3.0

            #include "UnityCG.cginc"

            struct appdata {

                float4 vertex : POSITION;
                float3 normal : NORMAL;
            };

            struct v2f
            {
                float4    pos : SV_POSITION;
                float3    normal : TEXCOORD0;
            };
            v2f vert(appdata v)
            {
                v2f o;
                o.pos = UnityObjectToClipPos(v.vertex);
                o.normal = v.normal;
                return o;
            }

            sampler2D _MainTex;
```

```

#define PI 3.141592653589793
inline float2 RadialCoords(float3 a_coords)
{
    float3 a_coords_n = normalize(a_coords);
    float lon = atan2(a_coords_n.z, a_coords_n.x);
    float lat = acos(a_coords_n.y);
    float2 sphereCoords = float2(lon, lat) * (1.0
/ PI);

    return float2(1 - (sphereCoords.x * 0.5
+ 0.5), 1 - sphereCoords.y);}

float4 frag(v2f IN) : COLOR
{
    float2 equiUV = RadialCoords(IN.normal);
    return tex2D(_MainTex, equiUV);
}
ENDCG
}

FallBack "VertexLit"
}

```

The Inverted Shader was applied to new materials with the correct textures. These materials were related further to the spheres, recreating the 360 environment inside, and allowing the camera to visualize the virtual ambient.

The 23 materials developed:



The next step was the importation of the camera inside, with the same coordinates. The camera needs to rotate inside the spheres to visualize the 3D environment recreated inside. It rotates around his axis and zooms the field of view to show better the details. For this scope, a new script was developed, which allows the rotations and also limits the Field of View (FOV) of the camera within 10 and 100 values (to not exit from the sphere with the camera). It also defines the speed of the movements and of the FOV.

Camera Code:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;

public class CameraScript : MonoBehaviour
{
    public float speedH = 2.0f;
    public float speedV = 2.0f;
    public float maxCamFOV = 100f;
    public float minCamFOV = 10f;
    public float fovSpeed = 10.0f;
    public Transform target;
    public Camera myCam;
    private float yaw;
    private float pitch;

    float initialFOV;
    float scroll;

    // Use this for initialization
    void Start()
    {
        myCam = this.GetComponent<Camera>();
        yaw = this.transform.eulerAngles[1];
        pitch = this.transform.eulerAngles[0];
        initialFOV = myCam.fieldOfView;
    }
    void ResetFOV()
    {
        myCam.fieldOfView = initialFOV;
    }
    // Update is called once per frame
    void LateUpdate()
    {
        if (Input.GetMouseButton(0))
        {
            yaw += speedH * Input.GetAxis("Mouse X");
            pitch -= speedV * Input.GetAxis("Mouse Y");
            if (yaw > 360) yaw -= 360;
            if (pitch > 360) pitch -= 360;
        }
    }
}
```

```

        if (yaw < -360) yaw += 360;
        if (pitch < -360) pitch += 360;

        gameObject.transform.eulerAngles = new Vector3(pitch, yaw,
0.0f);
    }
    scroll = Input.GetAxis("Mouse ScrollWheel");
    if (scroll!=0f)
    {
        myCam.fieldOfView += scroll * fovSpeed;
        if (myCam.fieldOfView < minCamFOV) myCam.fieldOfView =
minCamFOV;
        if (myCam.fieldOfView > maxCamFOV) myCam.fieldOfView =
maxCamFOV;
    }
}

```

4.2.3. Model navigation:

To navigate through the images, with a virtual tour, was developed a map that enables and deactivates the spheres clicking on the buttons of the rooms. The map is a "raw image" inserted in the UI hierarchy where the texture is the floor plan of the department. The buttons are created also in the UI hierarchy, and the only command added is:

"button" - Button - OnClick - + - Runtime Only - "picture" -
 GameObject.SetActive - Checkmark

For every button of each room is activated only the checkmark of the selected ambient, deactivating the marker of the other rooms.



Fig. 72 - Example of the Button inspector setup

When starts the runtime game mode, the camera change position inside the activated sphere through the "C# Alignment Function Code":

```
void saveInitialState()
{
    InitialCameraTransform.position = camera.transform.position;
    InitialImageTransform.rotation = myPict.transform.rotation;
    InitialImageTransform.position = myPict.transform.position;
}
```

4.2.4. Photo alignment:

It is important to see the coordinates of the mouse position and move the camera position through the enabled sphere ambient. To make this, was used the previous stated "C# Alignment function code".

Moreover, the code was applied to find the right alignment between photos and environment, which was done manually, selecting 4 points inside the images and the same 4 points in the model space. The alignment points for each sphere and the right camera position are submitted in the following tables:

Entrance 1							
	Camera	A	B	C	D	Position	Rotation
X	3,757	6,174	6,602	-2,221	-1,759	3,767	-0,451
Y	1,248	3,000	3,000	0,000	3,000	1,274	-129,042
Z	6,820	5,153	8,534	6,027	5,613	6,818	-0,786

Entrance 2							
	Camera	A	B	C	D	Position	Rotation
X	-9,860	-1,763	-2,250	6,171	-2,229	-1,082	-0,444
Y	1,210	3,000	3,000	3,000	0,000	1,252	-68,876
Z	7,140	5,613	8,526	5,156	8,525	6,813	-1,119

Waiting Hall 1							
	Camera	A	B	C	D	Position	Rotation
X	-4,470	-2,283	-2,287	-10,903	-2,966	-5,786	-0,542
Y	1,211	3,000	3,000	3,000	0,000	1,281	79,337
Z	6,890	6,027	8,522	5,597	5,597	7,014	-0,962

Waiting Hall 2							
	Camera	A	B	C	D	Position	Rotation
X	-9,860	-10,905	-2,986	-2276,000	-23,352	-10,557	0,471
Y	1,211	3,000	3,000	3,000	3,000	1,302	-135,813
Z	7,140	5,597	5,610	8,528	8,540	7,177	0,050

Waiting Hall 3							
	Camera	A	B	C	D	Position	Rotation
X	-13,310	-11,396	-11,808	-20,309	-23,361	-13,637	-1,018
Y	1,211	2,578	3,000	3,000	3,000	1,283	-123,275
Z	4,120	3,000	6,023	5,104	8,536	4,122	-1,260
Waiting Hall 4							
	Camera	A	B	C	D	Position	Rotation
X	-18,020	-20,316	-11,403	-11,399	-20,292	-18,544	-0,169
Y	1,211	3,000	3,000	0,000	0,000	1,256	-123,496
Z	4,210	5,103	2,577	5,126	5,107	4,030	-0,782
Technical Room							
	Camera	A	B	C	D	Position	Rotation
X	5,180	3,664	3,654	3,654	3,655	4,777	-0,186
Y	1,081	3,000	3,000	3,000	3,000	1,288	-17,838
Z	10,030	8,598	11,525	11,525	11,526	10,328	-0,448
Meeting Room 1							
	Camera	A	B	C	D	Position	Rotation
X	-0,900	-3,815	6,166	-1,767	3,581	-0,860	-0,729
Y	1,081	3,000	3,000	3,000	3,000	1,273	128,137
Z	11,380	8,596	14,943	14,124	8,598	11,468	-0,412
Meeting Room 2							
	Camera	A	B	C	D	Position	Rotation
X	3,190	6,581	6,172	3,585	-3,814	3,128	-0,298
Y	1,081	3,000	3,000	3,000	3,000	1,291	-79,235
Z	13,030	11,600	14,945	8,578	8,593	12,912	-0,687
Office 1							
	Camera	A	B	C	D	Position	Rotation
X	-6,460	-3,885	-8,320	-8,322	-3,893	-6,651	-0,414
Y	2,000	3,000	3,000	3,000	3,000	1,340	69,624
Z	11,030	8,594	8,600	14,889	14,888	11,651	-0,719
Office 2							
	Camera	A	B	C	D	Position	Rotation
X	-9,760	-8,396	-8,405	-11,342	-11,346	-9,757	-0,469
Y	2,000	3,000	0,000	3,000	3,000	1,276	48,154
Z	10,000	8,596	8,616	8,579	14,132	10,457	-0,888
Office 3							
	Camera	A	B	C	D	Position	Rotation
X	-14,052	-11,423	-11,419	-15,844	-11,849	-14,052	-0,335
Y	2,000	3,000	3,000	3,000	3,000	1,294	135,512
Z	10,000	14,127	8,597	8,596	14,133	12,534	-0,755
Office 4							
	Camera	A	B	C	D	Position	Rotation
X	-18,110	-20,356	-20,355	-15,918	-19,955	-17,973	-0,249
Y	2,000	3,000	3,000	3,000	3,000	1,274	9,260
Z	10,920	14,133	8,596	8,600	14,135	11,512	-0,145

Office 5							
	Camera	A	B	C	D	Position	Rotation
X	-21,920	-20,433	-23,376	-20,426	-21,846	-21,759	0,205
Y	2,000	3,000	3,000	3,000	0,000	1,289	-65,955
Z	10,360	14,124	8,577	8,595	8,596	11,667	-0,373
Study Room 1							
	Camera	A	B	C	D	Position	Rotation
X	-4,200	-2,249	-6,811	-6,786	-2,249	-4,587	-0,447
Y	1,211	3,000	3,000	0,000	3,000	1,291	108,794
Z	1,800	-2,876	5,518	5,506	5,124	0,049	-0,483
Study Room 2							
	Camera	A	B	C	D	Position	Rotation
X	-9,190	-10,904	-6,891	-11,326	-11,317	-9,228	-0,257
Y	1,211	3,000	3,000	0,000	3,000	1,289	-161,996
Z	2,190	5,522	5,524	5,126	-2,956	3,915	-1,009
Study Room 3							
	Camera	A	B	C	D	Position	Rotation
X	-9,12	-11,316	-10,904	-6,895	11,322	-8,983	-0,052
Y	1,211	3,000	3,000	3,000	3,000	1,277	-152,649
Z	-0,600	-2,972	5,517	5,510	5,114	0,231	-0,962
Office 6							
	Camera	A	B	C	D	Position	Rotation
X	-12,670	-14,316	-14,287	-11,397	-11,396	-13,524	-0,100
Y	2,000	3,000	0,000	3,000	3,000	1,278	169,497
Z	0,390	2,525	2,506	2,543	-2,974	-0,508	-1,306
Office 7							
	Camera	A	B	C	D	Position	Rotation
X	-15,780	-17,330	-17,304	-14,383	-15,864	-16,157	-0,248
Y	2,000	3,000	0,000	3,000	0,000	1,272	86,498
Z	0,820	2,534	2,506	2,545	2,526	-1,035	-0,771
Office 8							
	Camera	A	B	C	D	Position	Rotation
X	-18,490	-20,286	-20,285	-17,397	-17,396	-18,795	-0,389
Y	2,000	3,000	3,000	0,000	3,000	1,268	-134,679
Z	0,110	2,543	-2,974	2,526	2,523	-0,459	-0,630
Storage 1							
	Camera	A	B	C	D	Position	Rotation
X	-21,440	-24,816	-20,796	-24,816	-20,346	-22,533	0,223
Y	1,081	3,000	3,000	3,000	3,000	1,268	81,159
Z	4,360	5,521	5,521	2,662	2,600	3,991	-0,937
Storage 2							
	Camera	A	B	C	D	Position	Rotation
X	-23,140	-24,789	-24,792	-20,816	-20,796	-23,286	0,632
Y	1,081	2,400	2,400	3,000	2,140	1,285	106,926
Z	-3,180	2,492	-3,048	-3,048	2,512	-3,089	-0,407

The starting position of the camera was set approximately to the real position: it was placed randomly with the mouse, positioning where it was considered right the photoshoot position. Starting with this position the corrections that came out from the pose estimation have small standard deviations, this means that the alignment is done well. One camera property that doesn't change in the different cameras is the "Y" coordinate, which is the tripod height, and it's approximately 1,3 meters.

The last consideration is about the camera rotation: from the corrections appear different changes also in the "X" and "Z" rotation, these are contained into 0,5 - 1 degrees, and means that the camera wasn't perfectly perpendicular to the floor.

To save the positions and rotations when exit from the runtime mode, two scripts were developed: one for creating the SAVE_FOLDER, and defining the save or load settings, and the other to compile the saving and the loading of the positions and rotations.

SaveSystem Code:

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System.IO;

public static class SaveSystem
{
    public static readonly string SAVE_FOLDER = Application.dataPath +
    "/Saves/";

    public static void Init(string name)
    {
        // Test if Save exists
        if (!Directory.Exists(SAVE_FOLDER + name))
        {
            // Create Save Folder
            Directory.CreateDirectory(SAVE_FOLDER + name);
            Debug.Log("Created");
        }
    }

    public static void Save (string saveString, string name)
```

```

        {
            File.WriteAllText(SAVE_FOLDER + name + "/saveFile.json",
saveString);
        }

        public static string Load(string name)
        {
            if (File.Exists(SAVE_FOLDER + name + "/saveFile.json"))
            {
                string saveString = File.ReadAllText(SAVE_FOLDER + name +
"/saveFile.json");
                Debug.Log("SaveSystemLoad, " + saveString);
                return saveString;
            }else
                return null;
        }
    }
}

```

Save and Load Code:

```

using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System.IO;

public class GameHandler : MonoBehaviour
{
    // Start is called before the first frame update
    private void Awake()
    {
        string name = gameObject.name;
        SaveSystem.Init(name);
    }

    private void LateUpdate()
    {
        if (Input.GetKeyDown(KeyCode.S))
            Save();

        if (Input.GetKeyDown(KeyCode.L))
            Load();
    }
}

```

```

private void Save()
{
    // Nome
    string name = gameObject.name;

    // Posizione
    float pos_x = transform.position.x;
    float pos_y = transform.position.y;
    float pos_z = transform.position.z;

    // Rotazione

    Vector3 angles = transform.eulerAngles;
    Debug.Log(angles);
    float rot_x = angles.x;
    float rot_y = angles.y;
    float rot_z = angles.z;

    SphereData sphereData = new SphereData();
    sphereData.position = new Vector3(pos_x, pos_y, pos_z);
    sphereData.rotation = new Vector3(rot_x, rot_y, rot_z);

    string jsonToWrite = JsonUtility.ToJson(sphereData);
    SaveSystem.Save(jsonToWrite, name);

    Debug.Log("SAVED!");
}

private void Load()
{
    string name = gameObject.name;

    string saveString = SaveSystem.Load(name);
    if(saveString != null)
    {
        Debug.Log("LOADED!");

        SphereData sphereData =
JsonUtility.FromJson<SphereData>(saveString);

        this.gameObject.transform.position = sphereData.position;
    }
}

```

```

        this.gameObject.transform.eulerAngles = sphereData.rotation;
    }
}

private class SphereData
{
    public Vector3 position;
    public Vector3 rotation;
}
}

```

4.2.5. Model measurement:

The augmented BIM model, to be perfectly comparable with the images, needs to be measurable directly in Unity. To make this possible was developed a C# code that measures the distance between two selected points. The first step was the creation of two empty objects, which will change position when the mouse clicks on the model components (hits the mesh collider of the objects), the tool permits to measure the distance created between the two sets of coordinates. To facilitate the view of the measurer tool, was implemented a "line renderer" component on the main camera, which expresses graphically the distance between the hits.

DistanceMeasurer Code:

The distance measurement is allowed by the Raycast hit on the mesh collider of the objects. It is the difference between two sets of points coordinates. The line that shows the distance is made by the Line Renderer object, where an occluded material was applied, which consents to show it inside the images.

```

using UnityEngine;
using System.Collections;
using UnityEngine.UI;

public class checkDistance : MonoBehaviour
{
    private bool firstPoint = false;

```

```

private bool secondPoint = false;

public Transform firstTransform; // just an empty gameobject for these
public Transform secondTransform;
public LineRenderer lineRend;

public Text UIText;

// Use this for initialization
private void Start()
{
    lineRend = GetComponent<LineRenderer>();
    lineRend.positionCount = 2;
}

// Update is called once per frame
void Update()
{
    Ray ray = Camera.main.ScreenPointToRay(Input.mousePosition); //
gets mouse position on a floor/object
    RaycastHit hit;

    if (Physics.Raycast(ray, out hit))
    {
        if (Input.GetKey(KeyCode.A) && Input.GetMouseButtonDown(0) &&
!firstPoint)
        {
            firstTransform.position = hit.point; // hit.point is the
current mouse position
            firstPoint = true;
            lineRend.SetPosition(0, new Vector3(hit.point.x,
hit.point.y, hit.point.z));
            lineRend.SetPosition(1, new Vector3(hit.point.x,
hit.point.y, hit.point.z));
            Debug.Log("First Point Clicked!");
        }
        if (Input.GetKey(KeyCode.A) && Input.GetMouseButtonDown(1) &&
!secondPoint)
        {
            secondTransform.position = hit.point;
            secondPoint = true;

```

```

        lineRend.SetPosition(1, new Vector3(hit.point.x,
hit.point.y, hit.point.z));
        Debug.Log("Second Point Clicked!");
    }
}

    if (firstPoint && secondPoint) // when both conditions are true,
print out the distance
    {
        UIText.text = Vector3.Distance(firstTransform.position,
secondTransform.position).ToString();
        firstPoint = false;
        secondPoint = false;
    }

}
}

```

4.2.6. Model enrichment:

The final code developed allows the model enrichment by the importation of elements directly in the scene. The imported objects can translate and rotate by defined degrees, also, for the higher precision, were inserted inside the Game Engine snap elements, which permit the selection from the vertices of the elements meshes. The rotation is developed with the LookRotation function, that, defined the forward direction and the normal vectors, consents to rotate the element in the orthogonal direction of the normal. The object rotation is done around his local origin, so after the rotation the object needs to be translated again.

```

using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

public class instantiate : MonoBehaviour
{
    //Prefabs that need to be instantiated
    public GameObject inPrefab;

```



```

//Instantiated object
private GameObject inObj;

public new Camera camera;
public Selectable button;
public GameObject SnapBall;
public bool secondbool = false;
public bool thirdbool = false;

// Start is called before the first frame update
void Start()
{
    if (inPrefab == null) return;
}

public void SnapOnVertex(RaycastHit hitInfo, GameObject go)
{
    if (hitInfo.collider == null) return;
    Transform transform = hitInfo.collider.transform;
    //GameObject go = transform.gameObject;
    MeshFilter mf = transform.gameObject.GetComponent<MeshFilter>() as
MeshFilter;
    if (mf.mesh == null) return;

    Vector3 p = new Vector3();
    Vector3 hitVertex = new Vector3();
    float mindist = float.PositiveInfinity;
    float dist;
    int index = -1;
    Mesh mesh = mf.mesh;

    if (hitInfo.triangleIndex != -1)
    {
        Transform hitTransform = hitInfo.collider.transform;
        for (int i = 0; i < 3; i++)
        {

```

```

                p =
hitTransform.TransformPoint(mesh.vertices[mesh.triangles[hitInfo.triangleIndex * 3 + i]]);

                dist = Vector3.Distance(hitInfo.point, p);
                if (dist < mindist)
                {
                    index = i;
                    mindist = dist;
                    hitVertex = p;
                }
            }
            go.transform.position = hitVertex;
        }
    else
    {
        Transform hitTransform = hitInfo.collider.transform;
        for (int i = 0; i < mesh.vertices.Length; i++)
        {
            p = hitTransform.TransformPoint(mesh.vertices[i]);
            dist = Vector3.Distance(hitInfo.point, p);
            if (dist < mindist)
            {
                index = i;
                mindist = dist;
                hitVertex = p;
            }
        }
        go.transform.position = hitVertex;
    }
}

// Update is called once per frame
void Update()
{
    if (button.enabled == true)
    {
        if (Input.GetKey(KeyCode.F) && Input.GetMouseButtonDown(0))
        {
            RaycastHit hitInfo = new RaycastHit();

```

```

        bool hit =
Physics.Raycast(Camera.main.ScreenPointToRay(Input.mousePosition), out
hitInfo);

        if (hit)
        {
            inObj = Instantiate(inPrefab, hitInfo.point,
Quaternion.identity) as GameObject;
            inObj.SetActive(true);
        }
    }

    Vector3 newRotationAngles = new Vector3 ();
    if (Input.GetKeyDown(KeyCode.R))
    {
        newRotationAngles.x += 90;
        inObj.transform.eulerAngles = newRotationAngles;
    }

    if (Input.GetKey(KeyCode.G) && Input.GetMouseButtonDown(1))
    {
        RaycastHit hitInfo = new RaycastHit();
        bool hit =
Physics.Raycast(Camera.main.ScreenPointToRay(Input.mousePosition), out
hitInfo);

        if (hit)
        {
            SnapOnVertex(hitInfo, SnapBall);
            Vector3 snapOrig = SnapBall.transform.position;
        }
    }

    Vector3 normal = new Vector3();
    Vector3 snapOrig1 = SnapBall.transform.position;
    if (Input.GetKey(KeyCode.G) && Input.GetMouseButtonDown(0))
    {
        RaycastHit hitInfo2 = new RaycastHit();
        bool hit2 =
Physics.Raycast(Camera.main.ScreenPointToRay(Input.mousePosition), out
hitInfo2);

        if (hit2)
        {

```

```

        Vector3 snapDest = hitInfo2.point;
        normal = hitInfo2.normal;
        inObj.transform.position += snapDest - snapOrig1;
        SnapBall.transform.position = snapDest;
    }
}

Vector3 firstpoint = SnapBall.transform.position;
Vector3 secondpoint = new Vector3();
Vector3 thirdpoint = new Vector3();

if (Input.GetKey(KeyCode.H) && Input.GetMouseButtonDown(0) &&
!secondbool)
{
    Debug.Log("click1");
    RaycastHit hitInfo3 = new RaycastHit();
    bool hit3 =
Physics.Raycast(Camera.main.ScreenPointToRay(Input.mousePosition), out
hitInfo3);

    if (hit3)
    {
        secondbool = true;
        secondpoint = hitInfo3.point;
        Debug.Log(secondpoint);
    }
}

if (Input.GetKey(KeyCode.H) && Input.GetMouseButtonDown(1) &&
!thirdbool)
{
    Debug.Log("click2");
    RaycastHit hitInfo3 = new RaycastHit();
    bool hit3 =
Physics.Raycast(Camera.main.ScreenPointToRay(Input.mousePosition), out
hitInfo3);

    if (hit3)
    {
        thirdbool = true;
        thirdpoint = hitInfo3.point;
        Debug.Log(thirdpoint);
    }
}

```

```

        }
    }

    if (secondbool && thirdbool)
    {
        Vector3 forwardDirection = secondpoint - firstpoint;
        Vector3 rightDirection = thirdpoint - firstpoint;
        Vector3 z = Vector3.Cross(secondpoint - firstpoint,
thirdpoint - firstpoint);

        Quaternion orientation =
Quaternion.LookRotation(firstpoint-thirdpoint, normal);

        inObj.transform.rotation = orientation;

        secondbool = false;
        thirdbool = false;}
    }
}

```

Results

This methodology permits to compare the real world with the virtual environment recreated. The developed software is able to recreate an as-built environment where it's possible to visualize the properties or errors, take measures and place objects in the scene. The final augmented BIM model results precise with a centimetre as the margin of error.

In this case, the principal errors are based on omissions of details, such as the glass panels for lighting and the radiator inside the Storage, or the position of elements, like the door inside Office n. 3.

These are elementary errors, but useful to understand the potentiality of this methodology, which helps not only with the surveying but also with the modelling itself.

The placing of the MEP elements are other errors that were noticed in the comparison. It was particularly difficult to set the elements on the ceiling, because of the complication of surveying. In fact, the modelling of illumination, audio and venting was based on the substructure of the suspended ceiling. This method of planning was approximately correct but at the same time it leads to errors about centimetres unit. Through the translating and placing of the elements, these errors were completely corrected.

Model errors

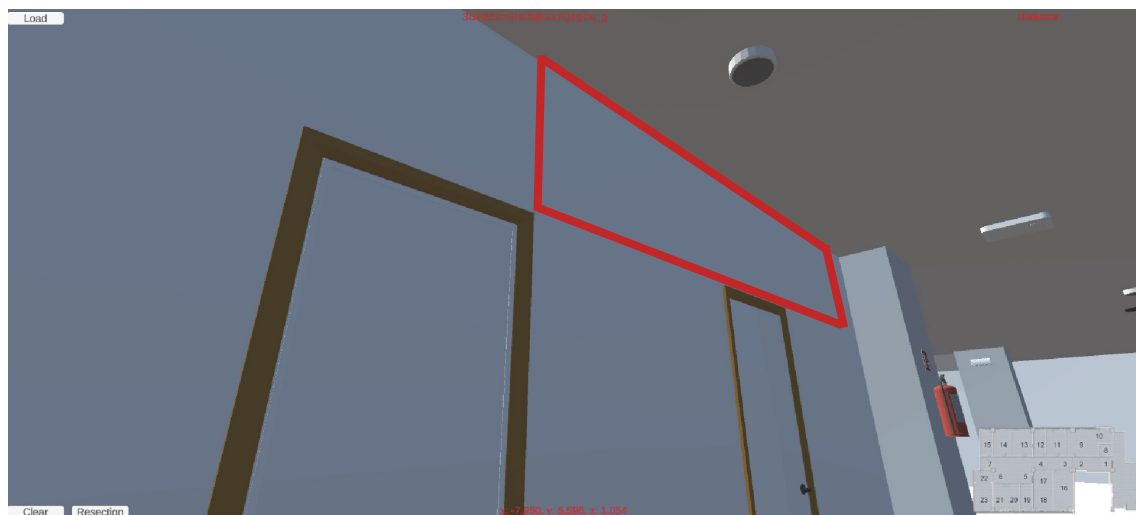


Fig. 77 - Absence of the windows inside the studying room

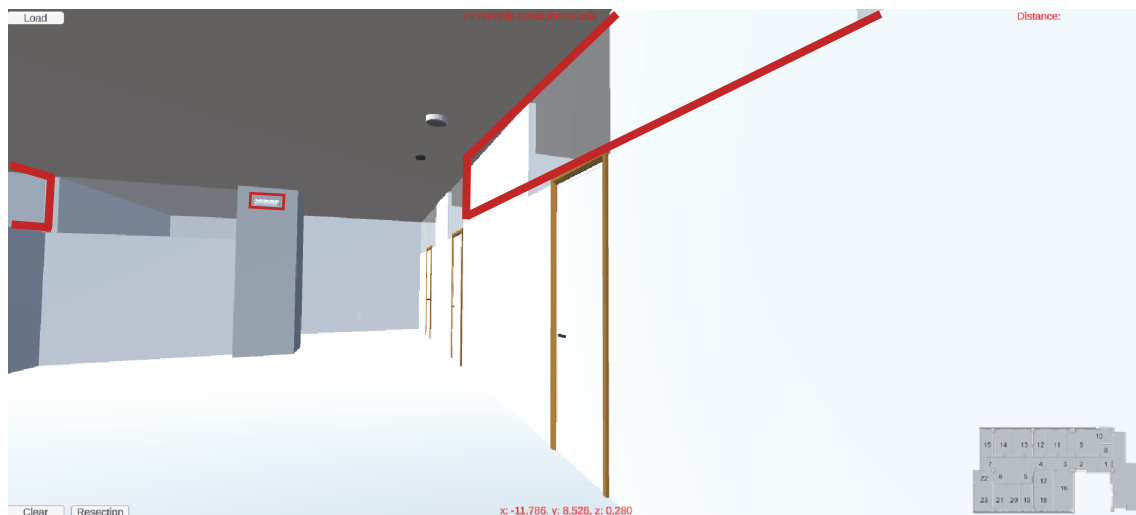


Fig. 78 - Absence of the windows inside the offices and wrong positioning

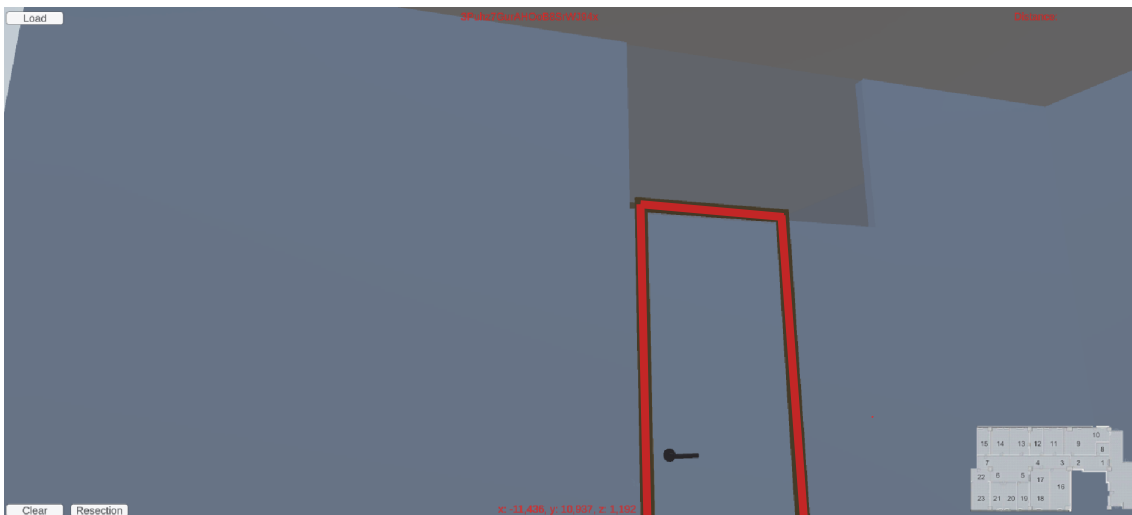


Fig. 79 - Wrong positioning of the door

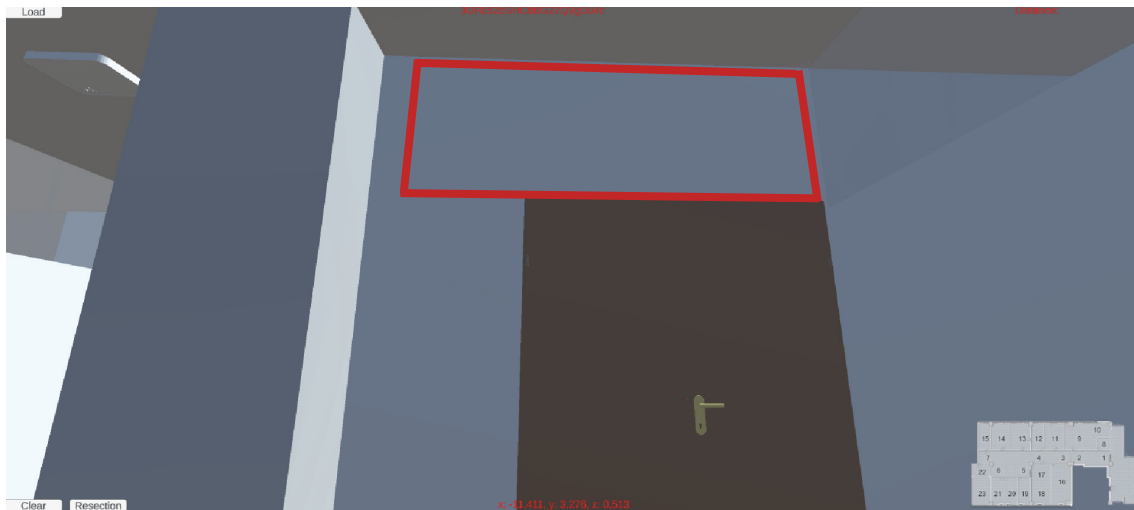


Fig. 80 - Absence of the windows inside the studying room

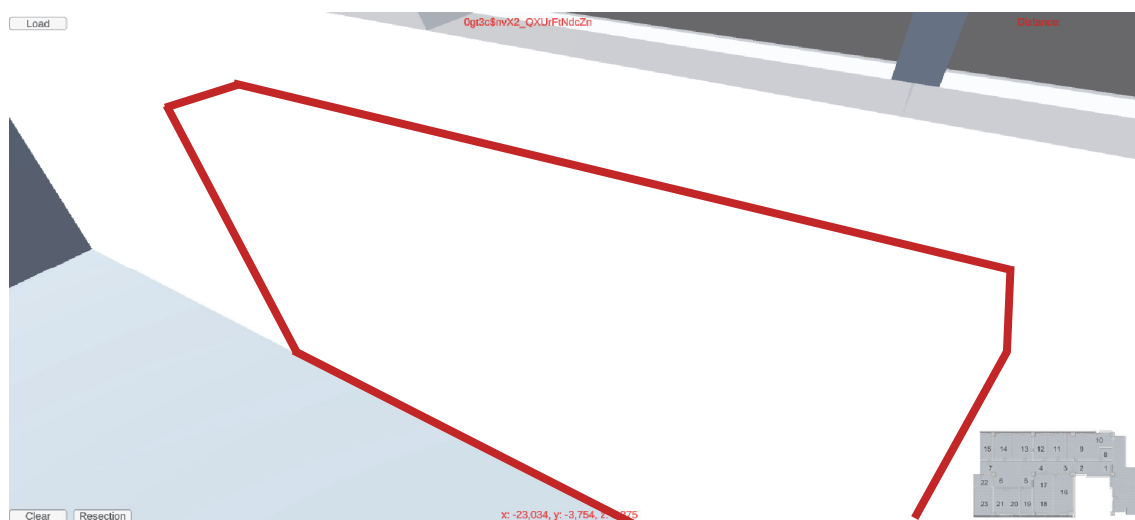
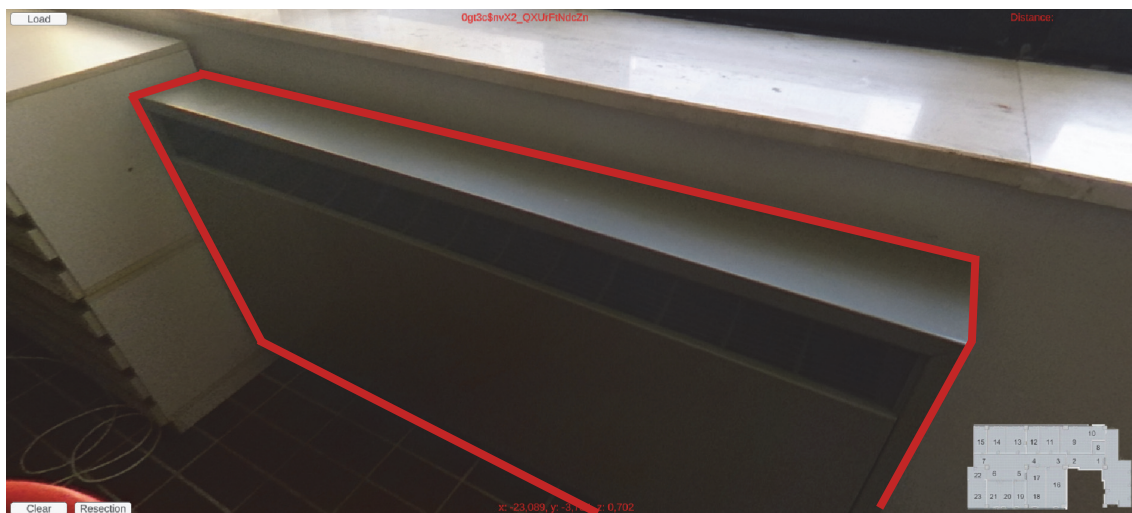


Fig. 81 - Absence of the radiator inside the storage

Model measurement

The two models perfect alignment, i.e. geometric and photographic, allows the accurate measurement on the pictures. This is available because of the 3D virtual model in the background, which is the only measured. By this technique, it is possible to quote and compute the entire photographic environment.

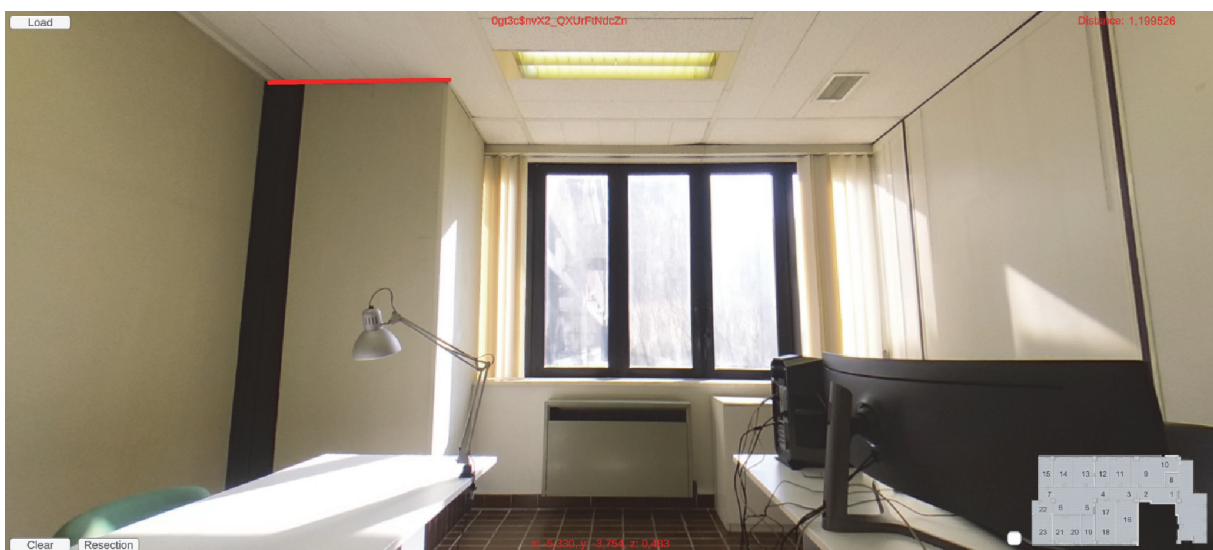


Fig. 82 - Examples of measuring

Model enrichment

The last result of the developed methodology is the placing of objects and details directly in the scene. Selecting directly from a panel, the elements can be translated, rotated and placed on the model. That allows the opportunity to create augmented models only when required in the project stage, leaving out the unnecessary elements.

The advantage of this technique is the precision, the time saving and the recreation of an as-built environment in a few steps, by starting from a poor geometric model without the necessity to survey directly the ambient.

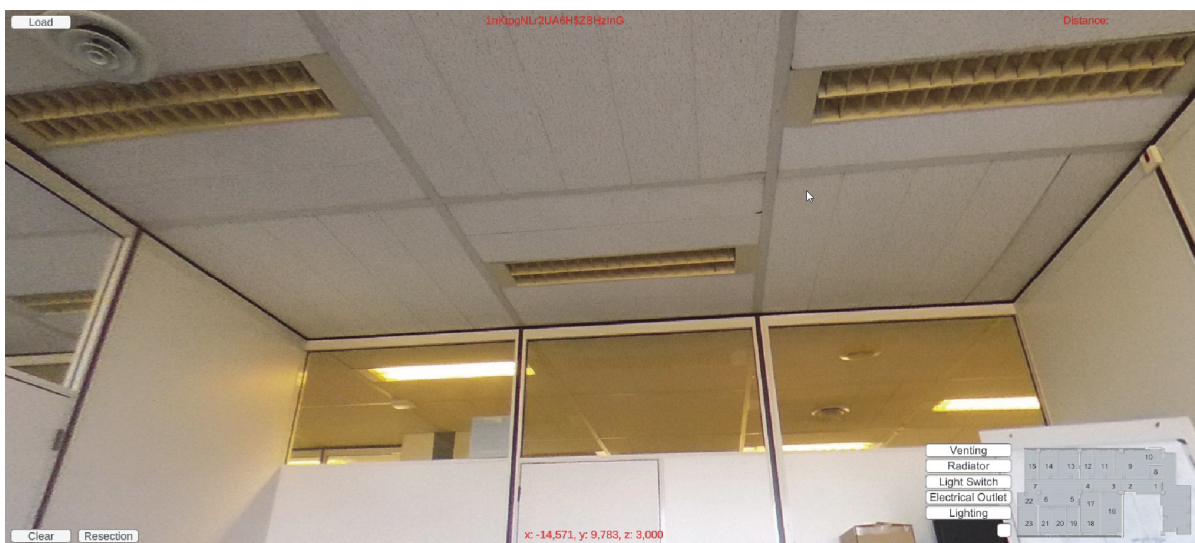


Fig. 82 - Absence of the lighting panel



Fig. 82 - Placing of the lighting panel

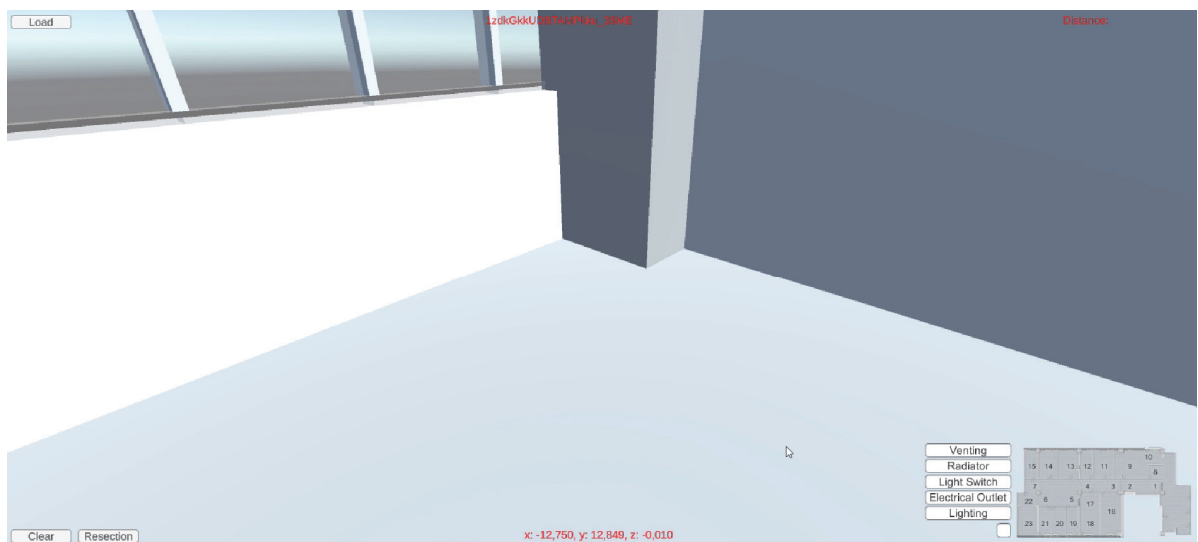


Fig. 82 - Absence of the radiator

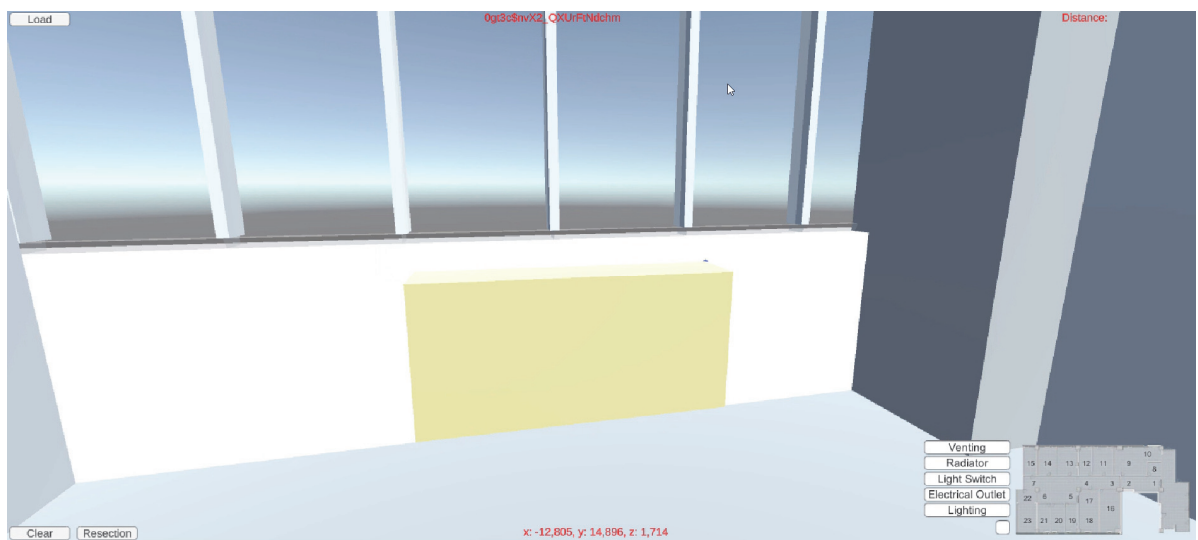
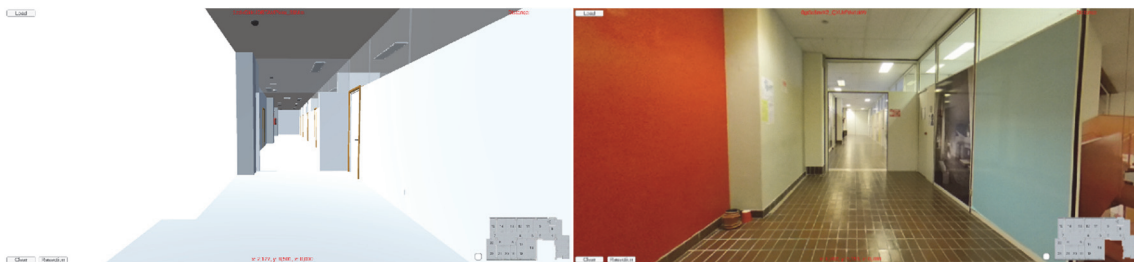
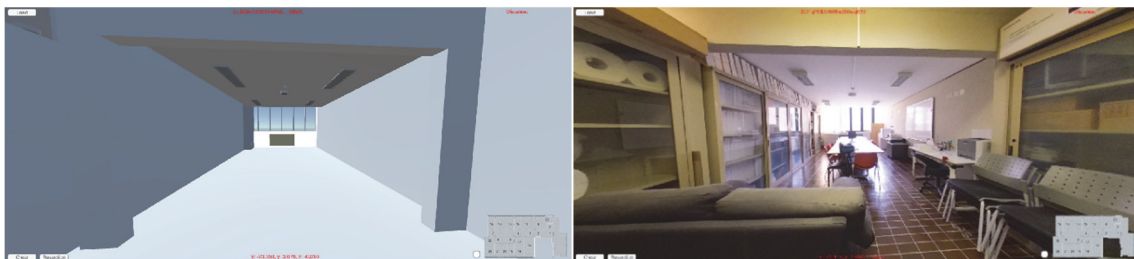
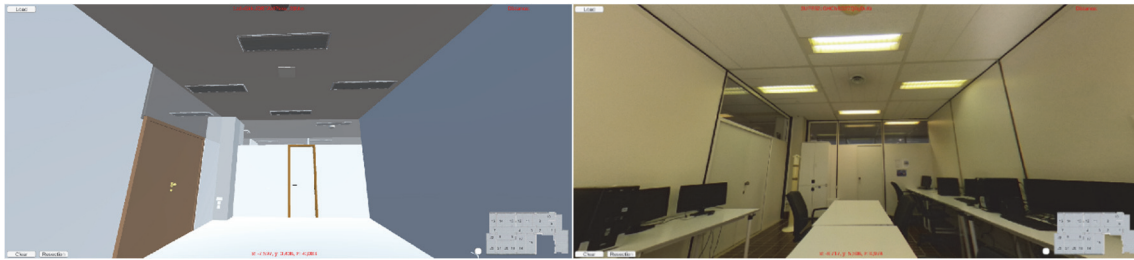


Fig. 82 - Placing of the radiator

As-built model







Conclusions

Starting from the principal issues analysis of the built environment management, this thesis proposes a new surveying approach, based on the cooperation between point cloud surveying technique, Building Information Modelling, photogrammetry and Game Engine software. Through these technologies it is possible to speed up the beginning stages of surveying and modelling, saving precious time and reducing the costs of the work. The system development is completed with an accurate camera pose estimation, where the connection between the pictures and the BIM geometries is precise. All the control points in the different ambients are correctly settled and the correspondence is precise, with an amount of errors contained inside the centimetre unit. This result demonstrates that it is possible to obtain an augmented as-built BIM model, like real-time rendered, only surveying the principal elements with a low level of detail and making a large number of detailed equirectangular images. The defined approach achieves time saving and consequently working costs reduction. In fact, comparing the traditional methodology with this, there is an enormous working time difference: a whole month was required for the surveys and the definition of the virtual representation, while the new method required only a few days to define the model.

The modelling error is reduced and the elements forgetfulness is eliminated by comparing the images with geometries, indeed the details direct visualization helps the correct placing of the objects. The principal benefit of this system is the possibility to postpone the detail modelling only when necessary, deleting the beginning slowdown process. Planning only the necessary components saves useful time and speeds up all the successive phases. This procedure develops a final archive, which can be used for the planning, working stage and building management. It can be always implemented with the changes applied to the environment, showing the historical development of the structure.

Through the creation of this software it is developed a professional working method, which helps the stakeholders to present the projects and the schedules to the clients. It is an augmented Interactive Production Delivery, where the works are developed through the interaction between all the parts involved in a direct visual way. There is also the opportunity for smart working, where the planners can work on the building environment in different places or countries. This is allowed by the network systems of the Game Engine and BIM platform, facilitating the cooperation between the different subjects involved in the project. The proposed methodology is a fundamental step for the construction industry digitalisation, both for building and managing, and creates a new working way which leads to 4.0 industry. It connects different disciplines such as building engineering, architecture, design with photogrammetry, informatic languages and gaming industry. In conclusion, the explained research should develop and improve in different directions:

- *Design*: the furnitures can be placed inside the various ambients;
- *Virtual Reality*: it is the most obvious consequence, in fact the project should be used inside VR platforms to interactively relate with the environments, planning and working inside the spaces;
- *Mixed Reality*: the MR should be used directly on site and working place, to compare the environment with the developed model;
- *Archive*: for the future works the archive can be useful for the non-invasive tracking of MEP elements that can't be seen. It is an accurate way to know exactly the correct position of the components;
- *Delivery of the project*: it is useful to verify that all the planning schedule is well defined before the building start;
- *Working progress monitoring*: the archive can help to compare the working schedule with the site working progress;
- *Comparison between built and project*: it should be helpful for the building commissioning, comparing the final construction with the project;
- *Artificial Intelligence*: it can be implemented with artificial intelligence to obtain building automation.

Acknowledgments

In this final chapter, for the better understanding by all my family and friends, I will write the acknowledgements in Italian, my mother tongue.

Desidero cominciare il paragrafo conclusivo di questa ricerca, ringraziando innanzitutto l'Università Politecnica delle Marche per questi lunghi anni di studio, per la preparazione fornitami e per tutte le esperienze vissute, facendomi maturare e crescere sotto ogni aspetto. Ringrazio i professori che mi hanno seguito e formato, soprattutto il professor Berardo Naticchia, per l'opportunità, datami attraverso questa tesi, di conoscere un ambito completamente nuovo, che mi ha coinvolto ed appassionato, per la pazienza, il supporto, la simpatia e la professionalità dimostrata.

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