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di Torino

Dipartimento di Architettura e Design
Corso di Laurea Magistrale in Architettura Costruzione Citta

Digital modeling, physical modeling, augmented reality, and AI for design communication.

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Acknowledgments.

“At times our own light goes out and is rekindled by a spark from another person. Each of us has cause to think with deep gratitude of those who have lighted the flame within us”.

-Albert Schweitzer

With deep appreciation, respect, and happiness, I wish to honor everyone who contributed to this journey.

To my supervisor, Prof. Roberta Spallone, for her guidance, and teachings during the master course and in this thesis. To my co-supervisors Enrico Puppi, PhD candidate Architectural and Landscape Heritage, Arch. Francesca Ronco and Arch. Valerio Palma for their availability and support. The opportunity to collaborate on the Campus Valentino project was enriching and proved to be an exceptional experience.

To my father, whose presence remains in my heart, and to my family, for their unconditional support and love that always pushes me to exceed my limits.

Abstract En

This thesis is rooted in the project of the new Campus Valentino - Torino Esposizioni for the recovery and renovation of a series of historical structures with multidimensional and culturally rich importance, including Sottsass Pavilion (pav.1), Nervi and the new Pavilion (pav.3A,3B) of To. Expo. In particular, the candidate is involved in the reconstructive 3D modeling of the urban and environmental context aimed at the digital fabrication of a scale model. This task has been assumed as a basis for developing a study about digital tools (for surveying, modeling, Renderization, and 3D printing) for design communication through MR and AI.

The theoretical and literature research will analyze the advancement of technologies and approaches for architecture documentation and digital reconstruction. At the same time, the design part of the thesis will involve the digital reconstruction of the urban context and several buildings of the Politecnico di Torino and the historic area of Valentino Park. This research seeks to draw a multidimensional work frame to facilitate the transition from the traditional complicated and time-consuming approach, to an approach of augmented phy-gital virtuality, based on the newest technologies, tools, and methods of digitization intended for Augmented and virtual architecture presentation that exploits the latest advances in technologies and techniques of surveying, modeling, Rendering, and 3D printing, to construct a solid Database managed by AI, enabling the full potential of the Industry 4.0

Abstract It

Questa tesi affonda le sue radici nel progetto del nuovo Campus Valentino - Torino Esposizioni per il recupero e la ristrutturazione di una serie di strutture storiche dall'importanza multidimensionale e culturalmente ricca, tra cui il Padiglione Sottsass (pad.1), Nervi e il nuovo Padiglione (pad.3A,3B) di To. Expo. In particolare, il candidato è impegnato nella modellazione 3D ricostruttiva del contesto urbano e ambientale finalizzata alla realizzazione digitale di un modello in scala. Questo compito è stato assunto come base per lo sviluppo di uno studio sugli strumenti digitali (per il rilievo, la modellazione, la renderizzazione e la stampa 3D) per la comunicazione progettuale attraverso MR e AI.

La ricerca teorica e bibliografica analizzerà l'avanzamento delle tecnologie e degli approcci per la documentazione e la ricostruzione digitale dell'architettura, mentre la parte progettuale della tesi riguarderà la ricostruzione digitale del contesto urbano e di alcuni edifici del Politecnico di Torino e dell'area storica del Parco del Valentino. Questa ricerca cerca di disegnare un quadro di lavoro multidimensionale per facilitare la transizione dal tradizionale approccio complicato e dispendioso in termini di tempo, a un approccio di virtualità aumentata e digitale, basato sulle più recenti tecnologie, strumenti e metodi di digitalizzazione destinati alla presentazione dell'architettura aumentata e virtuale, che sfrutta i più recenti progressi nelle tecnologie di rilievo, modellazione, rendering e stampa 3D, per costruire un solido Database gestito dall'AI, abilitando tutte le potenzialità dell'Industria 4.0.

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Chapter I. Introduction

I.1 Problem Statement.

Based on research papers that offer a broad and clear view of the Architectural use of AR in AEC and educational fields published by Prof. Roberta Spallone, Valerio Palma, Prof. Michele Russo, and other researchers, the idea of exploring and investigating the possibilities of creating a new ecosystem that merges all aspects of the Augmented Digitalization of architecture has emerged. With the increasing democratization of AR and AI in the field of architecture, we have the possibility more than ever to create an augmented/virtual experience simultaneously with the digital reconstruction process of each project while forming an extensive database of autonomous 3D models that harness the power of AI to tell the story of historic buildings, leading to a new type of interacting with architectural heritage.

In the Tu-Cult and TadArch projects, Valerio Palma has documented the development of two databases implemented with AI, specifically a CNN model for self-recognition, comparison, and data processing, to represent them in augmented form through accessible platforms. This research has demonstrated the potential value of using AI and AR in enhancing cultural heritage, which inspired the thesis project, which proposes and encourages the adoption of a fully digital approach to unify resources and processes of studying and approaching Architecture. Following the work frame highlighted in this research, we will explore the digital reconstruction phases of some elements of the Campus Valentino project, through which an alternative AI-based approach for architectural virtualization will be illustrated.

I.2 Context.

To.EXPO, Campus Valentino.

The Politecnico di Torino's Campus Valentino-Torino Esposizioni- project aims to long-term redevelopment of the Torino Esposizioni pavilions, ambitiously integrating them into the University's broader development plan. The aim is to transform a fragmented and disjointed structure into a compact and coordinated campus, recovering one of the most essential structures in Turin’s urban Fabric, together with the Architecture Campus in the Valentino area, which includes the historic site of the Valentino Castle, the Galileo Ferraris and Via Morgari spaces.

Figure 1 Parco del Valentino, Project area.
source: Brochure Campus Valentino.

Torino Esposizioni, located in Valentino Park, is a comprehensive testimony to the city's architecture and cultural history. Designed by Ettore Sottsass Sr. in the 1930s under the name of Palazzo della Moda (Palace of Fashion), the complex reflects the ideals of rationalism from its origins. The structure exemplifies the principles of modernism, emphasizing functionality, and minimalism while remaining deeply rooted in its cultural context (Brochure, 2024). In the middle of the 20th century, the area was transformed and extended with the help of Pier Luigi Nervi and Riccardo Morandi, who introduced innovative technical solutions to the project. Torino Esposizioni has played a dual role in the urban space of Torino City and Parco del Valentino. On the one hand, it has been a showcase for industrial progress, and on the other, it has been an integral part of the socio-cultural fabric of the city. It is also one of the most memorable places for the people of Turin, as it has hosted various cultural events over the years, including the 2006 Winter Olympics with ice hockey matches. However, after relocating the trade fairs to Lingotto in 1989, the building entered a long break period, with less use and gradual abandonment.

To-Expo today is balancing history and modernity, years of underuse have rendered parts of the complex already in disrepair, highlighting the need for intervention. The project aims to reclaim not only the physical structure but also to rethink its place in Turin’s urban and cultural fabric.

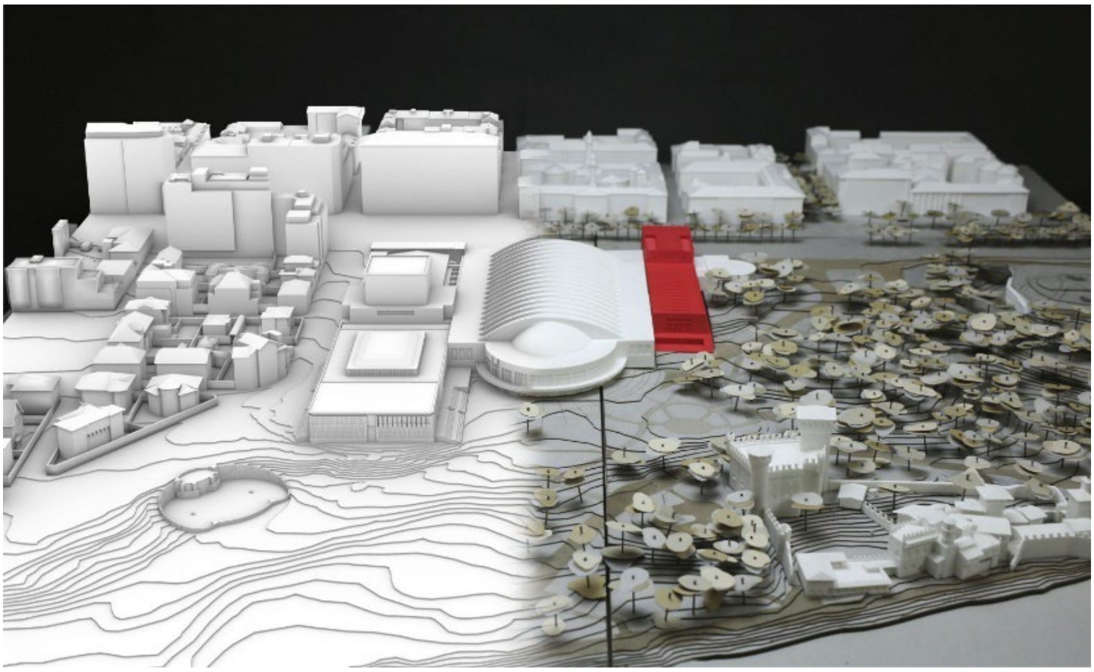


Figure 2 : To.expo, Phy-gital project communication
Source: https://campusvalentino.polito.it/ February 2024

It shows how architecture can adapt to the times, balancing the preservation of crucial historical architecture with the challenges and opportunities presented by contemporary building needs (Campus Valentino, Project Presentation. 14 December 2024). Utilizing both restoration and new tech tools, including AR and digital documentation, Torino Esposizioni serves as a noteworthy example of the progressive rethinking of cultural heritage management.

The project offers a unique opportunity to create a campus dedicated to architecture, developing and strengthening the ‘cultural axis of the Po,’ one of the city's main renewal guidelines.

In 1936, Ettore Sottsass Sr. won the competition for the Palazzo della Moda, represented by the open-air auditorium of the complex. In 1947, to repair the damage caused by the bombing of World War II, a project for the renovation of the entire complex, named Torino Esposizioni, was carried out by Roberto Biscaretti di Ruffia and Pierluigi Nervi. It was only in 1950 that Pavilion 3A, designed by Pierluigi Nervi, was built, with a large, vaulted hall resting on reinforced concrete arches.

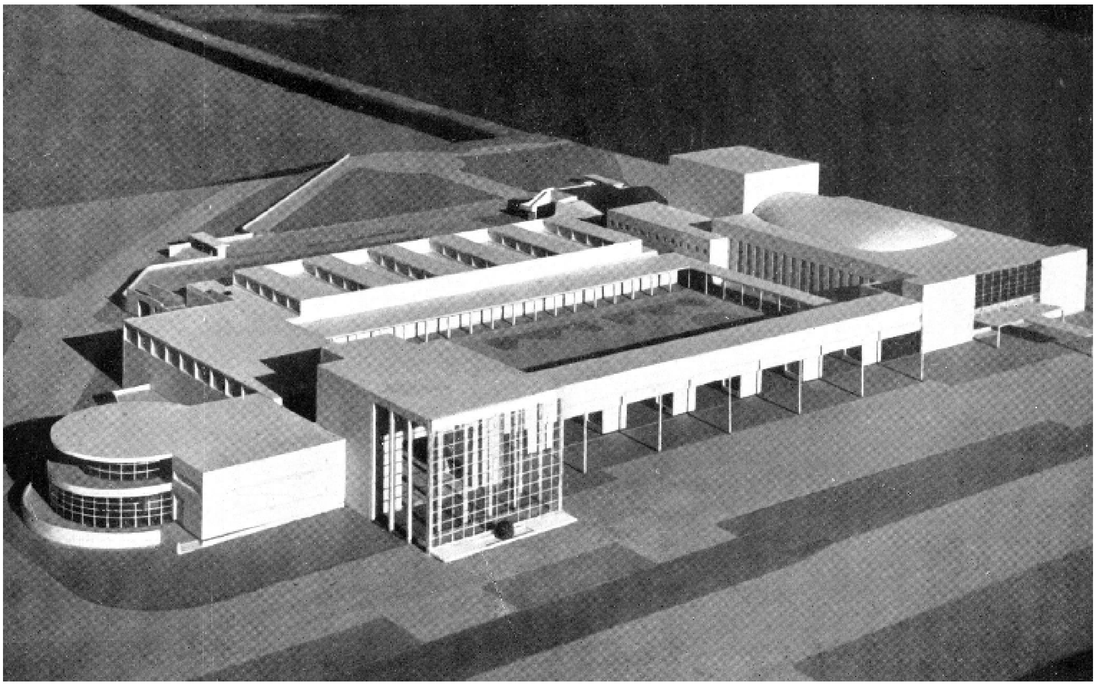
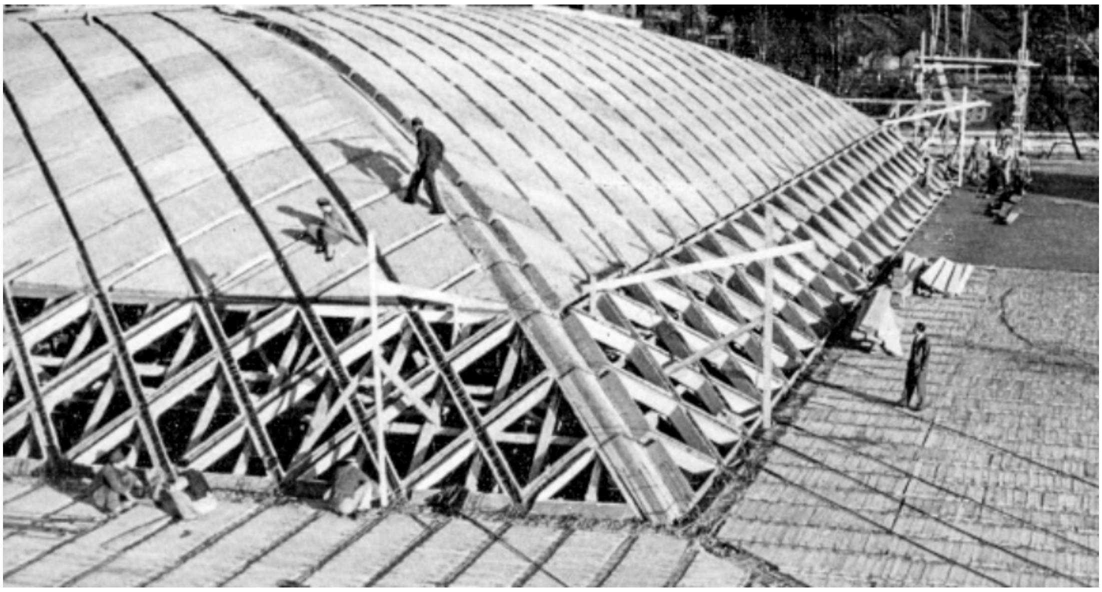


Figure 3: Top: Palazzo della Moda / Pad. Sottsass
Bottom: Pad. Nervi
Source: https://campusvalentino.polito.it/index.php/home/campus-valentino February 2024



The Politecnico di Torino is currently going through a period of significant change, with ambitious strategic plans to increase the number of students, the quality of life, the impact of its actions, and its spaces in an extensive building development program that exceeds € 300 million in investments, involving different locations and projects. The aim is to create a campus system dedicated to engineering and architecture that impacts the city's urban, social, and economic fabric.

In close and fruitful cooperation between the City of Turin and Politecnico di Torino, and with the intention and ambition of creating a complex and synergic cultural pole, the To-Expo project started. The pavilions granted to the university (Sottsass, Nervi, and The New Pavillion) will be used as multi-faceted and flexible spaces for university teaching. At the same time, those retained by the City (Pavilions 2, 4, and 4b) will house the Central Civic Library and the renovated Teatro Nuovo. This intervention is part of the broader "Valentino Project," which involves renovating and redeveloping its area, with PNRR funding of over 100 million euros. The synergy and cooperation between the initiatives guarantee significant operational and economic benefits, promoting a real and lasting regeneration of the entire area.

The work on three pavilions of the Torino Esposizioni complex, together with the historic premises of the Castello del Valentino and the spaces of Via Morgari, will finally bring together the teaching and research of the Architecture, Planning, and Design areas in one place, which will give new life to the entire Valentino Park, developing the so-called ‘cultural axis of the Po’(Campus Valentino, Project Presentation. 14 December 2024). The 50M € project of approximately 12,500 m^2, began in 2014 with the primary studies, checks, and hypotheses of possible recovery scenarios, which ended in 2022 with the approval of the concession scheme between the City of Turin, the Politecnico, and the University of Turin. According to the timeline in fig (4), the complex's opening is scheduled for 2026, while the project will be completed in 2028.

This thesis supports the objectives of the Campus Valentino project by documenting, modeling, and representing some of the cultural and historic buildings of the park. Integrating advanced technologies, the research moves from traditional methods to a hybrid digital approach (due to the use of different SDKs) that bridges physical and digital tools through augmented reality (AR) applications and 3D printing, serving as resources for education, public engagement, and cultural preservation.

The research captures the geometric, material, and historical traces of Torino's historic buildings, supporting site revitalization and demonstrating the transformative power of modern documentation techniques.

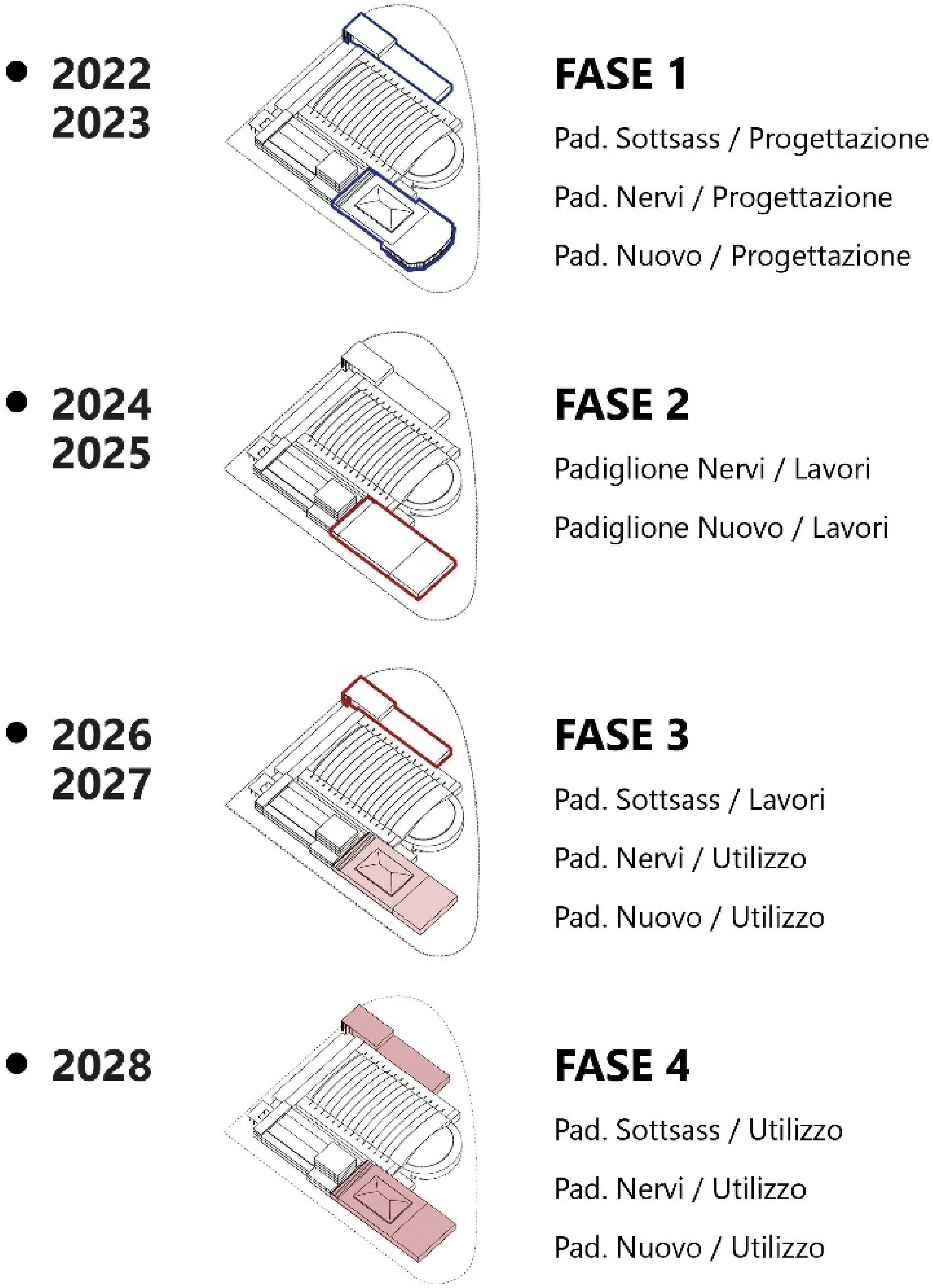


Figure 4:Project TimeLine, MasterPlan
Source: masterplan.polito.it/progettualita/campus_architettura_torino_esposizioni. February 2024

I.3 Campus.Valentino.

Thanks to a modeling and reconstruction phase that will be explored in more detail later on, it was possible to 3D print the entire built context inside and outside the park, while the environmental context, represented by the terrain, vegetation, and roads, was cut with a laser and put together manually, constructing a physical model on a scale of 1:500, measuring 1.37 by 2.27 meters (Campus Valentino, Project Presentation. 14 December 2024).

The communication of the project was then reinforced with an augmented experience based on the superimposition of digital information strips about the flow, uses and type of users involved for each structure of the Campus, through a webAR that is activated by markers and QR codes, without the need for apps or installations.

I.4 MR Expérience.

"Within this [reality-virtuality] framework it is straightforward to define a generic Mixed Reality (MR) environment as one in which real world and virtual world objects are presented together within a single display" (Milgram et al., 1994).

Before delving into the digitisation process and its components, it is important to understand the logic and mechanism behind the Real-Virtual Continuum (Fig 5) since it affects the whole process and project reconstruction.

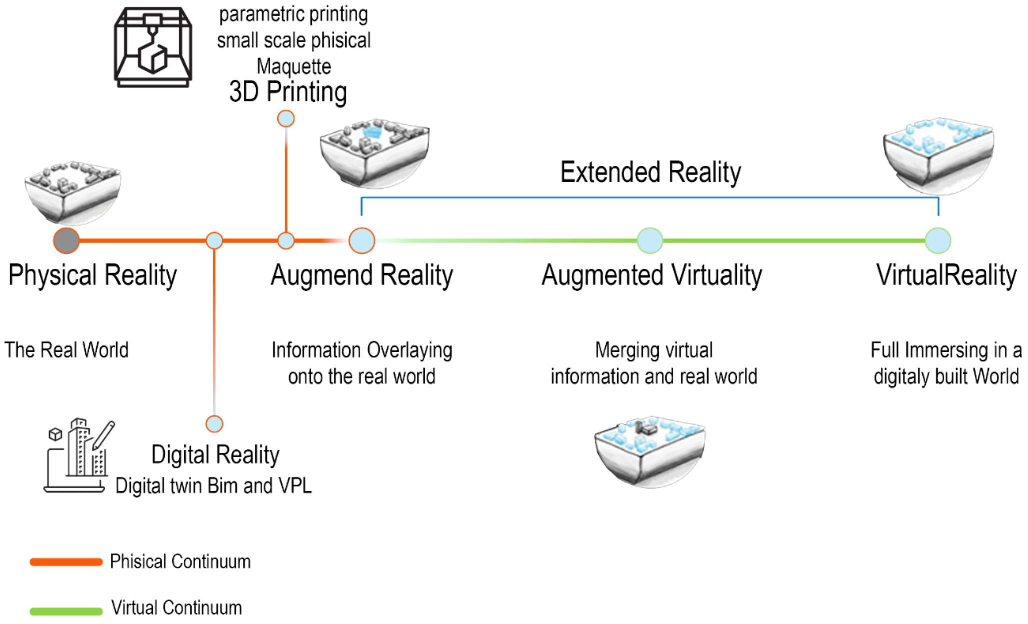


Figure 5:Re-interpretation of Milgram and Kishino's scheme for the architecture domain.
Made by the author: Sbai Oussama

Milgram and Kishino’s scheme has admirably stood the test of time. With the benefit of hindsights that shows the needed for updating the concepts to remain relevant in 2025 and beyond (Richard et al. 2021), the re-interpretation tries to place Digital Reality (Rendering and digital twin) and 3D printing in the already existing taxonomy of the Reality-Virtuality Continuum, in order to illustrate the benefits of innovative surveying process that enables the possibility to develop high informative experiences that may be adapted to the project type.

Innovative surveying reflects a switch from the manual and mechanic surveying tools for measurement, mapping, and site analysis - Measuring Tape, Plumb Bob,…- to Smart surveying technologies for point cloud generation, eliminating manpower needs and reducing the dependency on high-skill labor. However, most importantly, it allows for the virtual extension of the project from its earliest phases, streamlining decision-making and enabling seamless design modifications.

Aspect	Manual/Mechanical Tools	Smart Technologies
Accuracy	Moderate	Extremely High
Efficiency	Time-consuming	Rapid and automated
Data Output	Analog measurements	Digital models (e.g., 3D point clouds, BIM)
Skill and tools Requirement	High, and specific expertise needed with manual tools	Digital skills, and innovative tools (UAV, TLS, Photogrammetry)
Scalability	Limited to small or straightforward projects	Scalable for large and complex projects
Visualization	Minimal (2D sketches or plots)	Immersive (3D models, AR/VR applications)

Figure 6 Manual and digital surveying tools comparison for architectural use.
Made by the author: Sbai Oussama

Immersive technologies are blurring the boundaries between physical and virtual worlds, where virtual reality immerses the user's senses in a simulated world, while augmented reality alters our perception of the physical world, often via a smartphone or tablet screen (Portalés et al, 2018). the scope for the application of these technologies in architecture and CH is vast and ever-expanding. The use of VR technology gives a whole different level of reviewing and validating the design with exclusive visual feedback, that guarantees a more comprehensive and user-friendly experience interacting with the proportions, scale, and shape of the project design in a very efficient and practical way. This may bring a lot of benefits for architects since they can now focus on pure design, shapes, and geometries rather than the finishes and materials of the project. Approaching the valorization of our built environment in this way may also enable the manipulation of buildings in ways never been possible before, extracting and adding information to the model, testing and improving its structure, or simulating its functioning.

Putting together 3D surveying tools, 3D Modelling languages, and Virtual Experience Creation, it became possible to overlay what is digitally constructed, whether a full construction or a single element, to the real environment using walls, ground, tables, and any other surface that may support the anchoring or markers technologies. AR wish is a specific dimension between the whole immersive experience with VR headsets and the typical digital experience through the Mobile screen, became more accessible via telephones or tablets, and is currently undergoing a promising development phase with the presentation of new technological breakthroughs, enabling the integration of augmented visualization in light-weight regular looking glasses, that allow total transparency and an increased viewing angle of up to 70 degrees. However, it is still less investigated concerning the VR continuum, which became a fully developed market, especially in the AEC field.

Chapter II. Architectural Documentation.

II.1 Database.

II.1.1 Evolution of Architectural Documentation.

Before it becomes a physical reality, architecture evolves through a series of documentation, prototypes, and iterative developments that grow with the project. After its construction, it becomes an urban element subject to different interactions, interpretations, and transformations throughout its life, until it becomes a historical architecture or an abandoned one, developing an extensive library of documents ranging from texts, drawings, photographs, historical research, and physical models. This is where the reading of urban space is found. Historically, documentation was based on a simple presentation in terms of methods and materials - blueprint, drawings, texts - but communicatively it was very complex - geometric shapes, concepts related to the universe - with the passage of time and the development of technological, industrial and information fields, documentation and architectural survey have become much simpler and available to everyone, consequently moving towards a complex presentation - digital and virtual visualisation, immersive and augmented reality, 3d printing - for simple communication - volumes, This shift in methods and tools has opened up a new way of reading space, especially for digital architectural reconstruction, where in order to achieve the same quality as a simple image, in the digital modelling process you still need to collect an important amount of data, from dimensions to details and textures, the difference here is in the virtuality of the data documentation, which can be available at any time and from any place, in addition to becoming part of a vast database that forms our history for future reflection and reinterpretation. However, the variety of types of documentation and their state of degradation over the years complicates the process of reconstructive documentation.

The Renaissance saw significant development in geometry and perspective, dramatically improving architectural representation. Architects such as Filippo Brunelleschi and Leon Battista Alberti began to adopt aspects of mathematics with architectural principles to create accurate, realistic images of buildings (Tavernor, 1991). These improvements were the seeds of architectural surveying as a discipline, allowing for more accurate and systematic documentation of the newly constructed and existing building stock. These early methods were, however, labor-intensive, depended on individual draftsmen's skills, and involved the risk of errors in measurement and interpretation. Thus, much of the documentation of the time was narrow and offered in opaque formats as an administrative resource to those within the architecture profession. As architectural projects became increasingly complex, and there was more interest in preserving our built heritage, the need for more than rudimentary documentation practices arose. Architectural documentation began to change significantly during the Industrial Revolution, through different tools and technologies that increased the process's accuracy and efficiency. For instance, photogrammetry and theodolite, allowed precise measurements of angles, to generate a detailed visual record of many architectural features (Turner, 2000), these developments allowed the documentation of larger and more complex buildings, including cathedrals and historic cities. However, the constraints of physical media and hand processes remained a critical challenge for a long time, highlighting the demand for a more flexible and scalable mechanism.

The manual mapping and documentation of historical architecture using conventional tools is today considered a very time-consuming and labor-intensive practice, and thanks to technological advances, the use of digital tools to support architectural documentation efforts has provided significantly more in-depth results in architectural analysis, thus simplifying processes that were previously performed manually. Among the technologies used for architectural documentation, terrestrial laser scanning, photogrammetry and unmanned aerial vehicles, called ‘drones’, have found widespread use. In particular, surveys based on scanning and data capturing tools allow to obtain geometric facts of very high quality in terms of resolution, precision, and reducing uncertainty, as well as dense point clouds, which are valuable for architectural documentation. It is emphasized that the use of the laser scanning method, rather than traditional tactics, significantly reduces the time and effort required for field research and drawing procedures, as is common in studies conducted to confirm the usability of the terrestrial laser scanning method, which has proven to be a promising technique, especially in the last decade (Zachos et al., 2024; Wu, C. et al. 2022; Chiabrando et al., 2016).

II.1.2 Paper to Digital database.

The late 20th-century transition from manual to digital documentation signaled a paradigm shift in how architectural information is recorded, stored, and shared. With the introduction of computer-aided design (CAD) systems, architects could produce very accurate digital drawings that could be easily edited and duplicated. Although CAD changed the design process, it did not facilitate integrated data management and was ineffective for large-scale or multidisciplinary projects. The inability to represent both semantic data and geometry prompted the creation of Building Information Modelling (BIM), which is a dynamic, interactive database of architectural information that combines geometric modeling and material data (Volk, Stengel, & Schultmann, 2014), and later on the HBIM which is specifically oriented toward cultural heritage.

Architectural documentation is one of the fields for which HBIM is most valuable, it has become an indispensable solution in cultural heritage. Using various sources of information, including historical records, laser scans, and material analyses, the platform allows the generation of comprehensive digital models of historic buildings. These models reference not only the physical attributes of a structure but also metadata descriptions of its history, construction process, and physical condition. This encompassing method also helps to comprehend architectural heritage for a better renovation, which assists in conservation processes and provides a better foundation for decision-making.

GIS technology, on the other hand, adds a whole new geographical space to architectural documentation. Researchers use GIS to project buildings in the urban and environmental context, creating a relationship between buildings and other forms of cities and objects. This technology is applied widely to understand the historical growth of urban centers, including cities like Rome and Venice. Integrating BIM and GIS allows architects and historians to produce holistic documentation that fully addresses the buildings' micro-scale and the urban space's macro-scale. GIS-driven 3D reconstruction allows work processes to reduce cognitive workload, reducing human error and scale for large or complex projects. This functionality is valuable across different sectors. Urban planners use geolocalized models to visualize how proposed infrastructures may interface with existing cityscapes. In parallel, cultural heritage initiatives use geolocalization to digitally identify the presence of points of interest.

However, these technologies face significant challenges when dealing with the fusion of heterogeneous data sets (e.g., satellite imagery and terrestrial surveys) into a single model (Akçam, 2023). This requires highly specialized pre-processing and harmonization processes, as the data often differ in resolution and format, requiring a high degree of normalization of the data into a single state. Novel approaches such as multi-resolution coupling and contraction-based corrections for real-world populations have contributed significantly to reconciling these discrepancies. In addition, the computational cost of storing and processing high-resolution data is still high, especially in X.R fields (V.R, A.R, M.R), where real-time generation is required (Scianna et al., 2020), limitations in triangle count and texture resolution impose significant constraints on VR navigation systems, that must balance complex 3D models with reduced polygon counts and optimized textures, to ensure accessibility without compromising detail.

3D modeling techniques and methodologies are undoubtedly one of the most required skills in digital reconstruction. They represent an important tool for studying cultural heritage and enable complex structural analysis. Furthermore, incorporating BIM information from different sources enables a digital database of assets ready to be shared for more development, reducing the complexity of the surveying process and improving project management. For instance, the Cult project -that we will see further on-, is a web database service that works on different user interfaces, and is capable of storing information from different inputs, a fundamental aspect to guarantee the accuracy of the information and the accessibility of the platform to a maximum of users, Cult represents an important turning point for the digitalization of architectural documentation, emphasizing the need for modern, interoperable databases, as it provides open and easy-to-access documentation, merging various type of inputs from (e.g., text, images, 3D models, GIS maps) into a single and easy-to-use platform. In addition, it enables users to access a library of architectural data, making unreachable and complex information easy to understand and memorize. It is especially beneficial for the cultural heritage domain, as the documentation process often involves extensive on-site surveying and documenting, which is a lengthy process.

The accessibility of any database in terms of public engagement and education in Architectural documentation is crucial for its promotion (Ehab et al., 2023). Limited service for museum visitors or private use may present a boundary for its expansion, and the user experience, even if it's in the earlier phase of the project, offers valuable feedback that helps the development of any Architectural webAR experience (Hussein et al., 2023).

II.1.3 AI for architectural presentation.

A solid Digital Database must contain a sufficient number of documents (textual, iconographic, or three-dimensional) for its purpose. In our case, when it comes to architectural projects, the historical and design documentation of the structure is often consulted along with the entire survey phase, 3D reconstruction, and additional diagrams and schematics that contribute to the development and enrichment of the database. However, despite the value of these tools, they remain limited to their primary purpose, which is to document a project. Adopting Artificial Intelligence as a connecting element between the different components of the architectural documentation phase could have a transformative effect on presenting and communicating cultural heritage and architecture in general, expanding the use of already produced resources.

Artificial Intelligence represents a vast field that intersects with architecture, forming an interesting future development area. Artificial Neural Networks are computational models inspired by the human brain's and neurons' functioning. It is mainly used to recognize patterns based on an evolutional grid composed of layers and nodes (Lindsay, G., 2020), while it is controlled by parameters to elaborate an output, depending on the project's aims. The nodes, called neurons, are organized into layers Hornik, K., 1991., which simulate the interaction between neurons through an automated and parameterized data flow (Palma et al., 2019). These networks are used for various tasks, including image recognition, time series prediction, natural language processing, and control of complex systems (Palma et al., 2022).

Each connection between neurons (nodes in fig 7) has a weight that determines its importance. When data is transmitted between neurons, it is multiplied by the associated weight and passes through an activation function that decides whether the neuron should be activated (Lu Y. et al., 2017).

One of the earliest documented uses of CNNs in the field of architecture is related to urban façade analysis systems (Gozdenur Demir et al.,

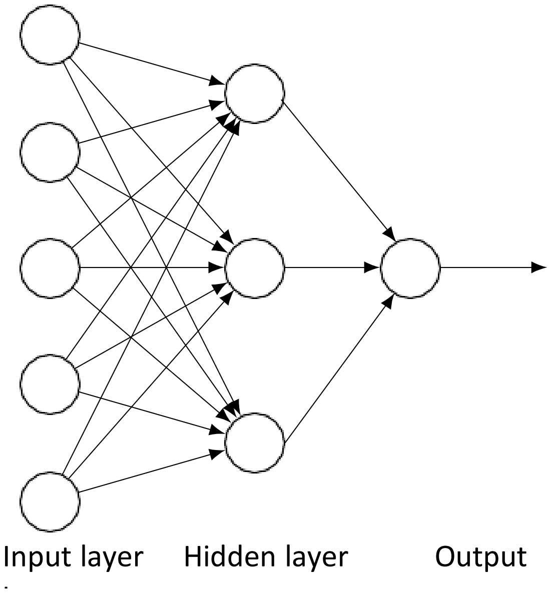


Figure 7 The artificial neural network example. Source: Palma et al 2019.

2021), where CNN models were trained to recognize architectural styles, identify decorative details, and distinguish historical periods based on photographic datasets. At the same time, in the field of cultural heritage, CNNs have been used to segment architecture, statues, and mosaics, helping to detect damage in historic buildings.

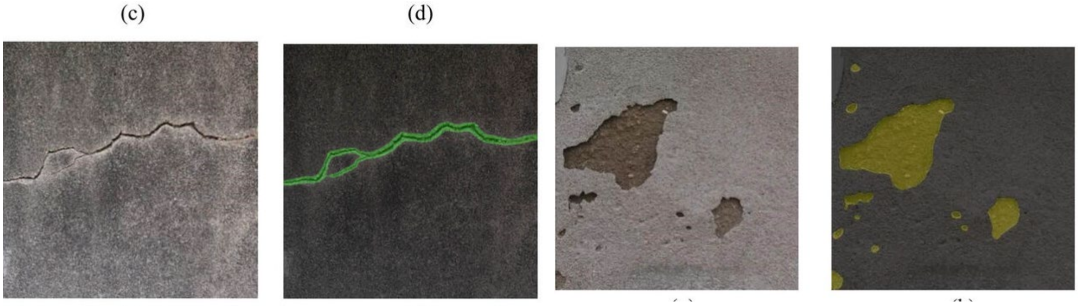
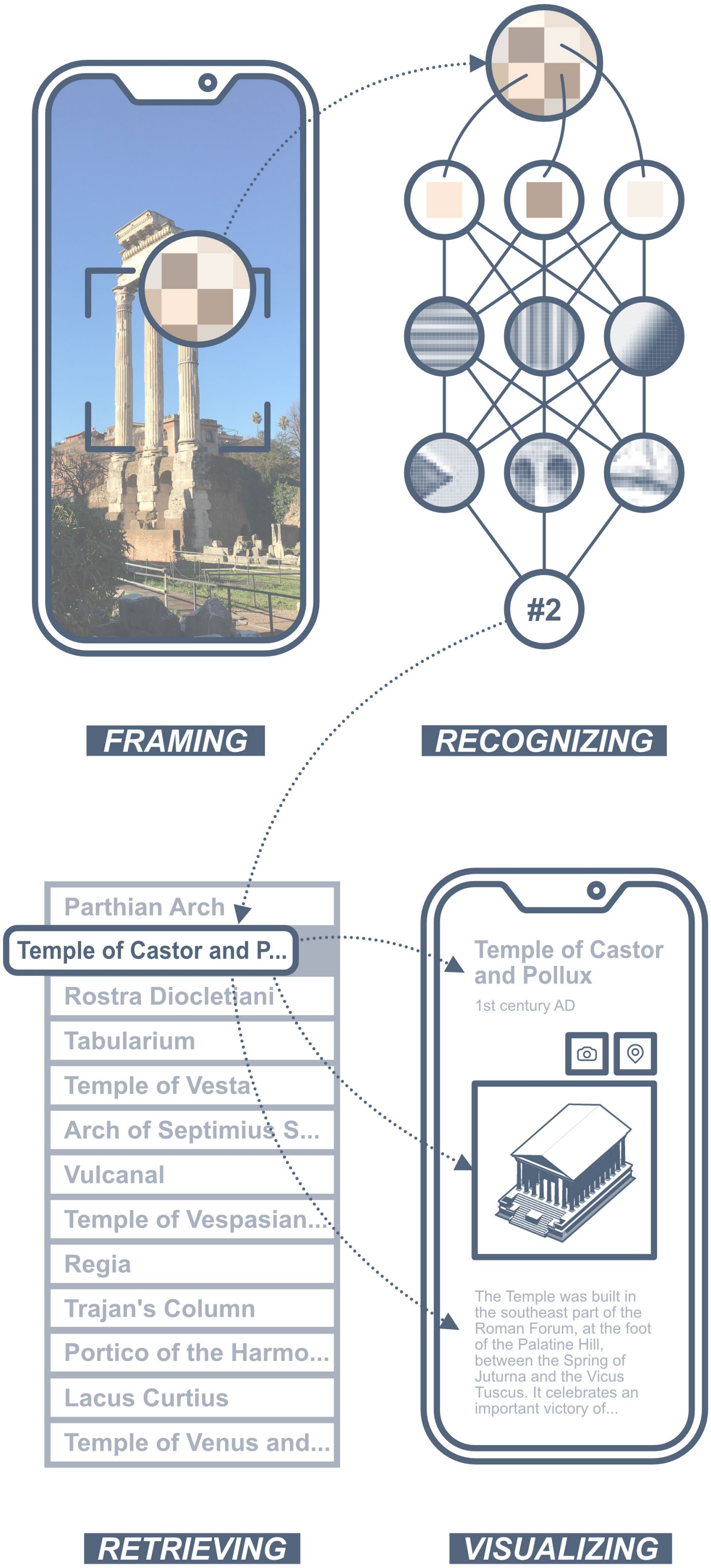


Figure 8 segmentation of surface defects with DL model
Source: Fu, X. & Angkawisittpan, N. (2024). Detecting surface defects of heritage buildings based on deep learning.

Tu-CULT Project.

The interesting approach of developing an AI-powered database for the Augmented reality experience presented by Valerio Palma in his doctoral research in collaboration with researchers at the University of Padova deserves to be promoted as a significant step toward democratizing AI and Augmented reality in the CH field. The Tu-Cult project was initially conceived to foster an ecosystem of fluid information, giving users a close-up view of some of Rome’s extraordinary monuments. Motivated by the preservation of cultural heritage and the desire to tell the story of architecture in a new dimension, overcoming real-world barriers, the researchers developed a web service that allows the upload of textual, iconographic, and digital elaborations (V. Palma, 2018), associating data with documents and re-establishing the modes of architectural presentation. This approach takes advantage of the information already uploaded to the AI algorithm that manages an ML model, which uses CNN to recognize architectural elements captured through the individual pixels of a phone or tablet camera (V. Palma, 2020). using geolocation data and the comparison of thousands of variables generated by the artificial intelligence, which requires an initial

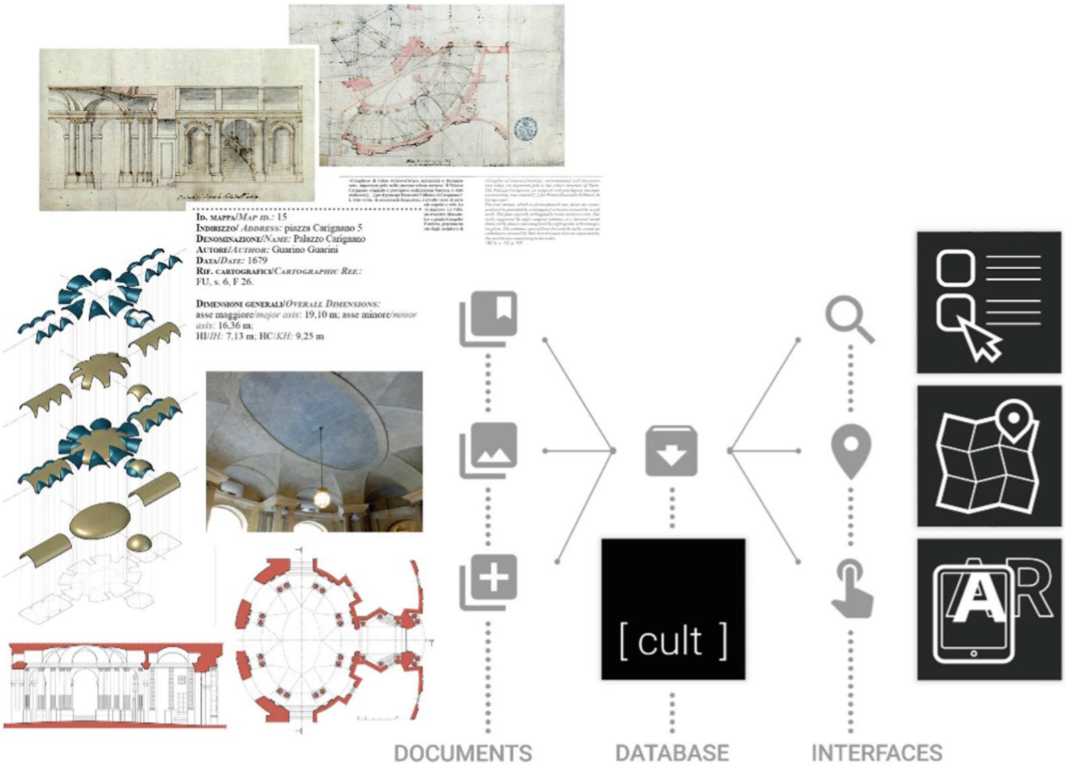


The Temple was built in the southeast part of the Roman Forum, at the foot of the Palatine Hill, between the Spring of Juturna and the Vicus Tuscus. It celebrates an important victory of...

Figure 9 Scheme of the connection between the main view of the app interface and the monument detail view.
Source: V. Palma, 2020

Training phase, during which the model is confronted with examples of potential geometric shapes or figures and given the correct answers(Bahrami et al, 2022). This complex and articulated system can perform an enormous number of calculations in a matter of seconds, providing access to information at various levels of detail.

With the app's small size in terms of data weight and system requirements, the user is ultimately presented with a very intuitive and user-friendly interface. By framing a monument with the phone's camera, a simple click is enough to display architectural details with a high degree of accuracy, resulting in an interesting approach, as the efficiency of the database increases exponentially with the use of AI technologies.



ID. MAPPA/*MAP ID.*: 15
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DENOMINAZIONE/*NAME:* Palazzo Carignano
AUTORE/*AUTHOR:* Guarino Guarini
DATA/*DATE:* 1679
RIF. CARTOGRAFICI/*CARTOGRAPHIC REF.:*
FU, s. 6, F 26.

DIMENSIONI GENERALI/*OVERALL DIMENSIONS:*
asse maggiore/*major axis*: 19,10 m; asse minore/*minor axis*: 16,36 m;
HI/*IH:* 7,13 m; HC/*KH:* 9,25 m

Figure 10 :Scheme of the interaction of the project with the digital archiving tool Cult, originally developed by the University of Padua. The input documents are texts, data sheets, photographs, architectural drawings, interpretative 3D models and archive materials (examples on Palazzo Carignano). The output interfaces are meant to make the Cult database accessible through different means, such as web pages, GIS tools and mobile apps with AR capabilities.
Source: Palma et al 2018

Tadarch.

Figure 11 AI-Powered Recognition App for CH: Bridging Digital and Physical Realms.
Source: shazarch.com

In the Tadarch project, Palma, in collaboration with Università di Roma Tre, Università di Padova (The ReLOAD Lab), The FULL (Interdepartmental Center of the Politecnico di Torino), and a commercial partner has launched an app that uses Cult Database to provide a spatial architectural experience through augmented visualization. The geolocation system and phone camera connect to the server, which hosts a digital platform implemented with artificial intelligence for data input and control (Palma et al., 2019). This allows the algorithm to generate personalized experiences of the historical narrative based on the initial input and the user's preferences with augmented visualization.

The app was built based on two different levels Fig (12); the first is the database containing documents of different types, while the second is the AI algorithm for data management, object recognition, and localization (Palma, 2019).

The AI in this project is also used to generate storytelling. The developers use generative AI to prompt some keywords to define the conditions while the algorithm generates the content. It is important to note that these operations are done within the developer platform without redesigning the virtual experience.

These two projects represent an important step in democratizing innovative technologies and an interesting change in how architecture is presented and communicated. They promise the development of AI-based architecture and heritage-oriented datasets capable of recognizing structures and spaces through camera or geolocation and then managing the virtual user experience. By combining open-source databases, new designs and projects, augmented and virtual visualization technologies, and ML models, a new and unique framework that can optimize both the process and the results of projects may be created.

For this reason, it is necessary to re-evaluate traditional documentation tools and methods and accelerate the transition to an automated digital approach to help us focus on important tasks and reduce documentation time and effort. In the following chapters, we will look at the tools, methods, and technologies of both the digitized documentation that has marked the new ways of surveying and the architectural presentation that is transforming our spatial intellectuality.

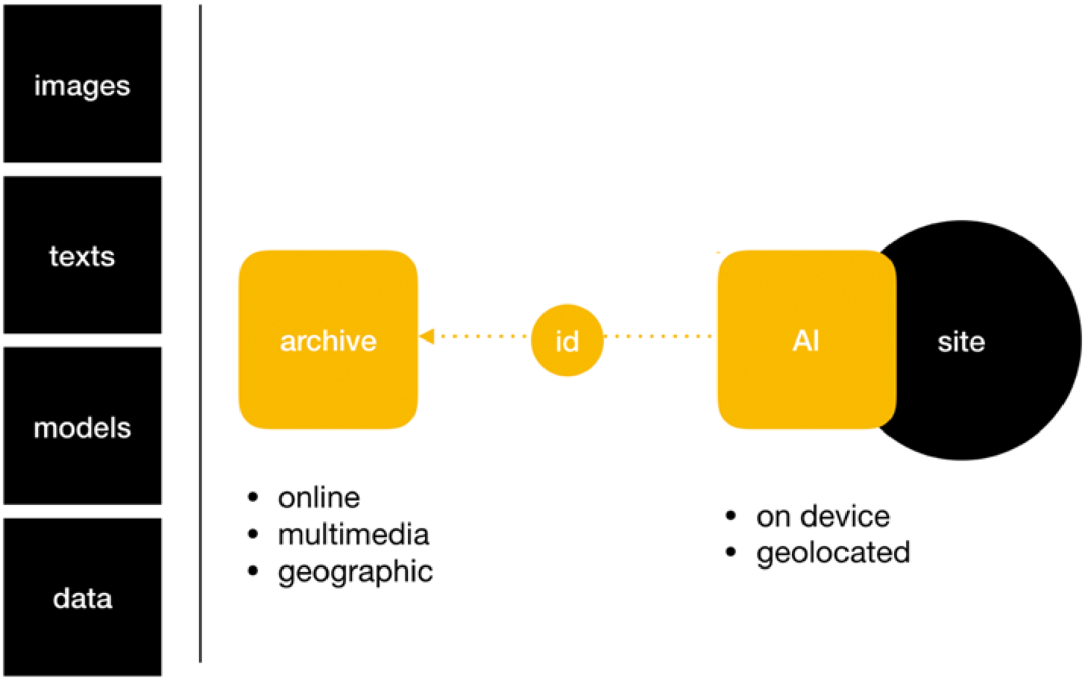

Figure 12 Scheme of the two main components of the app: the digital archive, storing data and documents, and the artificial intelligence engine, interacting with the site through the app.
Source: Palma et al 2019

II.2 Documentation tools.

II.2.1 Digital Revolution in Documentation.

The evolution of architectural documentation tools began with simple hand tools such as the compass, ruler, and plane table, which were the main tools of architects from antiquity to the Renaissance. Capable of producing highly complex drawings, these tools enabled early architects to produce plans and elevations by hand, using only a mixture of mathematical principles and artistic skills.

The Industrial Revolution, which far surpassed previous centuries, raised the bar and brought with it more sophisticated tools for documenting architecture. Instruments such as the theodolite provided extremely accurate angular readings needed to plot and record large structures in their surroundings. This period also saw the emergence of rudimentary forms of photogrammetry, which used photographic records to derive spatial information. These developments also drastically reduced the manual labor required, allowing surveyors to capture finer architectural details more efficiently. It has been used in various studies (Scianna et al., 2020), providing a valuable source of information for years. Nevertheless, such tools are limited in terms of speed, scope, and accessibility.

In recent years, architectural surveying has undergone a digital transformation, as photogrammetry and laser scanning have become new tools for reproducing accurate and georeferenced 3D models for various applications, including AR (Canciani et al., 2016). Photogrammetry was coined for the first time in the 19th century by Albrecht Meydenbauer a German architect and engineer, who developed the first techniques to use photographs for architectural measurements (Wolf, P.R. 1983), laying the foundation for modern photogrammetry that today uses advanced Structure from Motion (SfM) algorithms to produce higher-resolution 3D reconstructions from two-dimensional photographs (Scianna et al., 2020). In addition, with UAVs, surveying has become more efficient, offering a wide range of new viewpoints, laser scanning or LiDAR (Light Detection and Ranging), it has also changed the way data is collected, allowing a high flow of information to be captured, which then leads to a 3D point cloud model that incorporates spatial, dimensional, material and texture information, fundamental to the creation of augmented reality experiences (Vacca et al., 2023).

Recent applications of architectural surveying, including BIM and GIS, have improved 3D reconstruction modeling for AR, serving as a rich database of geometric and semantic data with which AR interacts, and to project complex architectural information into the physical world (Palma et al., 2021).

As documentation tools have evolved, so have the methods for accurately capturing real-world situations. Photogrammetry and laser scanning, technologies that rely on sensitive hardware to capture details in real-time and software to fuse the data into vivid 3D point clouds, are particularly useful for heritage sites that require minimal intervention. Recent research highlights the use of photogrammetry in the documentation of various cultural structures and museums, in addition Structure-from-motion (SFM) can use an arrangement of overlapping aerial photographs to generate incredibly comprehensive designs. In contrast, laser scanning uses LiDAR sensors to instantly capture vast numbers of location points, resulting in dense, highly accurate surface maps, these sensors have proven their value in documenting intricate architectural details, such as the Gothic facades of European cathedrals, where accuracy is critical for conservation planning and development.

What's exciting is how these tools are starting to work together. Drones equipped with photogrammetry systems can now be paired with laser scanners, creating a powerhouse for documenting even the most complex sites, Considering the example of the archaeological site of Machu Picchu in Peru (Jean D. et al., 2021).

The combination of photogrammetry, terrestrial laser scanning (TLS), and unmanned aerial vehicles (UAVs) has completely changed the way we approach reconstructive modeling, especially when it comes to Virtual reality. These technologies work together to create incredibly detailed 3D models that power AR experiences.

These tools also facilitate teamwork by sharing data online so experts from different disciplines can collaborate more effectively. This approach combines geometry, material properties, and historical detail to make reconstructions not only accurate but also deeply meaningful, ensuring that restorations feel authentic while also creating interactive tools for education and public engagement.

The Politecnico di Torino’s To.EXPO project is an example of this evolution, integrating state-of-the-art documentation tools to record Turin's historic architecture, focusing on creating a database of architectural elements, combining historical records with digital reconstructions and physical models, and demonstrating the critical role of documentation in preserving and communicating cultural heritage for future generations.

II.2.2 Photogrammetry & Software.

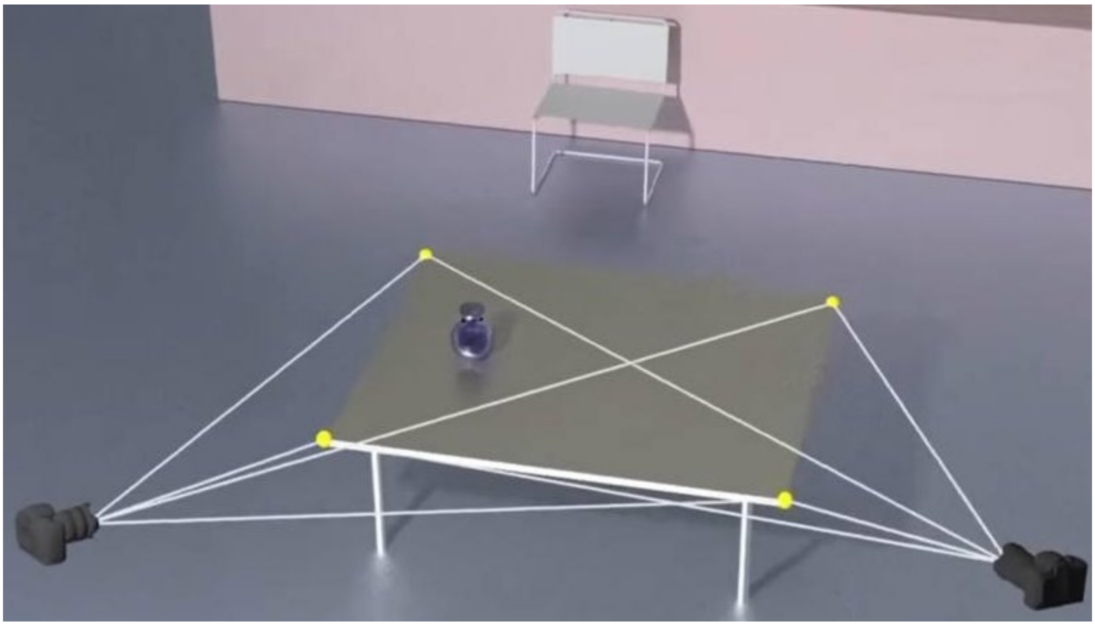

Figure 13 Multi-Angle Image Capture for 3D Reconstruction
Source: UnreaLab, 2022. What is Photogrammetry?

Photogrammetry in recent years is revolutionizing surveying, allowing the creation of detailed maps and 3D models without the need for manual measuring tools (Jaund et al., 2016; Li et al., 2016; Pyka. 2017; Smith et al., 2015). In the past, surveying was done manually, which was time-consuming and labor-intensive. However, thanks to advances in camera technology and computing power, photogrammetry can now be performed using consumer cameras and home PCs. Previously, the leading players in the photogrammetry software industry were Metashape – by Agisoft- and Reality Capture -by Capturing Reality-, both were expensive, but recently (2021), Reality Capture was acquired by Epic Games and made available for free, while new SDK enhanced with AI entered the race, facilitating photo alignment, data capturing and processing. The Image acquisition process of photogrammetry involves taking multiple photographs of the object from different angles; for effective scanning, the object must remain still while the camera is rotated.

Knowing the camera's specifications (such as focal length and sensor size), the software proceeds with the Triangulation[1] , capturing pixels and distances

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[1] Triangulation in photogrammetry is a geometric technique used to calculate the 3D positions of points by analyzing the intersection of lines (rays) projected from multiple camera positions to common points in overlapping images. It relies on camera calibration, known angles, and distances to reconstruct spatial data with precision.

included in the focal area (Vacca et al 2018). This creates a point cloud representation of the object (Daniele C., 2023**)** that can be converted into a 3D mesh then simplified, depending on its final use (Renderization, virtualization, 3D printing).

It is important to keep camera settings and lighting consistent when capturing small objects. In contrast, when scanning large objects, moving in a stable and coordinated path is necessary during image capture. These techniques provide a powerful tool for creating 3D models and maps using simple photographic techniques. Thanks to the availability of free software and consumer-grade cameras, processes that took so long a few years ago can now be done in a matter of minutes.

In an experiment comparing the most widely used photogrammetry software, Reality Capture, Metashape, Meshroom, and 3DF Zephyr, Jérôme Tabeaud demonstrates the results of data processing and point cloud processing by comparing the process and resulting quality of the following Photogrammetry software:

Metashape

3DF ZEPHYR

RealityCapture

MESHROOM

The comparison of the four photogrammetry software packages, 3DF Zephyr, Metashape, Reality Capture and Meshroom, was comprehensive and detailed, providing a series of precise numerical data on the processing times of the different software, each of which had strengths and weaknesses when applied to the scanning of an old factory. The comparison Produced a decent overall result, with a reasonable reconstruction of the roof shape and detailed textures on the rafters. However, it had some difficulty with roof holes and color problems due to direct sunlight. The walls were also of mixed quality, with sharp textures in some areas and poorer quality in others. Metashape worked very well, producing a clean mesh with no holes in the roof and a rounder, less noisy geometry. The textures were also detailed, especially on the facade and the inside of the roof. The only minor problems were the slightly blurred textures in places and the fuzzy appearance of the planks at the back.

	3DF Zephyr	Metashape	Reality Capture	Meshroom
Speed (637 photos)	1h 17min	58 in	1h 10 min	> 6h in total
Images Aligmed	628/637 (98,6%)	637/637 (100%)	588/637 (92,3%)	616/637 (93,7%)
Mesh Density	3,03 M faces	19,8 M faces	70 M faces	2,39 M faces (1/4 resolution)
Texture Quality	4x 8K texture Perfect	2x 8K texture Good with a bit of blurry	1x 8K texture is perfect	27x 4K texture Excessive amount of details

Figure 14 A comparison of the Result of Jérôme Tabeaud experimentation.
source : Jérôme Tabeaud, 2023. Which photogrammetry tool is the best?

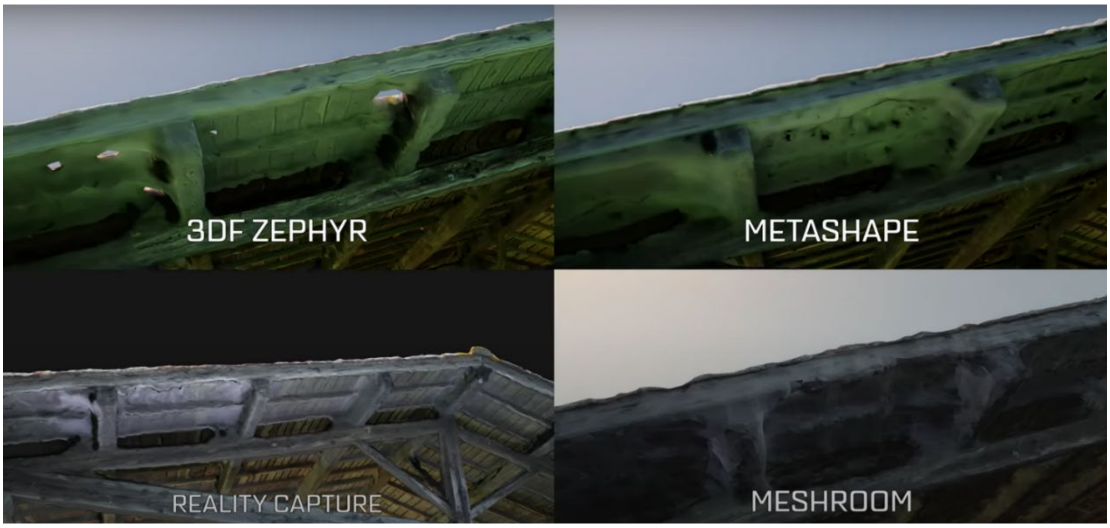

Figure 15 Comparison of the textured mesh reconstructed from cloud points.
source: Jérôme Tabeaud, 2023. Which photogrammetry tool is the best?

Reality Capture generated a high-resolution mesh (over 70 million faces), which had to be subsampled for visualization. This software excelled at reproducing the façade, overhangs, and roof, producing sharp textures and good 3D detail. It was the best software tested for Axis separation data processing and alignment, with additional tools such as orthophoto generation and georeferencing and offering higher quality meshes. However, it produces large files that must be simplified for complex pipelines. Meshroom, the free and open-source option, had the lowest geometry quality but the best textures, thanks to the 27 4K textures generated. The interior of the roof and the planks were not as well reconstructed, but the overall result was still impressive considering the limitations of the software.

To obtain high-quality 3D models through photogrammetry, it is essential to start with correctly acquired images and carefully configured alignment settings. A high design quality in the early stages guarantees a broader range of modifications after, with further possibilities to reduce the quality of some less important components if necessary. When starting from low to medium reconstruction parameters, this implies many limitations in terms of model management, mesh quality, and its development, even if we reduce the weights and lighten the data flow, it remains a bottom-up process, whereas aiming for the highest quality is a top-down process. having said that, a camera of at least 12-20 megapixels is required, ISO settings to reduce noise and lens aperture for sharpness can be handled automatically by the new generations of cameras and smartphones, but according to the literature Scianna, et al 2020, Canciani, et al 2016, and other experiments, the average values are iso:100, opening: f/8 or f/11 with shutter speed 1/100sec, overlapping[2]: 60-80%.

Uniform lighting is essential to avoid sharp shadows or overexposure. In fact, for an optimal exterior photogrammetric survey, diffuse light conditions -cloudy days-, are preferred to ensure uniform surface coverage and improve the quality of the capture and texturing of the reconstructed geometry. Direct light from point sources generates sharp shadows and high contrasts, which can emphasize surface geometry but also cause problems such as deep shadows and unwanted reflections, complicating the capture of details in shadowed areas.

RAW format for image saving is advisable for maximum detail and flexibility, although high-quality JPEGs may be sufficient if compression is minimal. In photogrammetry software, photo alignment must be set to high or maximum

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[2] Photogrammetry software relies on identifying and matching common features (tie points) across multiple images. These features are then used to calculate the relative positions of the camera and reconstruct the 3D geometry. Without sufficient overlap, the software may struggle to find enough shared features, resulting in gaps or errors in the 3D model.

precision for accurate feature matching, although some software is able to do it automatically or with AI.

Combined with well-prepared images, these settings provide a solid basis for generating accurate point clouds and high-quality 3D reconstruction. However, Highly complex and large-scale projects require a more accurate and sensitive approach. Hardwar's system features could become a limitation, leading to program closure or product non-visibility. A partitioning of the work file can compensate for the effort required by the system, while the industry is making great strides in improving the computing power and accessibility of graphique systems.

II.2.3 Terrestrial scanning laser and UAV.

Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicles (UAV) have represented transformative technologies in the last two years, enhancing significantly architectural documentation by addressing challenges related to precision, scale, and accessibility. TLS technology for architectural documentation offers unparalleled precision and details in capturing architectural elements' geometry and surface properties (Vosselman & Maas, 2010). Employing phase-based[3], or time-of-flight[4] Measurement principles TLS systems generate dense point clouds capable of accurately simulating complex structures in multiple dimensions. Such technology is especially important for capturing complex design components of façades, ornamental details, and indoor spaces with sub-millimeter accuracy. Due to its non-destructive nature, it ensures the safety and preservation of delicate sites, which is crucial for conservation projects. It plays a vital role in applications like deformation monitoring due to its capacity to capture detailed geometries over time and monitor structural shifts and stresses providing critical data for restoration, analysis, and digital archiving (Wu et al., 2022; Chiabrando et al., 2016).

However, TLS also has its limitations, needing a direct and stable line-of-sight to capture data accurately and multiple scanning positions in order to fully capture complicated forms, textures, and geometries and to achieve detailed quality documentation (Chiabrando et al., 2016), furthermore, the big

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[3] Phase-based measurement technology determines the distance by analyzing the phase shift between an emitted wave and the wave reflected back after hitting a target. This principle is commonly used in laser scanners for short- to medium-range measurements. (Schröder et al 2018)

[4] Time-of-flight measures the time it takes for a pulse of light or sound to travel to a target and back to the sensor. This principle is commonly used in lidar systems, laser rangefinders, and 3D scanning for long-range measurements. (Frangez et al 2022)

datasets generated from the scanning process impose significant computing and storage power, which strong hardware setups must support to avoid workflow problems (Di Stefano et al. 2021).

On the other hand, UAVs have been successfully deployed in projects that exploit their flexibility and aerial perspective, facilitating the generation of control points for aligning TLS datasets, ensuring a seamless integration of ground-based and aerial data (Chiabrando et al., 2016). They can provide high efficiency and scalability in architectural surveying, particularly for large-scale environments or hard-to-reach sites. Through high-resolution cameras, Drone-based scanning can capture aerial datasets, such as orthophotos and digital surface models, which effectively provide a visual overview of the spatial extent of the documentable site. This ability is especially beneficial in situations where ground-level techniques have limitations whether in mountainous regions, dense urban areas, or regions with high-height variations. The rapid data collection of UAV photogrammetry minimizes time and labor associated with documentation and provides site-wide information that extends TLS localized focus, but may be easily affected by several factors, like weather conditions and signal interferences in densely populated areas.
drones based photogrammetry generally provides lower geometric precision compared to TLS, making it less suitable for capturing fine architectural details, which gives them a complementary role to TLS, offering broader context and scalability rather than intricate accuracy.

Figure 16 3D textured model (altimetric model in false colors according to altimetry (m). source: Chiabrando et al 2016

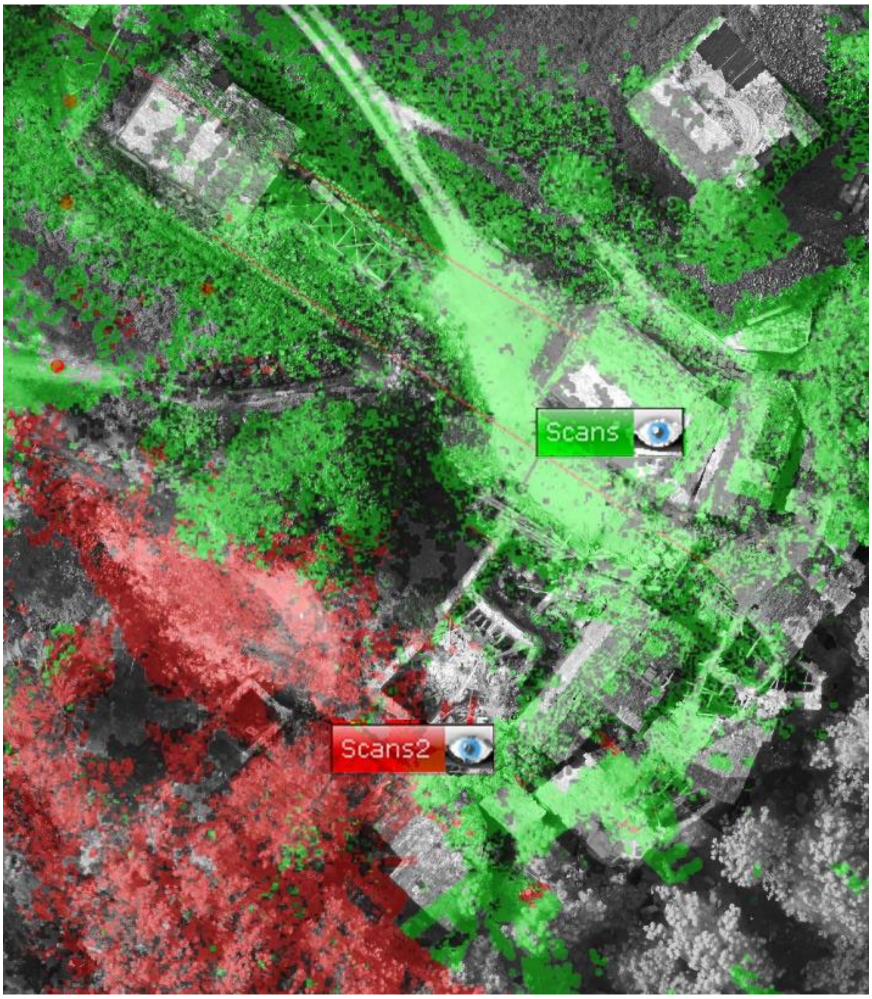

Figure 17: The two groups of scans covering the upper and the lower side of a small village. source: Chiabrando et al 2016

In research published by Chiabrando et al 2016, a high-scale mapping was produced by a Hexacopter drone equipped with six rotating wings, and a commercial digital camera that uses an infrared control system for image acquisition (Chiabrando et. al 2013), efficiently demonstrating the large-scale mapping capability of UAV systems, allowing reconstruction of the entire environment including terrain, vegetation, and structures fig (16, 17).

While in another research, focused on creating an immersive virtual experience for preserving and promoting cultural heritage, scientists started a TLS and UAV-based survey for mapping an ancient church in Greece. the researchers had to cover the interior and exterior shapes and geometries, minimizing occlusions by using auxiliary reflective spheres and georeferenced control points to align the data in the global coordinate system, allowing accurate registration and potential long-term monitoring (Zachos A. and Anagnostopoulos, 2024).

The integration of TLS and UAV data provides a holistic approach to architectural documentation by merging data sets to create a unified 3D model, that combines the geometric accuracy of TLS with the scalability and coverage of UAV photogrammetry. Specialist software such as Cloud Compare and Faro Scene was used to align and merge point clouds, enabling the production of detailed elevation maps and orthophotos for comprehensive model generation, which serves as the basis for advanced applications such as Historical Building Information Models (HBIMs) and digital twins, bridging the gap between accuracy and context (Di Stefano et al, 2021).

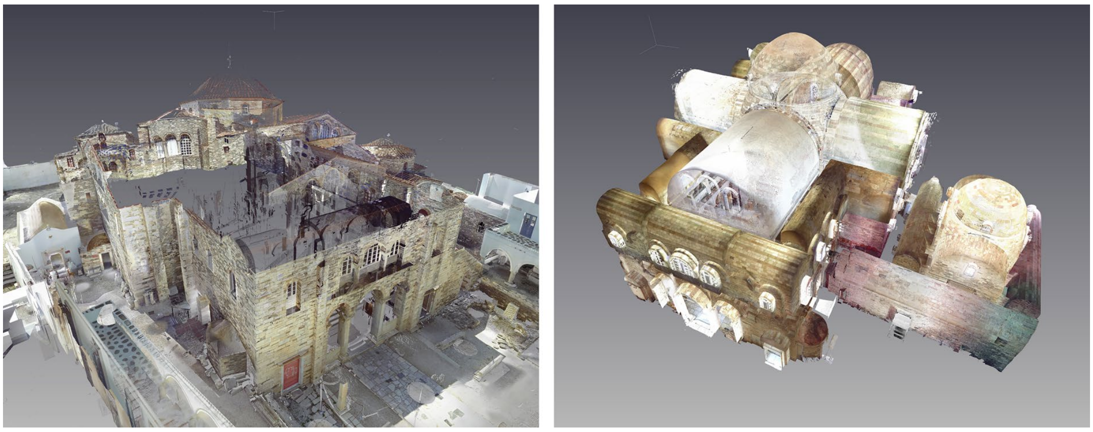

Figure 18 The overall TLS model.
Source: Zachos and Anagnostopoulos 2024

Mixed Reality (MR) applications derived from these datasets demonstrate the potential of immersive technologies for heritage engagement through virtual tours of monuments to promote CH. Augmented Reality (AR) experiences designed for mobile devices and headsets such as HoloLens or Meta Quest allow users to interact with 3D models of artifacts and architectural features in situ. These AR environments enhance educational and tourist engagement, making the historical and cultural significance of the monument accessible to a broader audience.

II.2.4 Phone Based 3D Scanning.

LiDAR technology, used mainly in smartphones (with their sophisticated cameras), provides a practical, low-cost, and accessible alternative to traditional scanning and photogrammetry methods in architectural documentation, making a significant contribution to the affordability, portability, and ease of use of such technological surveying tool. Unlike expensive terrestrial laser scanners, smartphone 3D scanning apps have a lightweight design and intuitive interfaces that allow the users to perform scans quickly and efficiently, reducing setup time and logistical complexity, enhanced with integrated GPS, IMU (Inertial Measurement Unit), and AI algorithms, the app ensures precise localization of scanned data within real-world coordinate systems for 3D point clouds generation.

The data generated according to different studies that have compared the results of TLS and phone Based scanning demonstrates promising accuracy for the last, with deviations typically below 5 cm when compared to high-end terrestrial laser scanning results, with a suitable level of precision for preliminary modeling, interior documentation, and capturing architectural elements (walls, columns, and smaller structural details). Smartphones' compact size and mobility enable rapid on-site surveys and real-time adjustments in seamless integration with AR applications for interactive visualization and design exploration. With the further integration of AI algorithms, the capabilities of these instruments expand, making them more efficient and accurate by automating object segmentation, feature extraction, and noise reduction through AI-driven optimization to produce cleaner and more accurate point clouds. Nvidia has also made significant contributions in this area, mainly through innovations in AI-powered 3D reconstruction, enabling real-time 3D modeling and point cloud processing, using deep learning models to predict missing data and improve geometric accuracy. In addition, Nvidia's advancements in Neural Radiance Fields (NeRFs) provide breakthrough solutions for capturing photorealistic 3D scenes with minimal input, reducing the computational power required.

However, due to their comparatively low sensor resolution and limited LiDAR range, smartphones fall short in large-scale structures and high-resolution surfaces. For instance, environmental factors like poor lighting or high reflectivity surfaces can create noise or otherwise disrupt the quality of both the captured environment and the created point cloud. Although smartphones are great for generating data adequate for basic visualization and the early phases of documentation, they are also inadequate regarding the accuracy and resolution needed for applications like heritage preservation or structural analysis. Additionally, large or complex datasets may not be ideal for smartphone handling, requiring external or cloud software solutions for data processing.

Considering the results of a study that aims to evaluate the performance assessment of phone and tablet camera+LiDAR and test the quality of 3D point clouds generated (Öcalan et al 2024), the accuracy of the 3D models obtained with smart mobile devices embedded with innovative technological sensors has revealed that these devices are a dominant alternative in many different sectors of the spatial information industry.

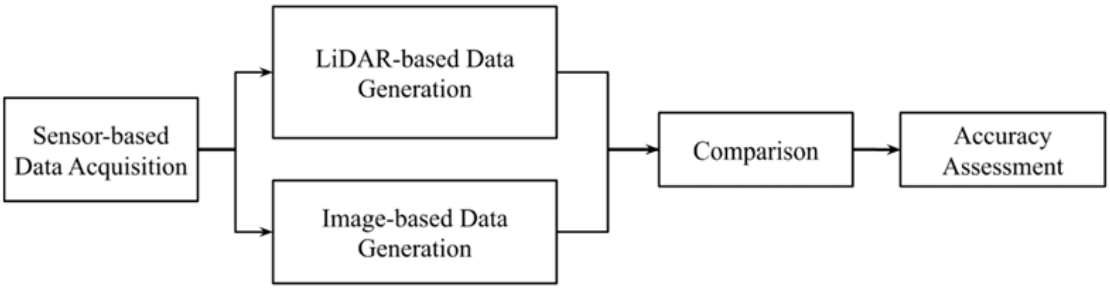

Figure 19 Flowchart of sensor-based point cloud generation.
Source: Öcalan T et al 2024

IRhino 3D, for instance, is an IOS app that uses LIDAR sensors to scan and measure distance, by detecting the corners of rooms and other furniture elements covering the wall surface. It then reconstructs the scanned surfaces based on the data collected and elaborates a 3D model with measurements ready to be exported to Rhino or any other 3D modeling program.

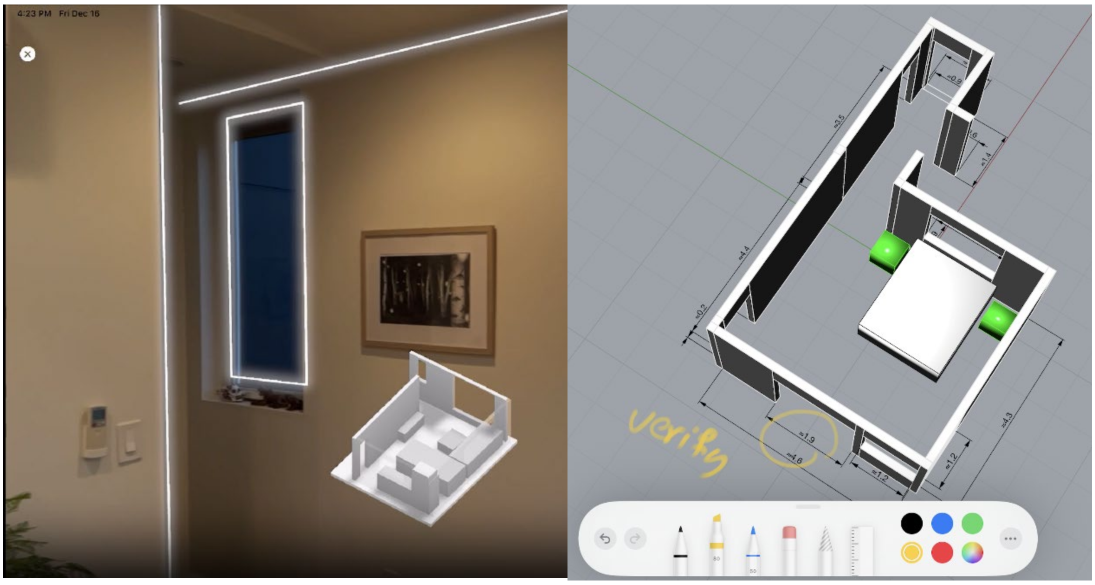

Figure 20 IRhino Real time Lidar scanning APP, and the generated 3dm file with measeurment and details.

3D Magic scan

Created by developers in partnership with Nvidia, Majic Scan is an AI-powered application for IOS and Android that allows companies and individuals to create high-quality 3D models of real-world objects and environments for further Virtual/Augmented visualization or 3DPrinting, with the ability to share them via social networks and export them in any format. This app was interesting in the research phase because of the partnership with Nvidia, leader in the digital revolution with GPU technology and computing platforms that enable 3D modeling, visualization, and architectural design through advanced tools such as NVIDIA Omniverse. The company focuses on real-time rendering, simulation, and AI-driven workflows that enable seamless collaboration and hyper-realistic results for the creative and design industries.

Figure 21 3D scanig App for Andoid and IOS

Chapter III. Experience Creation.

III.1 Documentation of Fontana dei 12 Mesi.

With the goal of creating a 1:500 scale physical model of the entire area of Valentino Park, Polito students and researchers under the guidance of Prof. Roberta Spallone, Prof. Marco Vitali, and Arch. Francesca Ronco, carried out the urban context modeling process. The author joined this team by modeling buildings of historical and cultural relevance and some residential blocks. Modeling at this phase was carried out in a hybrid[5] approach in order to optimize the 3D files for Printing. Parting from imported drawings, models, and surveys, the buildings in the table below, in addition to the context residential blocks and public structures, were designed and assembled into one digital model.

Torino Esposizioni	Blender
Expo Nervi	Blender
Expo Nuovo	Blender
Expo Sottsass	Blender
Expo Rotonda	Blender
Borgo Medievale	Blender
Promotrice delle Belle Arti	Rhino
Castello del Valentino_Polito	Blender
Museo Orto Botanico	Blender
Polito - INRIM	Blender/Rhino
Polito - Morgari	Blender/Rhino
Villa Glicini	Blender
Fontana 12 mesi	Rhino

One of the interesting structures in this process was Fontana dei 12 Mesi [6],. With its unique style and history, we chose to document and promote this monument reintroducing it in small-scale form along with the fountain,

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[5] combining diverse technologies, methodologies, and imputs to achieve a unified result, this integration enables flexibility, scalability, and the ability to address multiple objectives simultaneously.

[6] The Fountain of the Months is the only surviving architectural element of the vast array of buildings constructed for the 1898 Italian General Exhibition, organized in Turin to celebrate the

After using the app already mentioned to scan the statues of Fontana dei 12 Mesi, it has proven its capability to change how we document and approach real-world objects and structures, especially in architecture and 3D modeling. It is almost impossible for one person with a phone and a selfie pod to quickly capture such information and details (5 minutes in the premium version/25 minutes in the free version) without professional tools. For statues around 3m high, the Magic Scan application allows images to be captured directly through the camera, guiding the user with the required speed and stability. The data is then processed by artificial intelligence algorithms that complete the reconstruction of the object using triangulation technologies to produce a high-quality [7]Textured mesh of the scanned object.

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fiftieth anniversary of the Albertine Statute. According to a vocation that was consolidating after the 1884 Exhibition, the site chosen to host the event was Valentino Park, and the prestigious task of designing the pavilions was entrusted to Carlo Ceppi (1829-1921). An architect of great importance in Turin's cultural milieu, Ceppi's projects include the imposing Porta Nuova station building (drawn up with Alessandro Mazzucchetti) and several stately palaces in the center. While the other buildings of the Exhibition were constructed in wood, plaster, and canvas, the Fountain of the Months had a permanent structure built in ‘modern’ concrete. It is a large luminous fountain adorned with four groups of statues depicting Turin's rivers (Po, Dora, Sangone, Stura) and twelve female statues representing the months of the year. Critics consider it ‘a successful synthesis of academic eclecticism and openness to stylistic and technical novelties’.

[7] The quality of the object depends mainly on brightness, shooting stability, and context. The conditions under which the experiment was carried out were not optimal, with an overcast November day, and the architectural barrier created by the location's geography. However, the documentation process was relatively easy and feasible by one person.

III.1.1 Software and Reconstruction Process.

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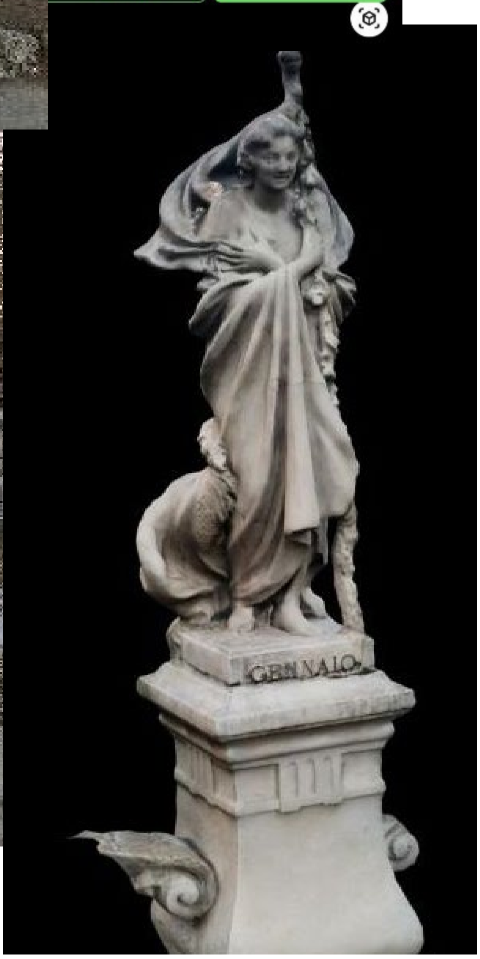
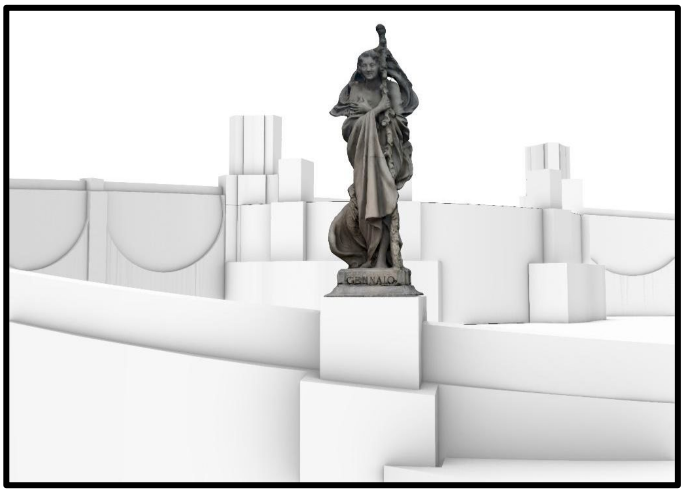
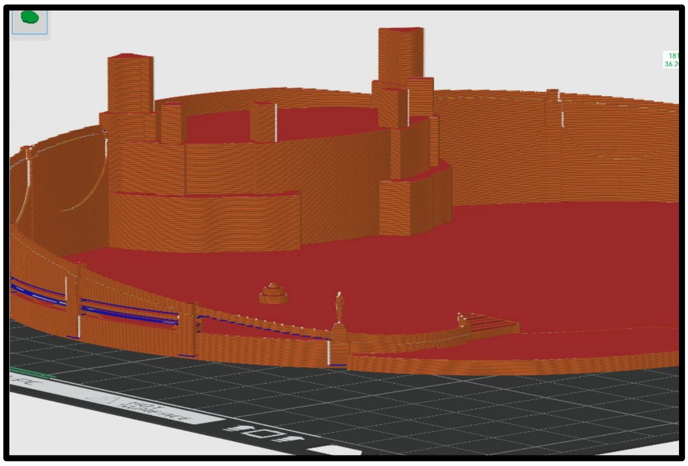


Figure 22 Statua Gennaio, Fontana dei 12 mesi. 3D model generated from Magic scan
Made by the author: Sbai Oussama

Instruments

Process





III.2 3D modeling.

When analyzing modeling processes, it is necessary to start with the software used to create, modify, or manipulate the studied architecture, as this is the first factor that influences the development conditions of the process. A good modeling program can smoothly and retroactively manipulate the creation of architectural elements through techniques and tools such as: *Nurbs* -Non-Uniform Rational B-Splines- a mathematical representation of 3D geometry that accurately describes any shape from a single 2D line, circle, arc, or curve defined by its degree, a set of weighted control points, knots vector, and evaluation rule, to the most complex 3D organic free-form surface or solid (Arturo Tedeschi, 2014). *Mesh*: In 3D modeling, a mesh is a collection of vertices, edges, and faces that define the shape of a 3D object in space. The mesh is a data structure that forms polygonal models required for rendering (and computation) in scenic visualization processes such as architecture, video games, and VR(Botsch., et al., 2010). *SubD*: short form of Subdivision Surface, is another modelling technique used in 3D computer graphics to create smooth, curved surfaces by iteratively subdividing a polygonal mesh into a low-resolution base mesh (control cage), then refining the surface by adding more polygons through subdivision algorithms, resulting in a smooth, high-resolution mesh.

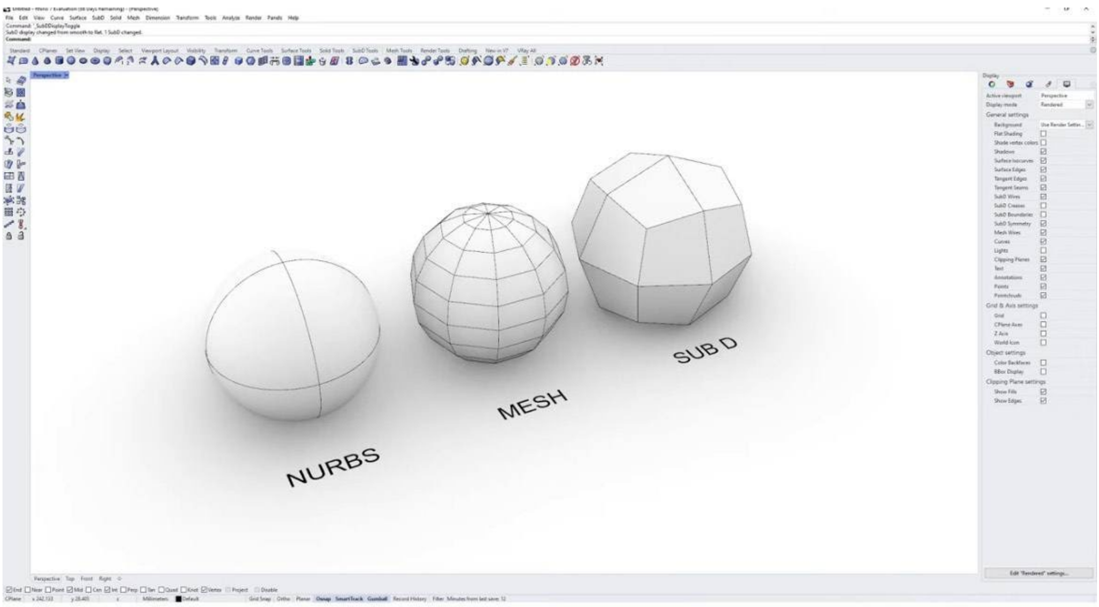


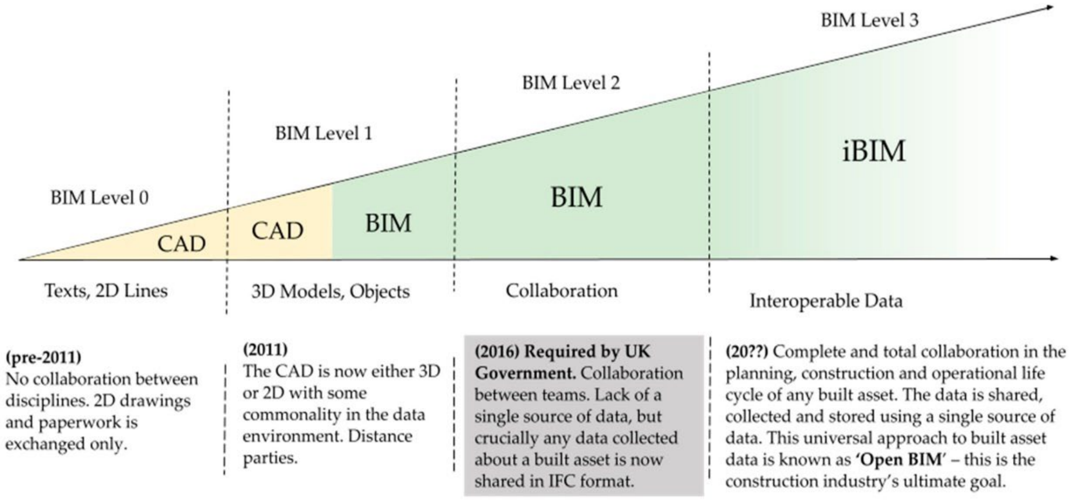
Figure 23 Nurbs, Mesh, and SubD modelling tools in Rhino

software	techniques	challenges
Building Information Modeling (BIM) Software	An integrated and collaborative approach to design Parametric modeling. 4D and 5D modeling: construction planning and budgeting.	Loss of data or translation errors between software. Inconsistent workflows. Difficult learning curve. Cost and lack of skilled personnel.
3D Modeling Software (Rhino, Blender,3ds)	Rhino provides powerful tools for modeling complex, organic shapes using NURBS. Blender's geometry nodes allow procedural modeling, automating complex design iterations. Open-source flexibility	Rhino and Blende models often need to be reformatted for integration into BIM workflows, creating inefficiencies. Geometry created in freeform tools may not align well with parametric or rule-based constraints in BIMdi. Dependence on plug-ins
Parametric and Algorithmic Design (Grasshopper, Dynamo)	Grasshopper (for Rhino) and Dynamo (for Revit) allow architects to create parametric designs, automate repetitive tasks, and explore complex geometries. Custom scripting, Integration with programming languages (Python, C#) allows the creation of custom tools and workflows tailored to specific project needs.	Complexity and Skill Gap knowledge requirement in both design principles and programming. Integration difficulties with Traditional Workflows (CAD or BIM). Performance Issues with Complex Algorithms.
Cloud-Based Collaboration Tools (e.g., BIM 360, Trimble Connect)	Cloud-based platforms allow teams to work on a single source of truth, reducing errors caused by version mismatches. Real-Time Updates: Changes made by one team member are visible to others in real-time, enhancing collaboration.	Storing sensitive architectural data on third-party servers raises security and data ownership concerns. Reliance on Internet Connectivity. Platform Fragmentation: Different teams may use different collaboration platforms, requiring complex integration or multiple subscriptions.

Figure 24. A confrontation between different modeling methods in terms of advantages and actual weaknesses. Made by the author: Sbai Oussama

Blender, Rhino, and Revit are the essential software for architectural modelling, even if they differ in both workflow and data handling, they represent a complementary work-frame for complex project. one software cannot replace another, nor can it be a complete and autonomous. Rhino, for instance, generates floating geometry consisting of NURBS surfaces to achieve a smooth, exact look, which can then be leveraged in parametric forms with more complex shapes. This feature integrates seamlessly with a visual programming framework -Grasshopper-, enabling designers to iterate through various design solutions rapidly (Ververidis et al., 2022). On the other hand, Blender uses meshes and polygon signatures to create volumes and is known for generating intricate visualizations and high-quality animations. However, its visual accuracy is nothing compared to Rhino's superb geometry definition, which means that Blender can only work well where there is little design complexity to trade on technical accuracy. Revit, instead, provides a semantical and numerically controlled BIM-oriented approach based on a detailed database of used objects, enabling new Dimensions of project management (Table 2).

Dimension	**Focus Area**	**Purpose**
3D	Geometry	Visual and spatial understanding of the project.
4D	Time	Project scheduling and phasing.
5D	Cost	Budget and cost analysis.
6D	Sustainability	Energy performance and environmental impact.
7D	Facilities Management	*Maintenance and lifecycle management.*
8D	Safety	*Construction and operational safety.*
9D	Social Impact	*Post-occupancy comfort and societal benefits.*



(pre-2011) No collaboration between disciplines. 2D drawings and paperwork is exchanged only.

(2011) The CAD is now either 3D or 2D with some commonality in the data environment. Distance parties.

(2016) Required by UK Government. Collaboration between teams. Lack of a single source of data, but crucially any data collected about a built asset is now shared in IFC format.

(20??) Complete and total collaboration in the planning, construction and operational life cycle of any built asset. The data is shared, collected and stored using a single source of data. This universal approach to built asset data is known as **'Open BIM'** – this is the construction industry's ultimate goal.

Figure 25 BIM s Dimensional Workframe and Collaboration Levels Maturity.
Sourc : Ververidis, D. et al 2022

Regarding data management and exporting, each software has pros and cons. Some of the versatile formats of Rhino include. 3dm. Dwg and. to stl, import, and export, keeping precision and compatibility. In particular, while it allows the conversion of NURBS surfaces into mesh, if not managed well, this can lead to heaviness in exported files by adding unnecessary complexity. Blender generates a lighter exported model, with formats like. Obj and .fbx, perfectly suitable for rendering and animation platforms. Furthermore, Blender incorporates AI, which addresses 3D data (Russo, 2021).

Modeling through VPL -Grasshopper, Dynamo, Blender- is a further privilege for architects since it enhances the potential of creativity and allows a new organic style to emerge. The BIM, on the other hand, allows for the complete project management using a digital model-based approach. (Riwinoto et al., 2024) With an often familiar interface, these programs, among the most developed in the market, are organized in layouts or viewports, windows through which the designer visualizes the workspace. Identifying the commonalities between these programs is important, as projects of medium to high complexity often require several programs.

Integrating cloud-based collaboration platforms, such as BIM 360 and Trimble Connect, has revolutionized workflows in the Architecture, Engineering, and Construction (AEC) sectors. These tools optimize interoperability between software such as Rhino, Blender, and Revit, enabling efficient data flow and collaborative design of complex projects. Both offer centralized environments for data storage and management, improving coordination between multidisciplinary teams. BIM 360, developed by Autodesk and integrated with Revit, offers a highly effective project information management system. It allows users to access BIM models, comments on revisions, track activity status, and manage issues in real-time. This flexibility is important for large-scale projects, where multidisciplinary approaches require a uniform data flow and detailed object description. When supported by Revit, BIM 360 offers a significant advantage in the building lifecycle by integrating BIM data with field operations. Trimble Connect, on the other hand, is a collaborative design interface that supports a wide range of formats, including IFC, it allows real-time data to be created for several users working on the same models simultaneously, improving communication and reducing the time required for visualizations. It also offers a 3D cloud Web view capability, allowing users to create and analyze models without having to install the software on local devices.

In the case of the Campus Valentino project, using both Rhino and Blender modeling software was very useful, as they are fully interoperable. Thanks to FBX, OBJ, and other formats, it was possible to exploit the strengths of each program. Blender was used to create contextual volumes with roofs, using vertex, edge, surface creation and manipulation tools. With a basic knowledge of Blender, the author noted the familiarity and similarity of commands and control methods, with an important difference in the logic of operation and commands: whereas Rhino uses NURBS to represent continuous surfaces, with a high degree of precision and supports modeling with SubDs and precise conversions between SubDs, NURBS and mesh. Conversely, Blender is based on polygonal meshes and uses vertices and modifiers to create and manipulate volumes, where each surface comprises triangles or quadrilaterals. It does not have the precision of NURBS but is excellent for artistic and conceptual modeling, with advanced tools such as digital sculpting to create organic detail.

Blender was also used to model the building of Istituto Elettrotecnico Galileo Ferraris (Istituto Nazionale di Ricerca Metrologica-INRIM-), Villa Glicini, and Promotrice delle Belle Arti, located in the Valentino Park. While Fontana dei 12 Mesi was made by Rhino for the simplicity of managing the counter lines and the different structure quotes.

Among the major differences found in the modeling process between Rhino and Blender was the ability to work on a complete model during creation, maintaining the connection between the different vertices that define the volume. Starting with Blender, the reconstruction of a digital model begins with a flat surface or cube, where each surface is then scaled and divided into parts that can be customized as needed. As the project's complexity increases, it becomes necessary to make some changes to specific parts of the model by removing, adding, or replacing an element initially modeled. With Blender, there are two ways to perform this operation: the first is to delete the existing element, removing its various vertices; then, by cleaning the corners, you can proceed with remodeling. With the F (FILL) command, you can define a new surface from which to extract our new shape. In both cases, the loops' initial continuity would be lost.

Although it may seem simple, this process takes a few minutes for small changes. However, a complex structure like the INRIM building created problems during the printing phase, particularly when slicing the digital model for printing in parts. In this case, the model deforms and shows errors of overlapping surfaces and vertices, a problem encountered in most cases with buildings modeled with Blender. Editing the original model becomes even more complex if the model is divided into parts, leaving fragments on the outer surface that are difficult to organize. In this case, the continuity of the loops initially created would be lost.

Topology is a key concept in 3D modeling with Blender, which concerns the structure and organization of vertices, edges, and faces within a mesh. A good topology is essential to ensure that the model is efficient, easily modified, and suitable for the purpose for which it was created, whether for animation, rendering, or 3D printing. The arrangement of polygons, often in quadrilaterals (quads), is preferable because it allows for uniform subdivision and allows for cleaner edge loops. These loops follow the main shapes of the model, ensuring that the mesh behaves well at every stage. Blender offers advanced tools for topology management in Edit mode: tools such as Knife, Extrude, and Edge Slide allow you to manually refine the mesh, while modifiers, such as the Subdivision Surface Modifier, allow you to add details while maintaining the overall structure. When the topology of a mesh is suboptimal, Blender supports retopology, a process for redefining the model structure that works best in sculpting, after sculpting complex details with the Dynamic Topology (Dyntopo) mode. In this mode, polygons can be added dynamically as needed during sculpting. However, these tools require extensive knowledge and manual skills to manipulate them properly, making the modeling phase.

Conversely, as a program created for industrial design and technical modeling, Rhino relies primarily on NURBS (Non-Uniform Rational B-Splines) surfaces rather than polygonal meshes. It remains ideal for projects that require high precision, such as architecture and CAD modeling. Unlike topology in Blender, which focuses on the distribution of polygons and the flow of edge loops, topology in Rhino is primarily concerned with the continuity and quality of surfaces, emphasizing the ability to generate smooth, mathematically accurate curves and surfaces. Here, topology is closely related to creating and manipulating NURBS surfaces defined by control points and degrees of curvature, allowing unparalleled accuracy in modeling complex shapes that offer greater flexibility than meshes. Rhino also supports mesh-based modeling and has recently introduced SubD tools that combine NURBS's precision with meshes' flexibility for less technical designs.

III.2.1 Modeling for Renderization.

Renderization, augmented/virtual visualization, and 3D printing have different modeling processes due to their different goals and technical needs. However, for simpler renderization, the primary goal is to render quality images, often prioritizing surface textures, lighting, and geometrical details to produce photorealistic results. These three criteria control the product's workability and the process's complexity. To achieve a realistic render, whether in Rhino or Blender, starting with a well-defined and clean topology that does not have to be continuous and unified (groups of objects may be layered without affecting the final results) is necessary. Even complex models can be partialized to lighten the data processing, while detailed modeling can be limited to the part to be visualized.

This is one of the advantages of modeling for photorealistic rendering or some cases of virtual Reality with respect to 3D printing. since models are usually rendered frame-by-frame, most software guarantees a real-time interaction with a reduced quality to check and guarantee details accuracy and visualization quality. Technically, the process starts with creating 3D models, which can include highly complex geometries. Software like Blender and Rhino are commonly used to achieve detailed surfaces, organic form estimates and precise architectural designs. High polygon counts in this phase are recommended for achieving high-fidelity renderings, especially when recreating intricate surface details. However, the computational demands of these models necessitate optimization techniques to ensure smooth rendering and real-time interactivity, particularly in AR and VR applications. The balance between detail and performance remains a key challenge in digital modeling and visualization.

Figure 26 from Top to bottom: Blender: INRIM model in; Promotrice delle Belle Arti; Villa Glicini; Rhino: Fontana dei 12 mesi.
Made by the author: Sbai Oussama

This is one of the advantages of modeling for photorealistic rendering or some cases of virtual Reality with respect to 3D printing. Since models are usually rendered frame-by-frame, most software guarantees a real-time interaction with a reduced quality to check and guarantee details accuracy and visualization quality. Technically, the process starts with the creation of 3D models, which can include highly complex geometries. Software like Blender and Rhino are commonly used to achieve detailed surfaces, organic form estimates, and precise architectural designs. High polygon counts in this phase are recommended for achieving high-fidelity renderings, especially when recreating intricate surface details. However, the computational demands of these models necessitate optimization techniques to ensure smooth rendering and real-time interactivity, particularly in AR and VR applications. The balance between detail and performance remains a key challenge in digital modeling and visualization.

Due to the growing interest in metaverse and virtual reality in recent years fig (24) and the unprecedented development of blockchain and AI technologies, the distance between the real and digital worlds is shrinking. Today, the metaverse has already established a highly developed experimental basis with an abundance of platforms, each with its unique features and limitations (Akbobek A. et al., 2023).

JP Morgan -one of the world's largest and most influential financial institutions, operating in investment banking and wealth management-bets metaverse is a 1 trillion yearly opportunity as it becomes the first bank to open in the virtual world (Yvonne Lau, Fortune Magazine. 2022).

3D modeling enables the creation of a database of elements to be visualized, documenting in detail the architectural features, materials, and historical changes of each structure. These databases are essential to digital preservation, ensuring that monuments at risk due to conflict, climate change, or natural deterioration can be preserved for future generations. Initiatives such as the ‘CULT Platform’ project offer a pioneering example with an interoperable database that collects 3D models, making them accessible to many users and applications.

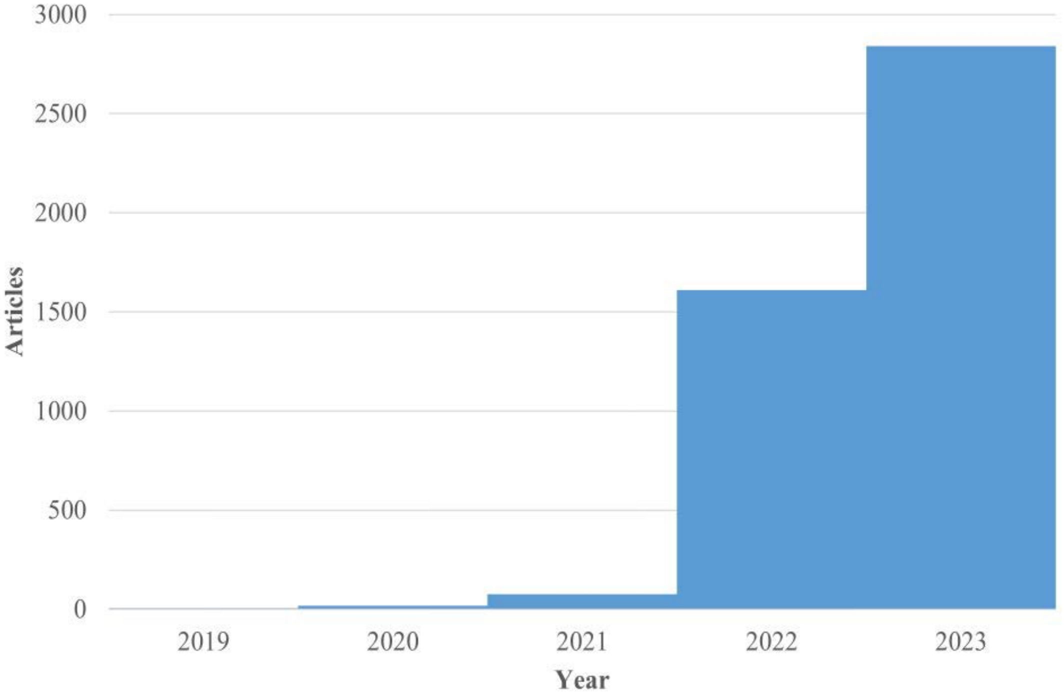


Figure 27 Metaverse-related publications' growth from 1996 to July 2023, based on Scopus, Web of Science, and Pubmed. The 2023 publication count was extrapolated proportionally to represent the entire year. Source: Akbobek, A. et al 2023

SDKs.

The choice of rendering engine can greatly impact the quality and performance of the final result. V-Ray, Lumion, and Twinmotion allow for highly accurate photorealistic and video-realistic results due to the physical light management properties they use. Ray tracing is the process of mapping the path of light rays as they hit a surface, resulting in reflections, refractions, and naturalistic shadows that can be calculated by the computer's GPU. When rendering a video, the need to process hundreds or thousands of frames significantly increases the computational load that low- to mid-range graphics cards cannot handle, causing the process to fail. Effective rendering has two main components: time and computing resources. Designers must work to optimize their models and to minimize rendering time while maintaining visual quality. Elements such as Displacement or Normal Maps are usually used to reduce the size and increase the details of geometries and their tracking. At the same time, adaptive sampling helps the software focus its computational power on complex scene areas, improving efficiency without compromising quality.

Post-production also plays a significant role in photo and video renderization workflows. Render passes, such as diffuse, specular, and ambient occlusion layers, are exported and composited in software like Adobe After Effects or DaVinci Resolve to fine-tune the visual output. This step allows for adjustments in color grading, depth of field, and motion blur, further enhancing the visual narrative. The modeling process for photo and video rendering is an intricate blend of artistic and technical expertise. It requires a deep understanding of geometry, materials, light physics, and rendering technologies to produce visuals that captivate audiences and convey the desired story or environment with precision and impact.

Blender, supported by Unreal Engine, is establishing itself as an all-in-one open-source solution for artistic and visual applications platforms to create high-quality Rendering and animations. However, it does not offer the same integration with BIM as Revit. Tools such as Enscape and Fuzor for real-time visualization and architectural simulation provide an integrated workflow from design to presentation, defining the benchmark in the AEC sector and consolidating the role of BIM modeling in the collaborative management of complex projects. On the other hand, Rhino and Grasshopper continue to be an innovation model for their ability to integrate advanced shape generation and analysis algorithms while maintaining good accuracy. Furthermore, the future of these software is promising due to the integration with (AI) and machine learning. Together, these platforms excel in the most complex projects, offering new opportunities for integrated, multi-dimensional approaches to architectural Heritage.

However, high-quality rendering for simple photos and videos often requires the use of other rendering software or plugins like V-ray, Lumion, or Twinmotion. Lumion and Twinmotion represent the top rendering programs offering various objects and materials to improve the texturing and renderization process while maintaining an intuitive and user-friendly interface. These programs have shown outstanding ability in producing high-quality images and videos but require some knowledge of adjusting the light, atmosphere, and other elements that contribute to a realistic effect in the rendering.

Through a series of photorealistic renderings and accurate model images, it has been possible to anticipate the future vision of the new campus, simplifying the transmission of information and highlighting the key points of architectural reading to ensure a solid understanding of the context. The brochure played an essential role in the communication and presentation of the project, laying the foundations for an extended phy-gital presentation.

Figure 28 Pad. Nervi. photorealistic Rendering.
Source: https://campusvalentino.polito.it/. February 2024.

Renderization Process.

The Renderization process for architecture involves multiple stages aimed at producing realistic photos/videos to accurately convey the design intent, relying on powerful rendering software such as Twinmotion, Lumion, Blender, and V-Ray, each offering distinct advantages in terms of rendering quality, speed, and flexibility. By focusing on software-based processes, we can better understand the techniques and considerations required to achieve high-quality render output from geometry preparation to final render settings. Twinmotion(free software) and Lumion (paid software with student license possibility) are the two most widely used rendering engines in terms of quality/accessibility for architectural use. Their ability to produce high-quality, real-time rendering allows users to interactively manipulate environmental factors such as weather, time of day, and vegetation through an intuitive interface, making them ideal for rapid iterations and real-time presentations, with an extensive asset library that allows users to populate scenes with life-like objects, enhancing the storytelling aspect of architectural visualization (Zhu, Li, & Cai, 2020). On the other hand, V-Ray represents a further improvement of the rendering-oriented design process, offering the possibility of modifying the original model in total freedom while viewing the final result in real-time, which is approximated with the eventually low-resolution presentation but sufficient to help the designer optimize the digital model; such a capability, even if often overlooked compared to the quality and user-friendly interface of other software, remains a key point that optimizes modeling times. The ability to view the modeled spaces with the chosen materials can guide the development of projects in the initial stages, reducing time and costs. At the same time, the physically accurate ray tracing engine simulates the behavior of light in a way that provides unparalleled realism, making it a preferred choice for high-end architectural renderings and cinematic visualizations (Kulla & Conty, 2019).

These tools require more time and technical expertise but offer a level of precision that other real-time engines may struggle to match in terms of time and hardware requirements. On the other hand, reliance on third-party software for rendering implies a constant return to the modeling software for significant changes to the original model.

Rendering engines follow a typical process that starts with importing a clean and optimized model. As these tools handle real-time rendering, the model must have well-defined geometry and correct UV mapping to avoid texture distortion during viewing. Once the model is imported, materials and textures are applied or enhanced using the built-in libraries provided by the different software. Both Twinmotion and Lumion offer extensive material libraries with pre-configured shaders for elements such as glass, wood, metal, and concrete, allowing materials to be applied quickly. At the same time, for Blender, it is possible to download several add-ons that give access to different materials and object libraries. Twinmotion's advantage lies in its seamless integration with Unreal Engine, which allows users to export scenes directly to UE for more advanced editing if required (Zhu, Li, & Cai, 2020). Lumion, on the other hand, excels at creating landscapes, offering detailed libraries of vegetation, water, and atmospheric effects that can be manipulated in real time. The ability to adjust environmental factors such as lighting, seasons, and weather conditions adds a level of realism and contextualization to architectural projects.

The ease of creating animations is a key feature of both Lumion and Twinmotion to create walkthroughs, flyovers, or time-lapse sequences while simultaneously setting camera paths and angles. Lumion's animation tools include pre-built character and vehicle motions that enhance the sense of scale and vibrancy of urban or residential environments. In contrast, Twinmotion's real-time path animation and camera control offer similar ease of use, allowing designers to create dynamic presentations without complex keyframing.

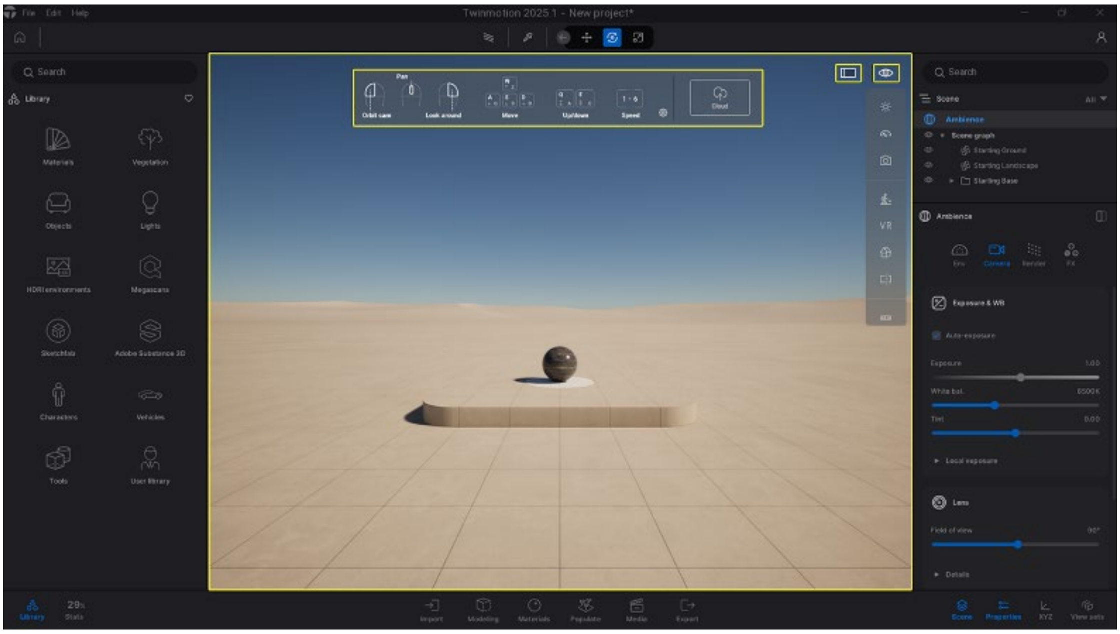
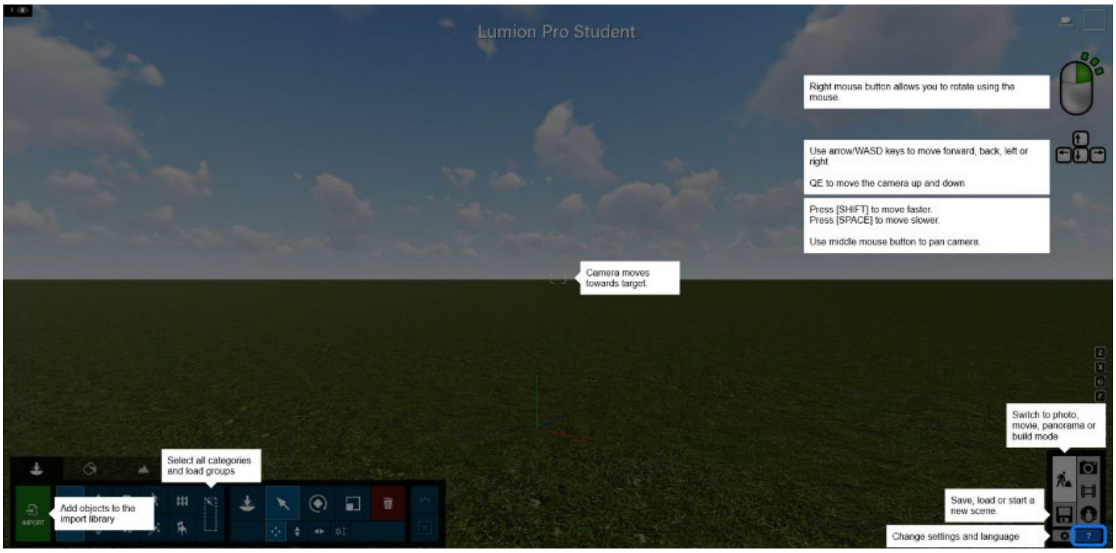


Figure 29 Twinmotion UI



Right mouse button allows you to rotate using the mouse.

Use arrow/WASD keys to move forward, back, left or right.

QE to move the camera up and down.

Press [SHIFT] to move faster.
Press [SPACE] to move slower.

Use middle mouse button to pan camera.

Camera moves towards target.

Switch to photo, movie, panorama or build mode

Save, load or start a new scene.

Change settings and language

Select all categories and load groups

Add objects to the import library

Figure 30 Lumion UI

Omniverse.

Launched in 2020, Nvidia’s Omniverse is a scalable, end-to-end platform that enables all industries to build and operate digital twins for scientific research, infrastructure, product design, architecture, and more. It is a real-time collaboration and simulation platform focusing on interoperability between different 3D modeling and rendering applications. Architectural representation and communication require a continuous connection through multiple design options to meet client's needs, which is still difficult and time-consuming.

Nvidia Omniverse provides powerful and easy-to-use tools for architects and designers to create, visualize, Render, and control advanced virtual experiences and then collaborate on these projects with clients or team members working simultaneously on the same project. It also features live connection to top design applications such as Revit, Rhino, and Blender fig (34), allowing architects and designers to work seamlessly across multiple design applications in real time. In the example shown in fig (31), a Revit model and a Rhino model coexist in the same 3d scene, and the designer can see the combined data sets in a shared virtual scene, the designer can make changes to the project data in either Revit or Rhino and view the photorealistic results live in omniverse view.

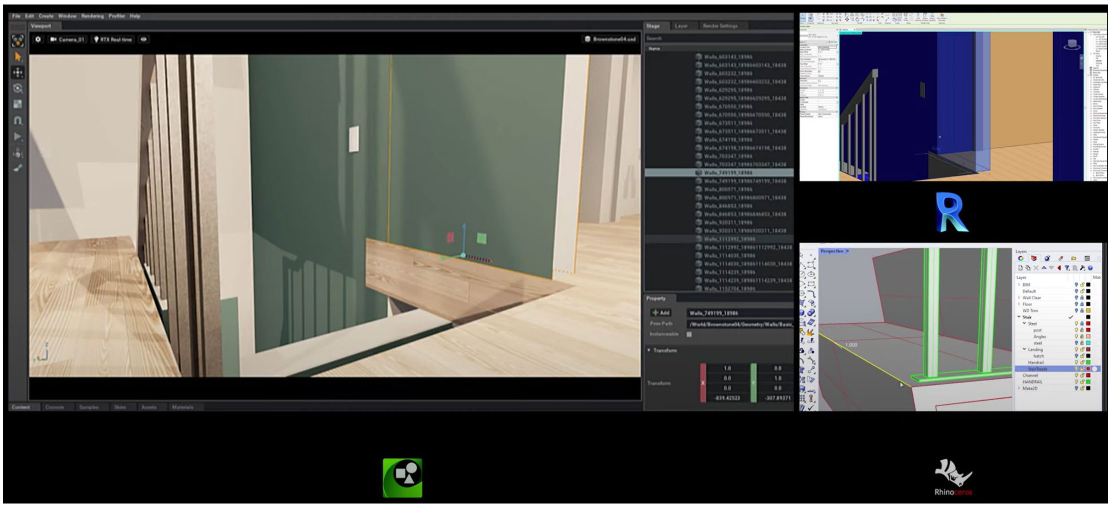


Figure 31 Real-time collaboration from different software (Rhino and Revit) through Omnivers Platform.
Source : https://www.youtube.com/watch?v=DFAUFMzIYtE

The Ray-traced rendering technology allows designers and architects to modify physically based materials geometry and lighting conditions in real-time and view the ray-traced results for rapid visualization and ideation. Its advanced features and technical complexity make it less accessible to general users. NVIDIA's marketing primarily targets specialized professional communities rather than a broader audience who can access most of the company's products for free, including Omnivers SDK.

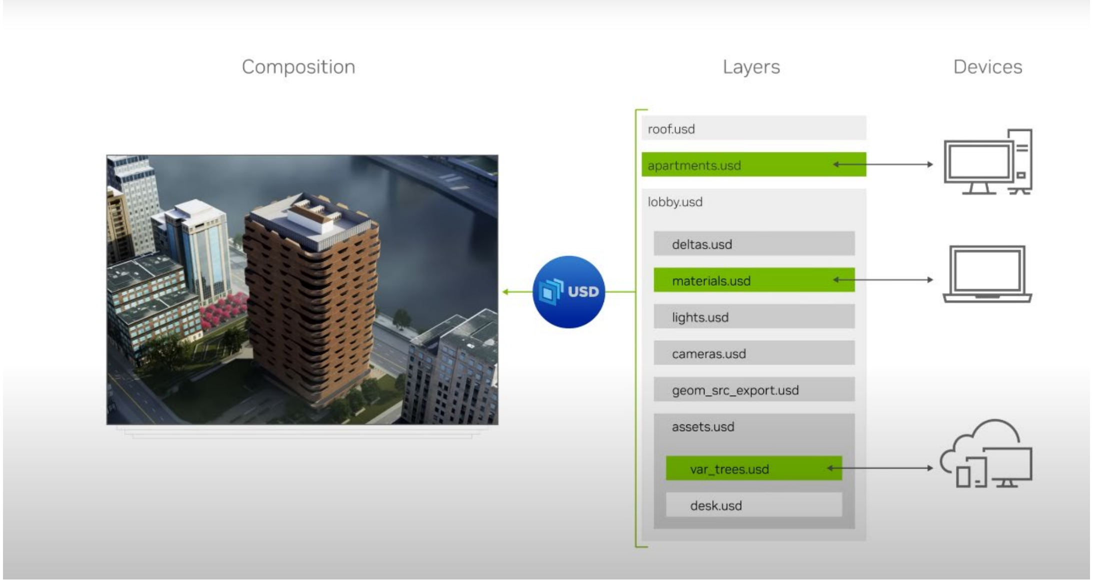


Figure 32:Usd layers categorization for exporting.
Source: Nvidia- https://openusd.org/release/index.html

This great platform is built around a new file format that enables an unprecedented level of interoperability. USD is a Universal Scene Descriptor format created by Pixar in 2016 but widely defused only in 2020 with the launching of Omnivers, allowing for the collaboration of hundreds of artists working with different programs.

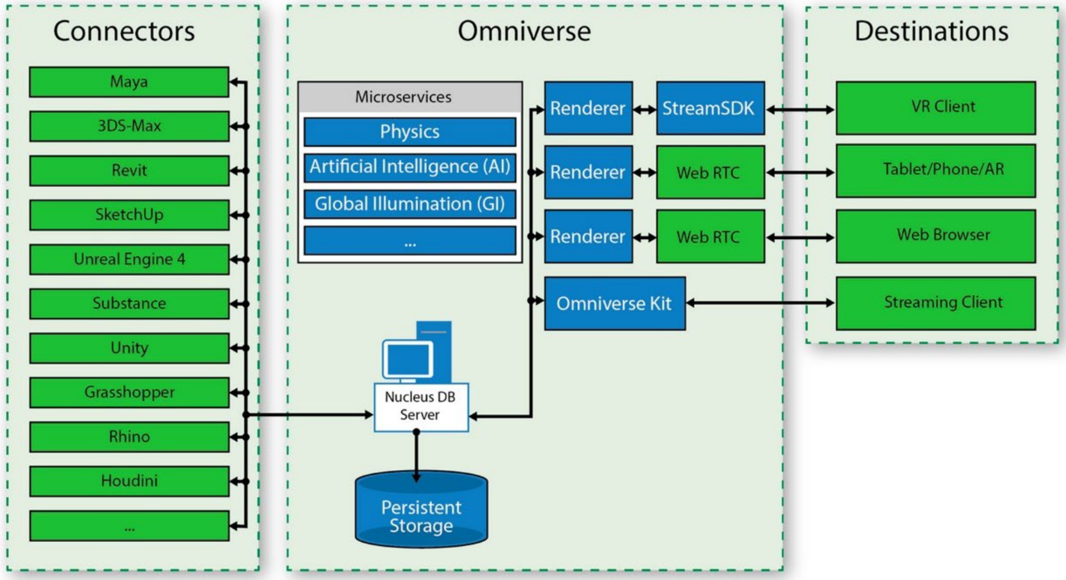
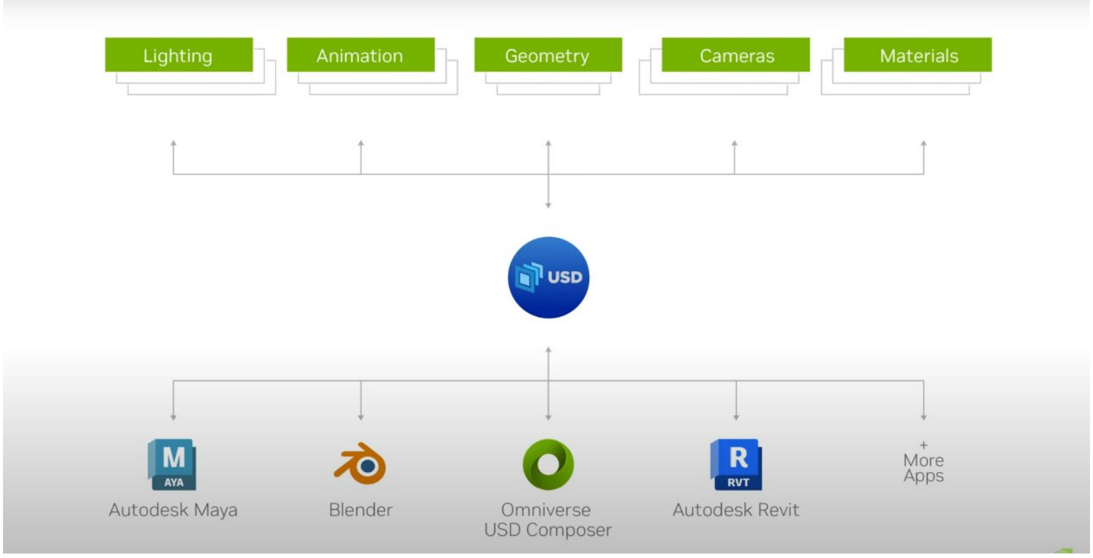


Figure 33 Omniverse s Architecture
Source: Ververidis, D. et al 2022

This file type can contain all of the 3D compositional data, textures, software-specific modifiers (blender or 3DS max), shader assignments (unity or UE) englobing by that different software in one unified platform for different uses, eliminating the need to convert to different file types or export from one program to another, by just opening, editing, and saving the USD file in a supported software and re-open that exact same file in the next program that you need to use. USD is also an API or an application programming interface that can be opened on any API editor for scripting and personalization, especially in the industrial field.

This format is becoming widely adopted by many software types and has already shown great promise for collaboration and connectivity.

open USD has been widely used in film and visual effects. However, we are really starting to see much uptake in industrial twins and digitalization of physical processes (Guy Martin -Nvidia 2024).



34 USD interoperability and Data management
Source: www.openusd.org

III.2.2 Augmented and Virtual Visualization, Modeling.

Augmented and virtual visualization prioritizes real-time interaction and performance optimization, which requires further optimization of the digital model designed for Renderization purposes. AR/VR experience must carefully balance visual realism and computational efficiency (Akenine-Möller et al., 2018). Unlike rendering, virtual presentation has strict requirements and demands lower polygons and more lightweight assets since the digital model must be uploaded to the virtual environment. Some tools such as the decimate modifier, apply a selective reduction of polygon amounts while keeping crucial geometries, allowing smooth interaction in environments like Blender and Unity (Riwimoto., 2024). Mesh optimizations through the fusion tools allow drawing calls[8] to be minimized, which is essential to optimize GPU performance and maintain interactivity at stable frame rates (Kajiya, J. T. 1986). For example, Unity's batch processing merges models that utilize the same materials into a single model, reducing the memory and processing load. Moreover, this is even more critical for mobile applications, where the fps target is 60 FPS (AR on smartphones or HoloLens devices for AR/VR) (Russo M., 2021). Additionally, these ecosystems must support dynamic lighting and spatial interactions, creating a need for implementations like Vuforia and ARKit, allowing for marker-based tracking and integrating digital assets into real-world views. Taking full advantage of VR and AR technology can be difficult and require years of experience. Artificial intelligence and software development have reduced this gap by automating data processing and machine learning models.

This process consists of creating the entire environment of interest or its most visible elements, from 3D modeling, images, textures, and data flow, to assimilate the actual environmental and contextual conditions and enable navigation and interaction with the project. The benefit of artificial intelligence can be perceived either as a pure information element, self-generated, based on feedback from the user, or as an educational tool capable of recognizing patterns through highly developed algorithms of ML and DL (Palma et al., 2019). Nevertheless, The need for knowledge and practical experience in programming and computer development is essential to ensure the algorithms' stability and efficiency, making it less accessible.

Game engines and specific SDKs like UnReal Engine and Omnivers are designed for 3D environment creation for various uses. They are suitable for the architecture and CH field, offering designers, programmers, professionals, and amateurs the ability to create immersive and overlayed information for MR experience.

The Mixed Reality pipeline represents a sophisticated workflow that aims at transforming 3D models into dynamic, immersive, and interactive environments (optimized for HMD and AR Glasses), where each stage of the

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[8] In computer graphics, a **drawing call** (or **draw call**) is a command sent by the CPU to the GPU to render an object or a part of an object (like a mesh) on the screen. Each draw call includes information about the object's geometry, materials, textures, shaders, and other rendering parameters. (Akenine-Möller, et al 2018)."

pipeline plays a key role in the overall success of the experience, requiring precise modeling, execution, and iterative refinement of the virtual environment.

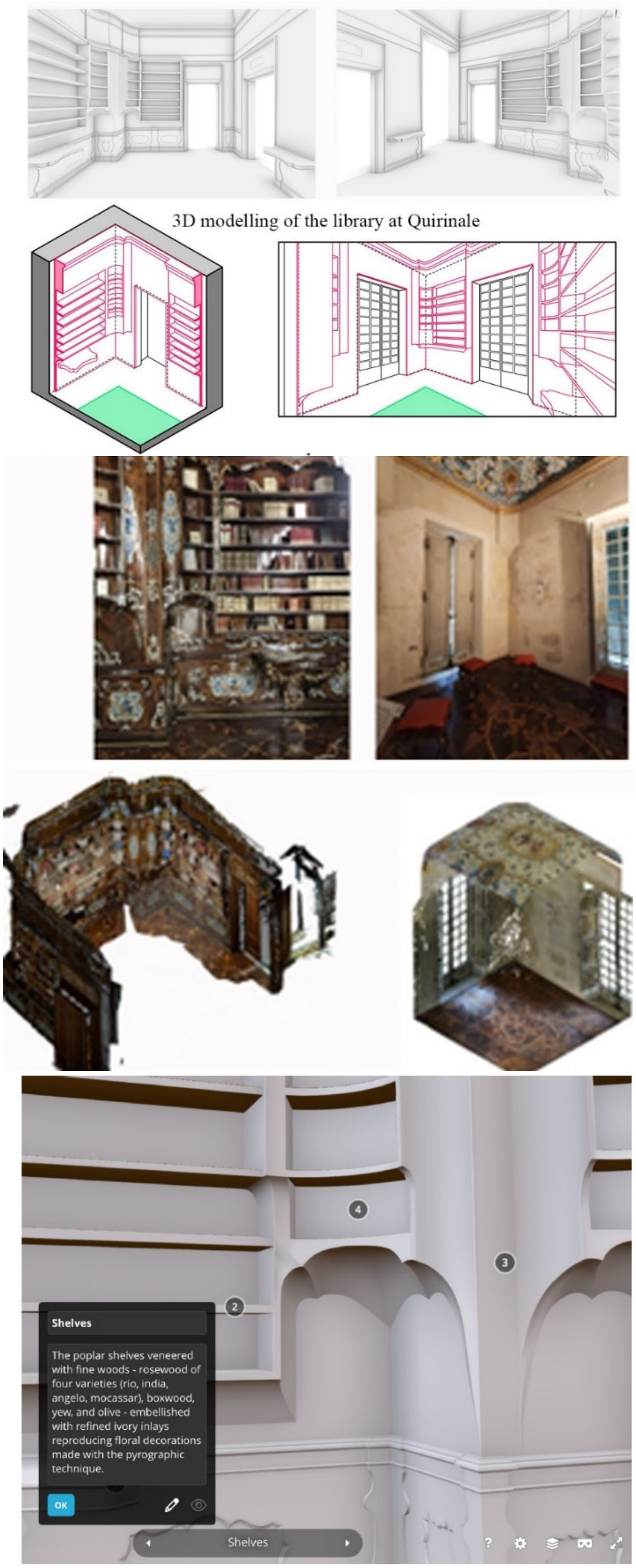
Modeling Process.

The process begins with establishing a clear understanding of the project's objectives, organizing assets to ensure scalability and ease of navigation, and defining whether the MR experience is for architectural visualization or industrial training and entertainment, reshaping the technical specifications and design approach in this way. Augmented Visualization imposes constraints on polygon counts and texture sizes due to limited computational resources (Zachos A. et al., 2024). VR headsets allow for more complex visual fidelity but demand high frame rates for immersive interaction (Zhou S et al. 2024).

Model preparation for the environmental reconstruction is necessary to ensure a stable visualization; with Rhino and Blender, it is possible to overcome some of the constraints that Augmented reality imposes, such as polygon counts and texture sizes. The model must be cleaned and refined before exportation, focusing on compatibility and efficiency optimization, keeping only the essential elements, to reduce file size and prevent interferences. Commands such as ReduceMesh in Rhino or Blender's Decimate Modifier allow designers to simplify models, maintaining the triangle count within the suitable range of 50,000–100,000 for complex scenes (Ververidis, D. et al. 2022). Smooth performance on MR devices also requires a manageable polygon count to ensure appropriate UV mapping, preventing texture distortion (Diestro M. et al., 2021).

For procedural materials used in Blender or Rhino, baking into texture formats—preferably .png or .tga—guarantees seamless compatibility with Unreal's rendering system, avoiding visual inconsistencies.

A good example of the modeling process optimization can be found in Spallone R. et al. (2023), where a multidisciplinary approach to the reconstruction and digital visualization of the Piffetti Library is presented. The research aims to improve the accessibility of cultural heritage through advanced 3D modeling and AR and VR technologies. By combining art history skills, digital sensing, and 3D modeling, an immersive experience for visitors is created.



Shelves

The poplar shelves veneered with fine woods - rosewood of four varieties (rio, india, angelo, mocassar), boxwood, yew, and olive - embellished with refined ivory inlays reproducing floral decorations made with the pyrographic technique.

Figure 35 Top right: Rhino 3D model optimized for Virtual visualization. Top left: Photogrammetry and Laser scanning Process. Bottom: The Sketchfab interface allowing to add and edit annotations. Source: Spallone, R., Russo, M., Teolato, C., Vitali, M., Palma, V. and Pupi, E. (2023) 'Reconstructive 3D Modelling and Interactive Visualization for Accessibility of Piffetti's Library in the Villa della Regina Museum (Turin)'

The methodology involves a digital survey using laser scanning and photogrammetry, which are then processed with Agisoft Metashape and Gexcel JRC Reconstructor software. The 3D modeling phase uses McNeel Rhinoceros for NURBS-based modeling and mesh-based techniques for more complex details, reconstructing the library in both its current and original configurations. For interactive visualization, the team developed AR applications using Unity and the Vuforia AR library, which exploit markerless image tracking and reference the library's inlaid floor as a reference point. In addition, the VR experience was created using Sketchfab, offering online access to a highly detailed 3D model with interactive annotations. This project highlights the potential of digital technologies in preserving and presenting cultural heritage, offering an innovative way to engage visitors and make historical artifacts accessible to a broader audience.

The export stage acts as a vital conduit between software, ensuring the integrity of assets during transmission. Filetypes like .fbx are usually preferred for their ability to maintain geometry, UV maps, textures, and motions. However, with the new Openusd format, we can finally achieve a fully interoperable ecosystem. In the Virtual environment engine (Unity, Unreal Engin, or Omnivers), the focus moves toward building the scene. The project must go through different phases, from Material and Texture application to environmental matching. Material alterations are regularly necessary, as Unreal Engine’s Material Editor offers state-of-the-art options for refining or reproducing materials to attain the intended visual effects.

The MR pipeline’s ability hinges on integrating multiple disciplines like design, computer science, and 3D modeling. Collaboration between architects, developers, and engineers is essential to address the diverse challenges of creating MR experiences. Scalability remains a significant consideration, as larger projects with complex scenes require meticulous optimization to balance visual quality and performance. The limitations of hardware platforms also dictate design choices until 2024, underscoring the importance of tailoring the pipeline to the specific capabilities of the target device. However, as MR technologies continue to evolve, the pipeline may constantly be enhanced by incorporating emerging tools and techniques, such as AI-driven optimization or next-generation rendering engines, which sustain the process by reducing hardware and software requirements.

Furthermore, integrating 3D models with blockchain and the Metavesr allows for tokenizing heritage elements, ensuring authenticity and traceability, and opening up new economic opportunities for cultural valorization.

Figure 36 The Propylaea entrance of the Temple of Jupiter.
Source: https://yorescape.com/

Projects such as ‘Rome Reborn’ (Frischer et al., 2010), which reconstructs ancient Rome in 3D, demonstrate the potential of 3D modeling in the cultural context.

These projects offer unique educational experiences and combine technology with historical storytelling to create engaging and meaningful experiences while TLS. Photogrammetry and BIM integration enabled high-precision detail

Figure 37 Rome’s digital reconstruction, Rome Reborn Project. Top: Real Aereal foto of Rome. Bottom; 3D Virtual model of Rome.
Source : www.yorescape.com

capture and enriched models with semantic information, useful for analysis and restoration.

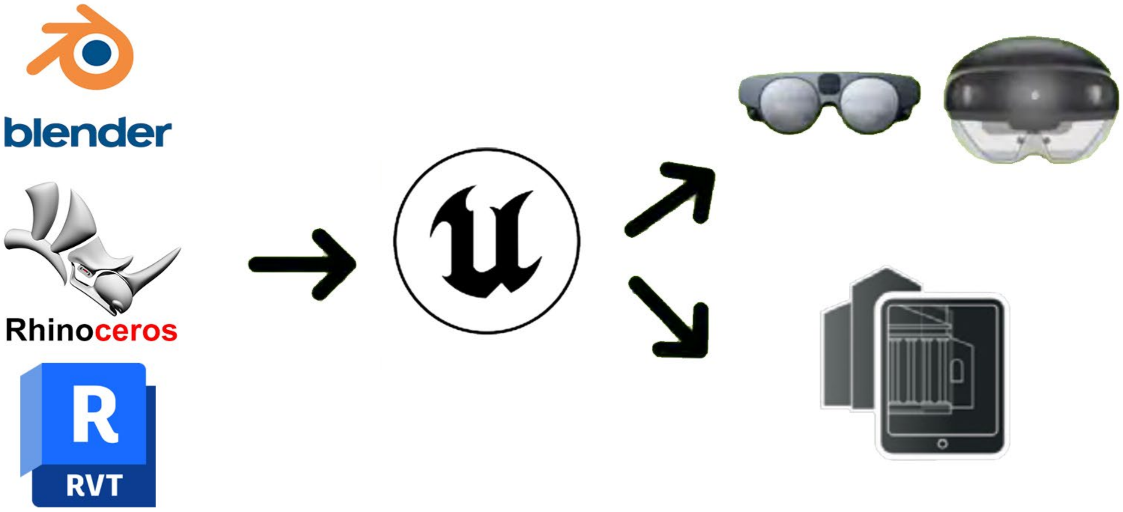


Figure 38 Abstracted framework for MAR project through unreal engine
Made by the author: Sbai Oussama

Digital Environment and HMD.

Creating digital environments and objects that blend seamlessly and naturally with the real world requires a well-considered approach, and this is where mixed reality-oriented modeling comes in. MR applications in architecture have been increasing in recent years, with architects and professionals from different fields relying on augmented and immersive experiences to deliver feelings and interactions in real-time. Therefore, the pipeline must address both visual realism and performance. First is geometry optimization, where models are built with just the right balance of detail, enough to feel real but lightweight enough to deliver a fluid experience on HMD. Material and texture management is equally important: using well-optimized high-quality textures to avoid processing failures.

Dynamic lighting, along with pre-baked ambient occlusion, on the other hand, has resolved the Lighting issues for MR experiences, adding depth perception by defining clear interaction zones and ensuring accurate collision detection. Users can interact with virtual objects naturally, which may enhance the sense of presence and immersion. It is also important to focus on scale accuracy since MR implies placing digital content on top of real-world spaces; the models must be built to the proper scale.

By appropriately harmonizing the workflow, the geometrical forms, textures, lighting, interactions, and scale, MR-focused modeling enables experiences that not only appear authentic but are also fluidly adaptive to the user and their surroundings, leading to engaging and profound MR applications and democratization.

Company	Primary Focus	Target Audience	Key Products
Apple	Mixed Reality (AR & VR).	Professionals, creators.	Apple Vision Pro.
Microsoft	Enterprise and AR.	Industrial, medical, enterprise.	HoloLens 2.
Meta	Social and gaming VR. AR experiences.	Consumer and Developers. Currently, only Developers.	Meta Quest Series. Orion.

Figure: 39 HMD commercial products comparison
Made by the author: Sbai Oussama

-Head Mounted Displays and AR Glasses.

Head-mounted displays (HMDs) are the link between their role in the evolution of augmented reality (AR) and virtual reality (VR), acting as interfaces that connect the digital and physical worlds to design immersive experiences for end users. These devices are changing how architects design, visualize, and engage with architectural projects. This distinction is fundamental and indicative of another type of division in visualization systems: immersive systems versus tangible modeling systems, both of which have a significant impact on future architectural practices. Immersive systems, popular in VR applications, take users into entirely virtual worlds, excluding their physical surroundings. In contrast, tangible modeling systems, used in augmented architecture, fuse physical interactions and digital mediations to establish an intuitive and spatially aware modeling process.

As augmented visualization involves sophisticated and complex data acquisition and processing, and requires adequate space around the glasses, companies have been forced to focus their research on VR visualization systems. With the immersive technologies trending in the past few years, HMD for VR and MAR systems for AR became developers' central focus toward finding a balanced blend of the virtual and real worlds, maintaining a high renderization quality that fits different lighting and location scenarios. Companies like Meta and Apple are working hard to reduce the technological complexity and, consequently, the price.

By blocking external distractions, VR devices rebuild the space through cameras and sensors that map the input data and use the space to overlay information, allowing accurate assessments of spatial relationships, material finishes, and lighting conditions. Apple Vision Pro, for example, merges ultra-high-resolution displays into spatial computing, in a fluid control mechanism that retraces the eyes and hand movements to control and navigate. However, Meta Quest is more appreciated in experimental projects due to its relatively low price and mobility. This makes it a practical device for on-the-spot design reviews and interactive walkthroughs.

a) the first solution is called a bird bath design (Bruder et al., 2017), which has a screen on top oriented down, with a straight mirror called a beam splitter that first shoots the image away from the eye into a curved mirror on the front, then reflects the properly focused image into the eye.

b) On the more advanced extreme, there are waveguide systems; a tiny projector sits typically in the stem of the glasses, from where it sends light into the sheet of glass and onto a set of tiny mirrors that reflect the light waves sideways so that they travel through the glass itself (Jang et al., 2024). it acts as a sort of fiber optic cable that guides the light waves; hence, it is called a waveguide, and this is generally the preferred method for thin and light AR glasses as it just needs a single slim surface for the whole thing to work.

c) mixed wave guide presented by a company called Ant Reality uses two displays, one on the bottom and one on the top, and then uses waveguides to combine them at the center, in a single wide 120° field of view.

d) the latest brake trough presented by Meta through the Orion holographic display technology with nanoscale 3D structure etched to the lenses so it can detract light and improve holograms' depth and sizes.

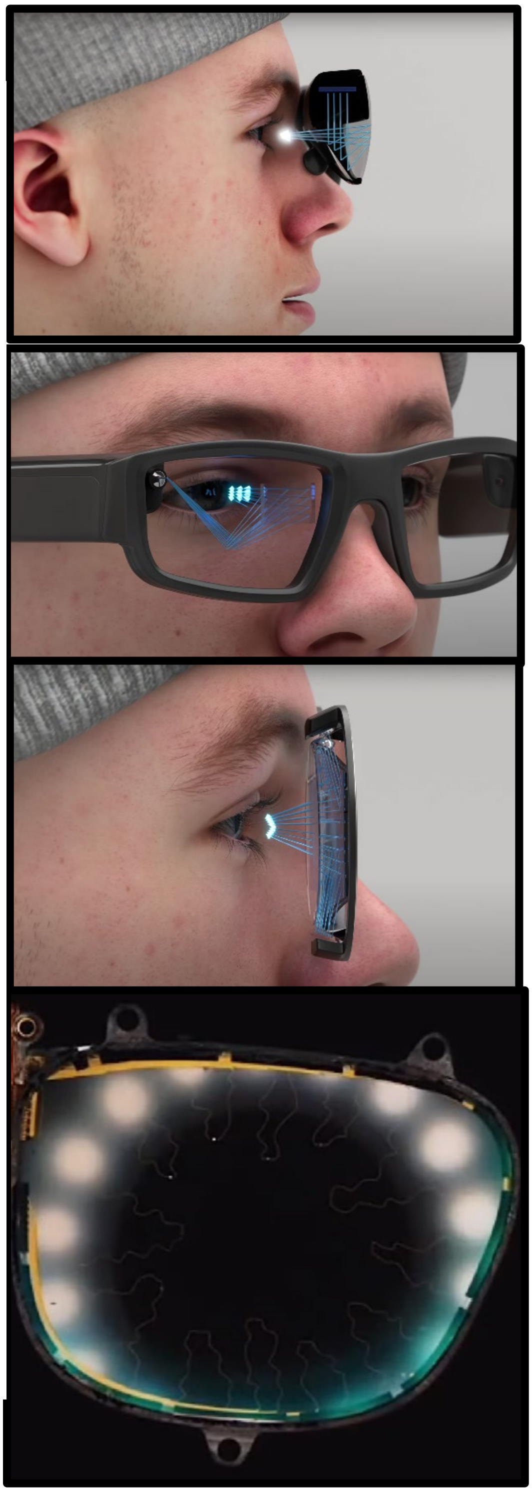


Figure 40 Birth bath, Wave Guided and Hogram technologies for AR Glasses
Source : Getty Images, AP Archive, youtube, Meta.

The ability to simulate environments with great detail is something that CH and Architecture, in general, can benefit from, as scholars engage in a controlled platform for analysis and restoration planning, and visitors experience monuments and spaces as they were in their glory. However, the immersive nature of VR also has its constraints, as users lose track of their immediate environment, which might entail specific space requirements.

AR glasses instead present a different way of exploring the sites: augmenting instead of substituting reality by overlaying digital reconstructions, annotations, and interactive elements without interrupting the visualization of the actual environments. AR glasses employ transparent or semi-transparent displays such that users are engaged with situational awareness, backed up by sensors that comprehend the spatial environment dynamically in real time and are integrated with remote controls, which allow command control and navigation dynamically.

One of the significant advantages of AR technology in the field of heritage conservation is its ability to enhance on-site experiences, thus using AR to superimpose proposed restoration models onto damaged structures, enabling real-time assessment and iterative design adjustments, which could bridge the gap between the real physical and the virtually designed digital (Bekele et al., 2018). Implemented then with artificial intelligence, as already explained at the beginning of the thesis, it could offer an anticipated experience of a future where interactive narratives and augmented experience of space will become a lived reality, enriching the catalog of tools available to the final user. The challenges currently faced in the use of AR Glasses in cultural heritage are still significant in terms of both software and hardware, with lighting and weather conditions and environmental factors that may interfere with AR performance and the displaying technology that is still under development AR devices require a very accurate spatial mapping, and object tracking and anchoring hard to achieve with the small object size. AR glasses, in this respect, are disadvantaged compared to HMD, which offer more stable visualization in controlled environment conditions, which can enhance the effectiveness of overlayed information.

Both technologies share limitations, including costs and technical barriers. However, they complement each other. VR can be used to develop highly detailed reconstructions that can be adapted for on-site AR use, creating a hybrid workflow that maximizes immersion and practicality.

Figure 41 Orion, Meta's AR GLASS with a controller and wrist band sensor.
Source: https://about.fb.com/news/2024/09/introducing-orion-our-first-true-augmented-reality-glasses/. February 2024

In 2024, Meta introduced Orion AR glasses as a prototype, highlighting a significant advancement in incorporating augmented reality (AR) technology into smaller, more portable devices. Designed to seamlessly blend digital information with the physical world, these glasses mark a bold attempt to redefine how users interact through technology, highlighting a significant advancement in the incorporation of augmented reality (AR) technology within smaller and more portable devices in a brave attempt to redefine how users interact within space. These glasses are designed to seamlessly blend digital information with the physical world, bringing together impressive breakthroughs in science and technology, including the new holographic display systems, hand and eye tracking, cameras, speakers, and microphones. The challenge of balancing advanced technology with a compact, aesthetically appealing design and acceptable battery life further underscores Meta's ambitious vision.

One of Orion's standout features is its optical design. Unlike standard AR headsets, Orion's technology uses exterior cameras to gather real-time video flows to lay digital parts. In contrast, the innovative holographic visualization technology allows potentially more lightweight and natural integration of digital content and objects overlaying to the real environment, with a 70° field of view, which puts it on the top ranking of AR Glasses (Alex Heath, The Verge, September 2025). These features make it suitable for the dynamic visualization of 3D models in real-world conditions, among other uses. Architects would be able not only to navigate through virtual buildings overlaid on real-life locations but also to customize the virtual model and make it always visible as a virtual continuum, creating a new layer of project communication. AI would further be able to enhance the experience by smoothening the work processes, recommending design optimizations or material selections based on environmental data, and customizing the content to fit a user's interests and needs.

Meta's vision places the glasses as a consumer-ready device even if it is still in the prototype phase, knowing that if it works as envisioned, it could transform technology usage and trigger a transformative "iPhone moment" for computing, offering a more natural and intuitive platform than smartphones for Augmented reality.

Mobile Augmented Reality (MAR).

Mobile Augmented Reality (MAR) is a technology that integrates virtual objects into the physical world through mobile devices, enabling seamless interaction between users and digital environments and enhancing the user experience through intuitive interfaces and adaptive content. Over the past two decades, MAR systems have progressed from experimental prototypes to versatile tools introduced in smartphones and tablets, allowing access to digital content and facilitating interaction with augmented environments, whether for navigation, information access, or collaborative activities (Jacky Cao et al., 2023).

The literature review available on MAR technologies profoundly examines their frameworks, visualization techniques, and potential applications. A study offered by the Academy of Finland identifies 37 MAR frameworks and categorizes them according to their platforms, tracking, and features, among other criteria. Again, machine learning and artificial intelligence play a crucial role in improving the functionality of MARs through real-time data recognition and processing and user-adaptable interfaces.

The Table in fig (43) summarises the evaluation of the different frameworks. A key observation is the wide variation in the technical capabilities of these frameworks, reflecting the diversity of applications and user requirements: some frameworks prioritize real-time interaction and adaptability through advanced tracking mechanisms, while others focus on collaborative functionality and cross-platform compatibility.

The research not only provides a comprehensive overview of the current state of MAR, it also lays the foundation for advancing technology through focused innovation and interdisciplinary collaboration. These insights are crucial for researchers and developers who want to exploit MAR systems to create virtual experiences.

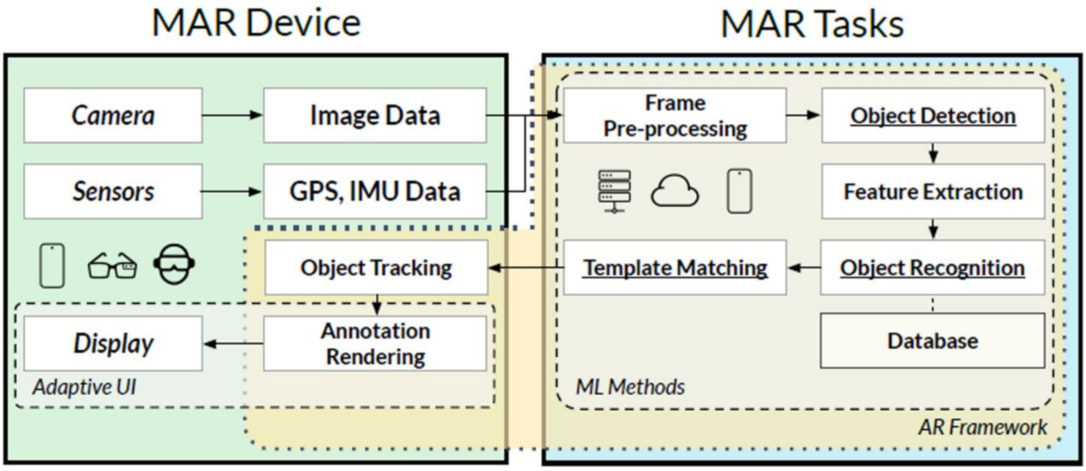
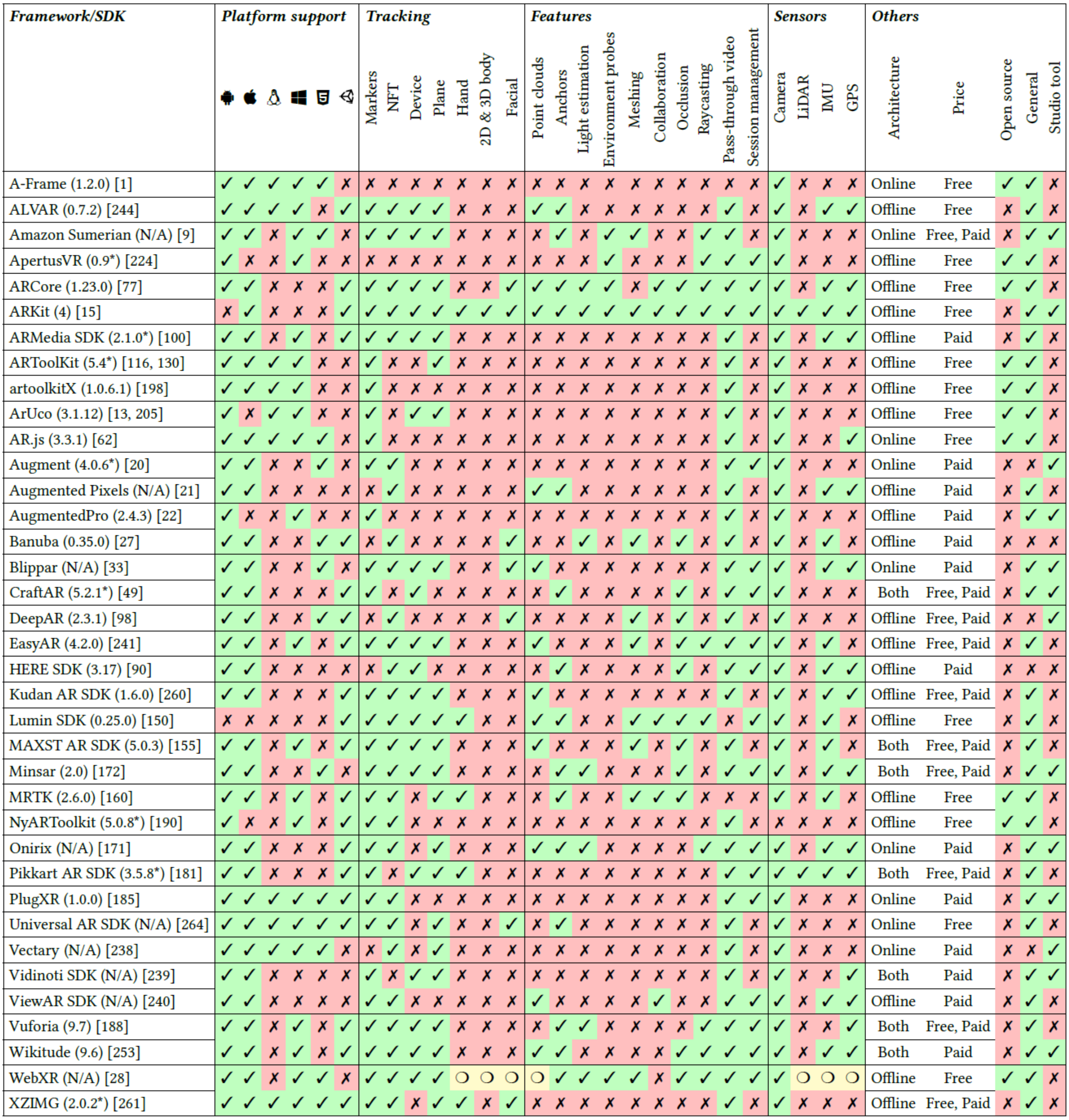


Figure 42 A typical MAR system pipeline, splitting into MAR device and MAR tasks. ML methods can be utilized in the majority of required MAR tasks
Source: Jacky Cao et al., 2023



Framework/SDK	***Platform support***						***Tracking***							***Features***										***Sensors***				***Others***				
							Markers	NFT	Device	Plane	Hand	2D & 3D body	Facial	Point clouds	Anchors	Light estimation	Environment probes	Meshing	Collaboration	Occlusion	Raycasting	Pass-through video	Session management	Camera	LiDAR	IMU	GPS	Architecture	Price	Open source	General	Studio tool
A-Frame (1.2.0) [1]	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	Online	Free	✓	✓	✗
ALVAR (0.7.2) [244]	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	Offline	Free	✗	✓	✗
Amazon Sumerian (N/A) [9]	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✗	✓	✗	✗	✗	Online	Free, Paid	✗	✓	✓
ApertusVR (0.9*) [224]	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	Offline	Free	✓	✓	✗
ARCore (1.23.0) [77]	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	Offline	Free	✓	✓	✗
ARKit (4) [15]	✗	✓	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Offline	Free	✗	✓	✓
ARMedia SDK (2.1.0*) [100]	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	Offline	Paid	✗	✓	✗
ARToolKit (5.4*) [116, 130]	✓	✓	✓	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Offline	Free	✓	✓	✗
artoolkitX (1.0.6.1) [198]	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Offline	Free	✓	✓	✗
ArUco (3.1.12) [13, 205]	✓	✗	✓	✓	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Offline	Free	✓	✓	✗
AR.js (3.3.1) [62]	✓	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	Online	Free	✓	✓	✗
Augment (4.0.6*) [20]	✓	✓	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	Online	Paid	✗	✗	✓
Augmented Pixels (N/A) [21]	✓	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	Offline	Paid	✗	✓	✗
AugmentedPro (2.4.3) [22]	✓	✗	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Offline	Paid	✗	✓	✓
Banuba (0.35.0) [27]	✓	✓	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	Offline	Paid	✗	✗	✗
Blippar (N/A) [33]	✓	✓	✗	✗	✓	✗	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓	Online	Paid	✗	✓	✓
CraftAR (5.2.1*) [49]	✓	✓	✗	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✓	✓	✗	✗	✗	Both	Free, Paid	✗	✓	✓
DeepAR (2.3.1) [98]	✓	✓	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✗	✗	✗	Offline	Free, Paid	✗	✗	✓
EasyAR (4.2.0) [241]	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✗	✓	✗	Offline	Free, Paid	✗	✓	✗
HERE SDK (3.17) [90]	✓	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	Offline	Paid	✗	✗	✗
Kudan AR SDK (1.6.0) [260]	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✓	✓	Offline	Free, Paid	✗	✓	✗
Lumin SDK (0.25.0) [150]	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	Offline	Free	✗	✓	✗
MAXST AR SDK (5.0.3) [155]	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗	✗	✓	✗	✓	✗	✓	✗	✓	✗	✓	✗	Both	Free, Paid	✗	✓	✗
Minsar (2.0) [172]	✓	✓	✗	✗	✓	✗	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓	✓	✓	✗	✓	✓	Both	Free, Paid	✗	✓	✓
MRTK (2.6.0) [160]	✓	✓	✗	✓	✗	✓	✓	✓	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✓	✗	✓	✗	Offline	Free	✓	✓	✗
NyARToolkit (5.0.8*) [190]	✓	✗	✗	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	Offline	Free	✓	✓	✗
Onirix (N/A) [171]	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✗	✓	✓	Online	Paid	✗	✓	✓
Pikkart AR SDK (3.5.8*) [181]	✓	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	Both	Free, Paid	✗	✓	✗
PlugXR (1.0.0) [185]	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	Online	Paid	✗	✓	✓
Universal AR SDK (N/A) [264]	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Online	Free	✗	✓	✗
Vectary (N/A) [238]	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Online	Paid	✗	✗	✓
Vidinoti SDK (N/A) [239]	✓	✓	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	Both	Paid	✗	✓	✓
ViewAR SDK (N/A) [240]	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✓	✓	Offline	Paid	✗	✓	✗
Vuforia (9.7) [188]	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✓	Both	Free, Paid	✗	✓	✗
Wikitude (9.6) [253]	✓	✓	✗	✓	✗	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	Both	Paid	✗	✓	✓
WebXR (N/A) [28]	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	❍	❍	❍	❍	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	❍	❍	❍	Offline	Free	✓	✓	✗
XZIMG (2.0.2*) [261]	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	✗	✗	✗	Offline	Free, Paid	✗	✓	✗

Frameworks and SDKs marked with an asterisk (*) have not been updated in 1+ years.
Features or functions optionally supported in different platform are marked with ❍.

Figure 43 Comparisons of several available features in MAR frameworks and SDKs.
Source: Jacky Cao et al., 2023 Mobile Augmented Reality: User Interfaces, Frameworks, and Intelligence

Markers and Anchoring.

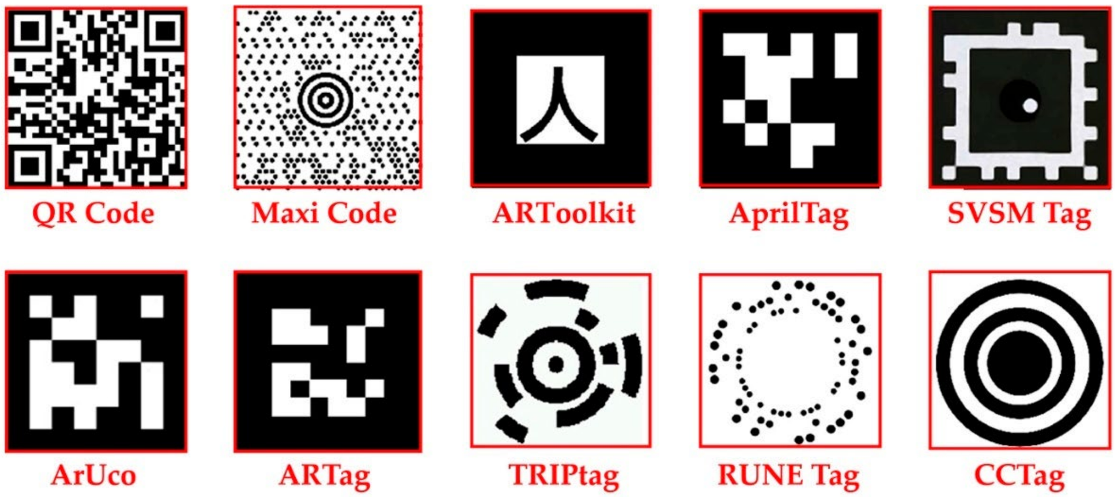


Figure 44: Marker Types. AR IN ARCHITECTURE DOMAIN: State of the Art, Michele Russo 2021

Marker-based augmented reality (AR) operates on a mechanism where physical markers or images serve as anchors for virtual content within the real world. They depend on the exact detection of the markers, making it possible to accurately place and orient digital overlays like a 3D model, an animation, or text. The process starts with the device's camera, which captures and recognizes the marker with the help of pattern recognition algorithms supported by the web database already uploaded to the server. The system uses the marker's position and orientation as a reference to render and display virtual content that seamlessly relates to the physical environment, creating a virtually augmented presentation.

AR system markers can be classified as marker-based and markerless technologies: Marker-based systems that rely on predefined visual anchor points (QR codes, ArUco markers, or other fiducials) reflect a traditional approach that involves embedding identifiable markers into the built environment (Russo, 2021), for instance, physical markers are often integrated into scale models of architectural designs allowing users to visualize 3D renderings of proposed structures in real-time. On the other hand, markerless solutions have become more prevalent in outdoor and dynamic settings, by relying on advanced algorithms such as (SLAM), GPS and using existing architectural features (walls, edges, terrain) as the foundation for the virtual overlay (Diestro M. et al., 2021), Environmental anchoring enables more accurate localization of AR content, replacing physical markers with natural terrain features, this technique updates in real-time based on the surrounding environment, extending it use beyond basic markers utility and address the challenge of ensuring good stability and high accuracy of virtual content (Comport et al., 2006). Another essential approach is geospatial anchoring, as seen in the Tadarch project, where geographic information systems (GIS) and GPS data are combined to ensure spatial accuracy in real-time. Geospatial anchoring has enabled industrial-scale and urban-scale projects where AR elements interact with larger geographic and architectural environments.

Building marker-based AR experiences requires the use of different software or web services essentially, whether it is Unity paired with an AR SDK such as Vuforia or, similar solutions provide a set of tools that can create, track, and render markers within the augmented space, making it accessible to developers. Marker templates can be designed manually using web-based marker creation tools to activate the AR content. The patterns should be different and easily identified to get better detection accuracy.

Markerless AR tracking instead uses cameras, LiDAR, and depth sensors to scan the environment and create a three-dimensional spatial map that allows virtual components to be accurately registered in the physical environment (Kumar et al 2024), ensuring a stable and virtual experience. Furthermore, the integration of markerless AR and BIM offers significant practical applications in the AEC sector, supporting on-site validation and allowing users to compare digital BIM models with the physical construction environment (Palma et al., 2022), ensuring fidelity between design and execution. This interactive visualization enhances usability, allowing users to explore 3D models, highlight specific elements, and report discrepancies directly within the AR environment, improving project management, collaboration, and communication across different teams.

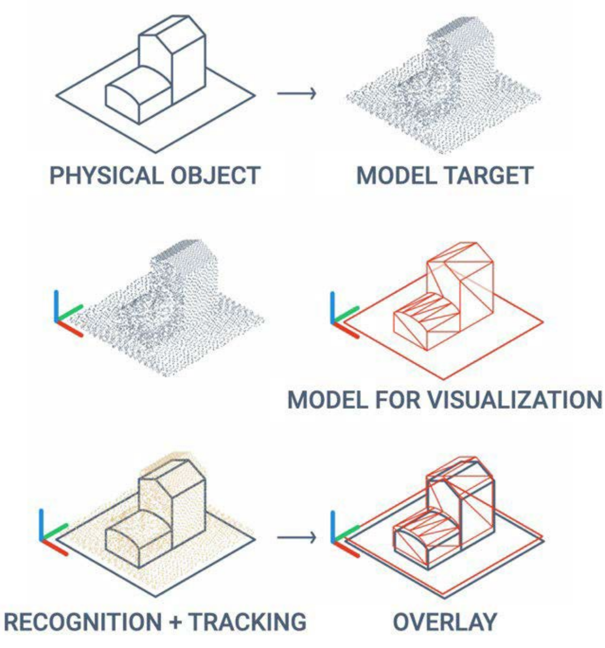


Figure 45 Scheme of the markerless AR tracking behavior. *Source:* Palma et al 2022.

III.2.3 Modeling for 3D printing.

In contrast, 3D printing models emphasize manufacturability and structural integrity over visual representation. What distinguishes 3D printing is that, unlike AR/VR, it does not allow the user to interact with the models but rather converts them into physical goods. The process requires impermeable, non-collapsible geometries that allow the 3D printer to interpret the design and build it layer by layer. Technological constraints such as material compatibility, printer resolution, and technical properties must be considered. Support structures are usually required for protrusions and other complex geometries, while the slicing phase transforms the models into layered instructions for the printer. Rhinoceros is particularly preferred in this respect, due to its precision and ability to develop extremely accurate and dimensionally stable models. Third-party applications may further help translate these designs into formats compatible with specific printing hardware, as well as transform complex CAD data into formats such as G-code[9]. Robust modeling practices emerge in practical cases, such as historical details of different architectural styles that make up our cultural heritage. Indeed, the tolerances of an architectural heritage scale model must be perfect to guarantee stability during assembly and printing (A. Scianna et al., 2020).

Unlike virtual visualization, 3D printing supports a large number of polygons due to the physical fidelity, which depends on the printer's capacity and not on computational performance. For these reasons, designers must adapt their methodology to the specific use case, effectively linking digital products to physical processes.

Modeling Process and Technologies.

When creating models for 3D printing, it is essential to carefully balance several key factors (geometric complexity, wall thickness, support requirements, and material properties) to achieve functionality and printability. Designs with intricate details or significant overhangs often demand additional support, particularly in FDM printing, where unsupported features can weaken structural integrity or compromise the final result. Reducing overhangs and incorporating self-supporting angles can help

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[9] G-code is a language used to control CNC (Computer Numerical Control.) machines, including 3D printers. It contains instructions for movement, speed, and toolpath, guiding the printer layer-by-layer to create the physical model from digital designs.

mitigate these challenges (Rayna & Striukova, 2016). Equally important is ensuring adequate wall thickness; too-thin walls can result in fragile prints, especially when working with brittle materials in SLA and DLP printing. A minimum thickness of 1–2 mm is generally recommended, though this varies depending on material type and intended application (Bikas, Stavropoulos, & Chryssolouris, 2016). Support structures are also critical for maintaining complex geometries during printing, though they introduce the need for post-processing. While FDM supports can be more challenging to remove and may affect surface quality, SLA and DLP supports are more straightforward to detach and typically result in a cleaner finish. Lastly, understanding the mechanical properties of different materials helps ensure that printed parts meet functional requirements; for example, FDM materials like PLA and ABS provide strength and durability, whereas SLA and DLP resins excel in producing fine details but may lack robustness.

The recent advancement in instant 3D printing technology eliminated the necessity for mechanical hand work to create the physical model, enabling the replication of intricate architectural models at reduced expenses and time and paving the way for new interaction and approaching methods in communicating to promote the built space. Desktop 3D printers, characterized by their comparatively low acquisition costs and increasingly user-friendly interfaces, have expanded the reach of museums, schools, and cultural centers, allowing intricate models of historic structures, archaeological sites, and architecturally noteworthy works to be produced tangibly. This availability has unlocked novel possibilities for promoting cultural heritage by offering educational and communicative tools that enhance comprehension and appreciation of cultural assets among a more diverse audience. Complex models can now capture fine architectural details, while the basic designs or a virtual experience may provide the overview. Even in delicate fields such as restoration, architectural presentation, or AR experience, tasks that require time and multiple costs are now easy to do in a few minutes, offering the possibility to evaluate different solutions before working on the original artifact and Detailed copies to test the visual and structural impact of hypothetical modifications, reducing the risk of project conceptualization. Museums, as one of the major actors in adopting AR and 3D printing for presentation and communication, are studying through different research and projects the use of 3D-printed replicas without affecting authentic artifacts.

The 3D printing of architectural models holds valuable opportunities in project presentation and communication; as seen in the Campus Valentino Project the physical model is 90% made with 3D printed objects offering an effective visualization from different perspectives and on different dimensions, in fact the implementation of the physical model with the virtual experience is a further option to guaranty an excellent level of communication for the most complex project. A more hybrid approach has been evolving since 2018 with the ROMA project (Peng et al., 2018) that tests a robotic 3D Wirframe Printing arm dedicated to real-time Augmented modeling through HMD. Divided into three zones, the station of the Robotic Arm offers a rotatable platform that helps the contemporary process of modeling and printing (zone 2), while modeling if the user touches the platform (zone 3), the printing process gets interrupted, and the robotic arm turns back allowing complete control of the model for further modification, the first zone instead is when the user moves away from the station. Hence, the Robotic arm takes complete control of the model.

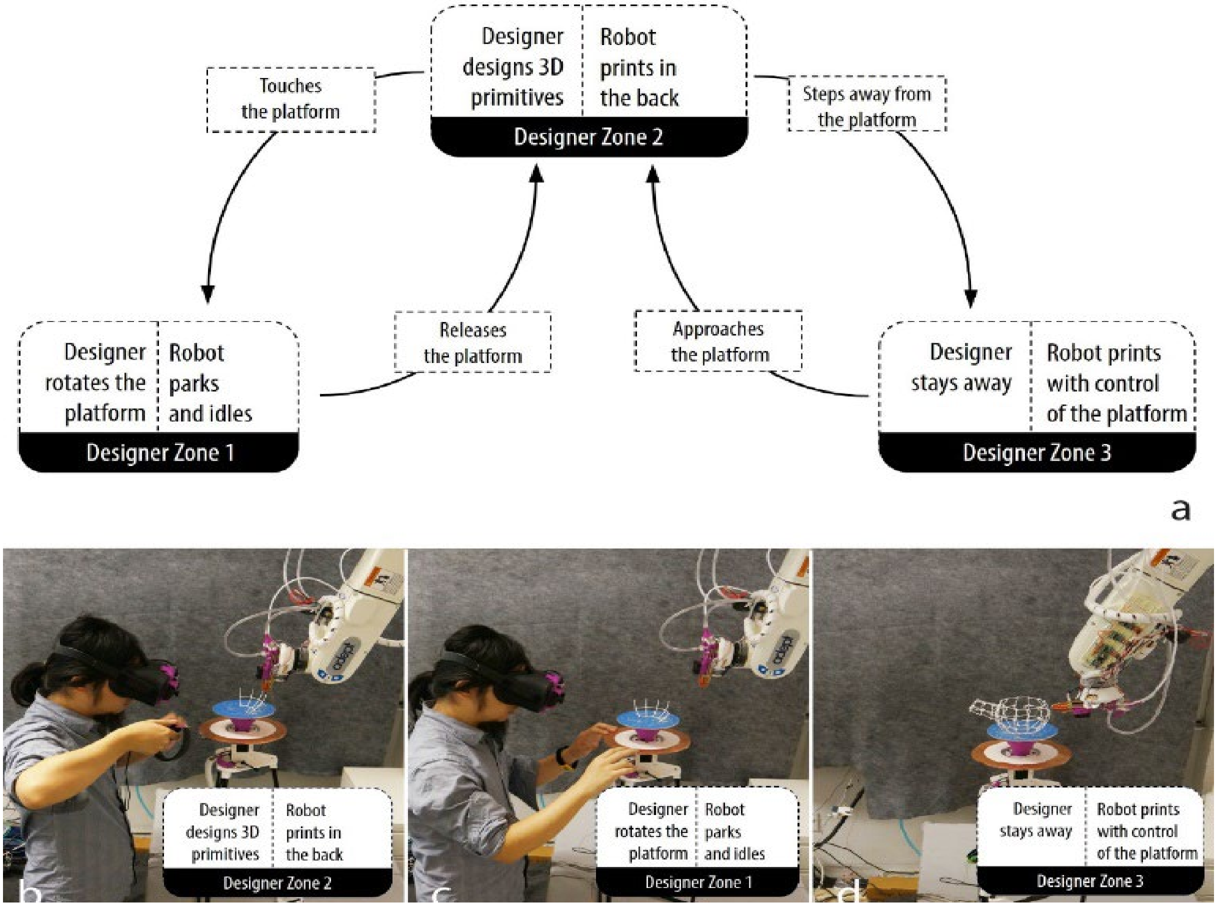


Figure 46 Robotic Modeling Assistant ROMA.
Source: Peng et al. 2018

Providing revolutionary methods for building accurate and detailed models, the three main 3D printing technologies currently used are fused deposition

(FDM), stereolithography (SLA) and digital light processing (DLP), they have dominated the academic field in different areas, especially in architecture, where digital and physical structures merge into one model. They actively participate in the digitisation (phy-gitalization) process by incorporating and anchoring data. FDM represents the most widely used 3D printing technology for rapid prototyping and conceptual artifacts, with the layer-by-layer extrusion process of thermoplastic, it represents a cost-effective solution that meets various needs in architecture and CH. offering advantages such as the complex geometry printing, low cost and ease of use with a variety of materials including PLA, ABS and PETG, the flexibility of both mechanical properties and surface finishes get enhanced (Gibson, Rosen, & Stucker, 2015). However, this technology still has some challenges to overcome, including lower resolution and surface finish compared to other technologies, complex geometries often require support structures that can be time-consuming to remove and can affect surface quality, while the visibility of layer lines, the mechanical strength of the final product, and the sensitivity of the process can vary depending on the type and performance of the printer. SLA and DLP, on the other hand, offer greater precision and detail, making them suitable for applications that require specialised results and refinement.

	Technology Used	**Accessibility of Materials**	**Level of Use Complexity**	**Final Quality**	**Costs**
FDM	Fused Deposition Modeling, Works by melting and extruding thermoplastic filament through a heated nozzle, layer by layer.	Wide range of affordable and available filaments (PLA, ABS, PETG, etc.).	Easy to use. Occasional calibration and troubleshooting are required.	Decent quality; visible layer lines. Suitable for functional parts but requires post-processing for a smooth finish.	(~€300-€500). Filament costs ~€20-€30/kg. Low maintenance costs.
SLA	Stereolithography Uses a laser to cure liquid photopolymer resin layer by layer, producing high-resolution models.	Limited material options require liquid resin; handling requires safety precautions.	High complexity; involves post-processing (cleaning and UV curing).	High-quality prints with fine details and smooth surfaces. Ideal for detailed models, but prints are fragile.	~(€700 to €900). Resin costs ~€50-€100/liter. Post-processing equipment adds costs.
DLP	Digital Light Processing Similar to SLA, but uses a digital projector to cure entire layers of resin at once, resulting in faster printing.	Requires photopolymer resin, but slightly faster curing resin may be needed.	involves post-processing. Faster printing but requires careful handling.	excellent detail and smooth surface. Faster for larger models with high precision.	~(€700 to €800). Resin costs ~€50-€100/L. Post-processing equipment adds costs.

Figure 47 Comparative table of the main 3D printing Technologies.
Made by the author: Sbai Oussama

4D parametric printing.

4D parametric printing is an active area of development that takes the concept of additive manufacturing one step further than traditional 3D printing by incorporating the fourth dimension of time. 4D printing is the process of producing an object with the potential ability to change its shape using heat, moisture, light, or mechanical forces (Tibbits, 2014)– unlike traditional 3D printing that creates a static object. In this context, parametric denotes a design-generating algorithm (based on flexible parameters) that determines the states of the model. Tools like Grasshopper for Rhino and Dynamo for Revit used for parametric design enable designers to create flexible models that can shift based on rules that can be set beforehand aiming for a parametric and kinetic future in both vision and process, this technology offers a new approach that start with modeling process of the digital object with logic built into it through Grasshopper or dynamo to define its conditions and control its characteristics. Next comes the careful selection of smart materials that allow the object to transform. Some of the most common smart materials are shape-memory polymers for their responsiveness to heat and hydrogels, which react to the presence of water either by expanding or contracting (Momeni et al., 2017). The printing phase employs advanced technologies like multi-material extrusion or stereolithography (SLA) printing technology, allowing for various materials with unique properties to be accurately layer stacked in accordance with the parametric arrangement. After the object is printed, it goes through an activation phase, where the intended transformation happens once the object is exposed to certain external stimuli.

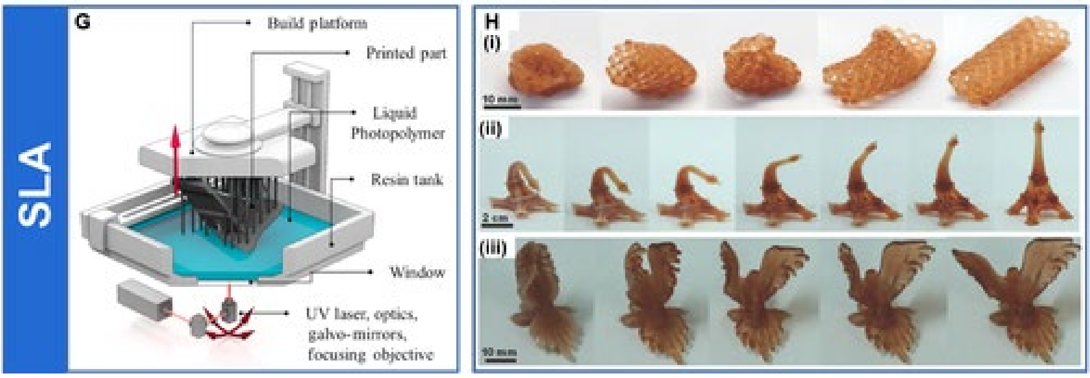


Figure 48 (G) Schematic of the printing process of SLA. Reproduced with permission from [79]. Copyright 2020 Elsevier. (H) Complex structures printed using SLA: (i) a model cardiovascular stent, (ii) an Eiffel Tower model, and (iii) a bird.
Source: Yan S, et al., 2023.

The study describes the process of designing and implementing an adaptive 4D-printed parametric façade, which functions as a self-morphing climate-adaptive skin on a building. The primary focus of the research is on the prototyping of a kinetic architectural skin that does not require any mechanical system, such as an electromagnetic actuator, for its adaptation to environmental variations. Instead, the facade is controlled by a programmable two-way shape memory composite (TWSMC) consisting of shape memory alloys (SMA) and shape memory polymers (SMP) that facilitate reversible, thermo-responsive phase transformations.

The research is constructed with a methodology that contains parametric design, material synthesis, simulation, and physical prototyping exploring different types of parametric modules. The design uses an interwoven tessellation pattern inspired by Erwin Hauer's work and involves three types of parametric modules (fig 48) with varying deformation properties. Multi-material 3D Printed modules are fabricated by a special 3D printing machine in a process that integrates both rigid and flexible SMP matrices with embedded SMA fibers to obtain the targeted shape-memory effects. Theoretical modeling of the materials' behavior, including thermal and mechanical properties, was conducted in the research to predict their performance under different environmental stimuli.

The results of the study demonstrate that the façade modules can achieve effective two-way shape memory effects, with deformations occurring in response to changes in temperature. However, the authors identified several challenges, including inconsistency in deformation with slow response times due to the thermal properties of the materials and the need for high activation temperatures, which limit applicability in standard building environments. Additionally, scaling up the prototype for real-world applications presents issues related to manufacturing complexity, cost, and energy efficiency. Despite these limitations, the paper highlights the potential of using 4D-printed smart materials in architecture to create lightweight, sustainable, and adaptive building skins and conceptual designs. The study contributes to the growing field of kinetic architecture by demonstrating a novel approach to responsive design using advanced digital fabrication techniques.

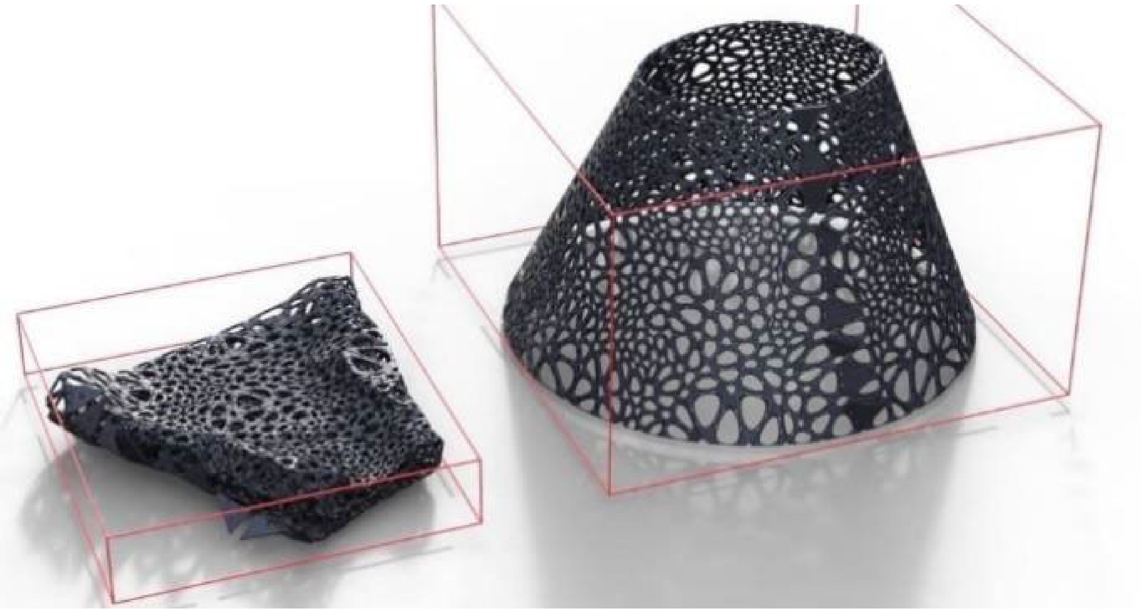


*Figure 49 87% of volume reduction as a result of the application of external stimuli (3D Learning Hub, 2023)***).**

Source :4D Printing: Technology Overview and Smart Materials Utilized. Journal of Mechatronics and Robotics, Kantaros et al 2023

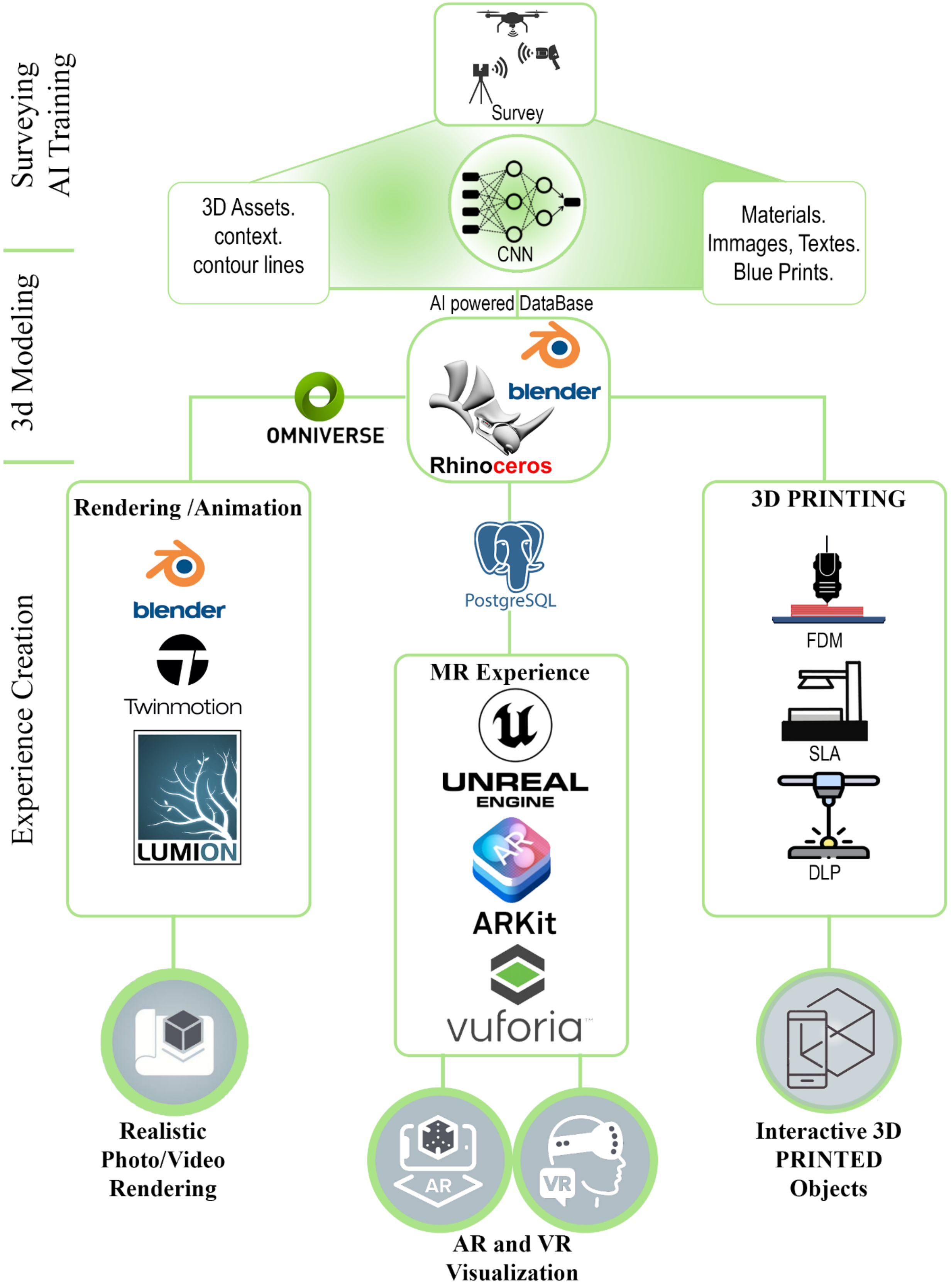


Figure 50 summary diagram of the different SDKs and Data integration for Design communication through Renderization, MX experience and 3D printing.
Made by the author

Chapter IV. Information Optimisation.

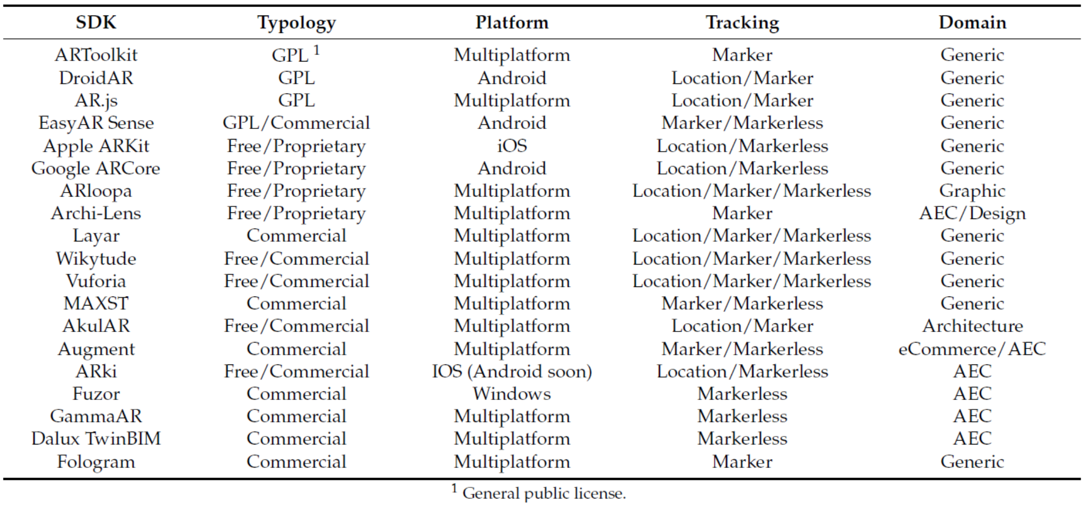
IV.1 Experience Optimisation.

Augmented and virtual Experience creation in architectural visualization represents a confluence of technology, design, and storytelling by integrating advanced modeling and interaction, and with the increasing availability of AI, these systems may offer unparalleled opportunities for CH. As these technologies continue to evolve rapidly, they promise to redefine how we engage with architectural spaces, bridging the gap between imagination and reality.

Figure 51 M. Russo's Pipeline for the creation of An augmented Reality Experience. AR in Architecture Domain. State of the Art.

Michele Russo's pipeline on augmented reality (AR) in architecture (Russo 2021) offers a comprehensive framework that incorporates conceptualization, content production, system design, and application assessment into a collaborative pipeline specifically designed for architecture practitioners. Starting at the conceptual phase, the project objectives, scope, and audience must be clear and aligned with the project's broader goals. preservation of cultural heritage, and accessibility. The pipeline starts by outlining the project's domain, aims, location, and values application. which define tracking methodology, digital content creation, and project limitations. In the virtual content phase, the generation and transformation of different assets (2D/3D models, textures, annotations) and the integration of the database (PostgreSQL) must be accurately done, taking in consideration the requirements of the MR experience creation. These assets may be reality-based models, constructed from digital documentation tools to test design options. The third phase, The Complex AR Systems, and Platforms include both hardware (smartphones, head-mounted displays, AR glasses) and software platforms

(ARKit, ARCore) where complex functions like tracking, environmental mapping and active human interaction support are provided, ensuring accurate tracking (marker-based or markerless) and geospatial anchoring, reliying on advanced technologies like SLAM (Simultaneous Localization and Mapping) and GIS data. With a heavy focus on user interaction and experience design, Russo has documented durable and thoughtful interfaces and features like floating annotations, interactive 3D models, and multisensory storytelling elements to capture the user and foster understanding. A valuable list of SDKs was presented in the paper, which offers a wide view of the platforms available on the market until 2012



SDK	Typology	Platform	Tracking	Domain
ARToolkit	GPL [1]	Multiplatform	Marker	Generic
DroidAR	GPL	Android	Location/Marker	Generic
AR.js	GPL	Multiplatform	Location/Marker	Generic
EasyAR Sense	GPL/Commercial	Android	Marker/Markerless	Generic
Apple ARKit	Free/Proprietary	iOS	Location/Markerless	Generic
Google ARCore	Free/Proprietary	Android	Location/Markerless	Generic
ARloopa	Free/Proprietary	Multiplatform	Location/Marker/Markerless	Graphic
Archi-Lens	Free/Proprietary	Multiplatform	Marker	AEC/Design
Layar	Commercial	Multiplatform	Location/Marker/Markerless	Generic
Wikytude	Free/Commercial	Multiplatform	Location/Marker/Markerless	Generic
Vuforia	Free/Commercial	Multiplatform	Location/Marker/Markerless	Generic
MAXST	Commercial	Multiplatform	Marker/Markerless	Generic
AkulAR	Free/Commercial	Multiplatform	Location/Marker	Architecture
Augment	Commercial	Multiplatform	Marker/Markerless	eCommerce/AEC
ARki	Free/Commercial	IOS (Android soon)	Location/Markerless	AEC
Fuzor	Commercial	Windows	Markerless	AEC
GammaAR	Commercial	Multiplatform	Markerless	AEC
Dalux TwinBIM	Commercial	Multiplatform	Markerless	AEC
Fologram	Commercial	Multiplatform	Marker	Generic

[1] General public license.

Figure 52 List of SDKs and relative characteristics.
Source: Michele Russo 2021. AR in the Architecture Domain: State of the Art.

. The process was concluded with an evaluation phase that analyses user feedback, along with performance metrics to validate best practices for the development of high-quality AR applications that successfully achieve educational, cultural, and functional goals.

in the next part of the research, we will analyze some of the most relevant aspects that affect the success of the augmented or Virtual Experience.

IV.2 The Virtual Environments.

Virtual environments are the backbone of any immersive experience, enabling the creation of spaces that simulate real-world scenarios and design concepts with extraordinary detail and precision. Texturing is one of the basic methods of creating accurate environments, applying surfaces that simulate materials such as wood, stone or metal with high fidelity. Several studies document the benefits of virtual museum experiences in the valorization and reconstruction of historical artifacts due to textures that accurately represent the deterioration of age to add authenticity to the experience (Zhe G. et al., 2022). Conversely, lighting is equally important, allowing designers to play with natural sunlight, moonlight, or artificial sources to evoke emotion or highlight features. As in the physical world, shadows, light, and dynamic lighting adjustments create depth and realism, immersing users in the space (Mustafa Doga et al., 2022). In addition to the immediate visual components, terrain, vegetation, and atmospheric conditions - rain, fog, or snow - add contextual realism. Such components are particularly useful in architectural simulation, where the relationship between structures and their environment needs to be understood.

Lighting acts as a game changer in dictating the ambiance and dimensionality of a scene. by simulating natural and artificial light sources a combination of lighting types (ambient, directional, and spotlights) creates shadows, highlights, and reflections that animate the environment. Animation software propels the potential of dynamic lighting to convey different scenarios between day and night, allowing designers to perceive spatial characteristics and aesthetic attributes of any design in different lighting states. Realistic lighting is computationally costly and requires specialized algorithms for rendering indirect lighting, reflection, and refraction (i.e., global illumination and ray tracing) and a high computer setting to support data processing. That is where software like Twinmotion and Real Engine comes in handy. Compared to Lumion, which requires a very good setup, epic games have succeeded in equilibrating the energy consumption of computational dataflow and the tools offered for animation, the ability to read and modify imported models with a different format, and the fluidity of the environment controlling tools guarantee a realistic experience for Augmented and virtual use giving the user powerful tools to simulate extreme fidelity in their lighting, while still maintaining performance.

Geolocalization is a key factor that ties virtually experienced environments with the real world accurately enough to simulate physical terrains. Using GIS platforms such as ArcGIS and QGIS, geolocalization takes topographic surveys, satellite imagery, and geographic coordinates and integrates them into data-rich, geographically accurate models, inside the 3D creation tool (Unreal Engine, Bleder, Omniverse). revolutionizing the areas of architecture/cultural heritage and urban and immersive environments. such workflow has been used in various applications, from the reconstruction of cultural sites to the visualization of urban environments by providing world-mapped precision and the ability to interact with models in 3D (Diestro M. et al 2021) .

Importing data from Revit, Rhino, and Blender for the modeling process or Unreal engine, City Engine for virtual experience creation is quite easy and intuitive, but it is important to highlight the interoperability of these programs, especially through USD as an innovative format for growing interoperability. The other production steps for both Renderization and Viruale/immersive experiences accept different file format from obj, Fbx, Map data, live synchronization. seen the multiple data transfers between different software with various data inputs and outputs, the Integration of GIS data helps significantly create accurate terrain modeling, contextual urban modeling, and detailed site analysis in this phase, which enables architects to align actual designs with the real-world setup.

Enhanced with powerful user interface (UI) design and interaction capabilities, the ArcGIS database provided by Unreal Engine or Cityengine software is a game changer for designers, offering the ability to create complex interaction panels that enhance the user experience and allow seamless navigation through virtual space. using communicative panels and buttons to present contextual information about specific objects. real-time 3D data visualization and navigation controls enable the access to different views.

Creating virtual spaces accessible to a wide audience raises issues of hardware performance and user accessibility. The heavy textures and lighting require powerful GPUs [10]with lots of memory, which some users with mid-range or low-end machines cannot afford. Developers are addressing this issue with techniques such as Level of Detail (LOD) models that dynamically change object complexity based on the user's distance. Texture streaming and adaptive lighting are commonly used methods to scale fidelity based on the capabilities of the target device, providing smoother performance without compromising visual quality (Akçam E., 2023).

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[10] GPUs (Graphics Processing Units) play a critical role in the process of virtual 3D models creation and optimizatione for digital and immersive **Mixed Reality (MR)** experiences due to their parallel processing architecture, which is optimized for the calculation of complex graphical data.

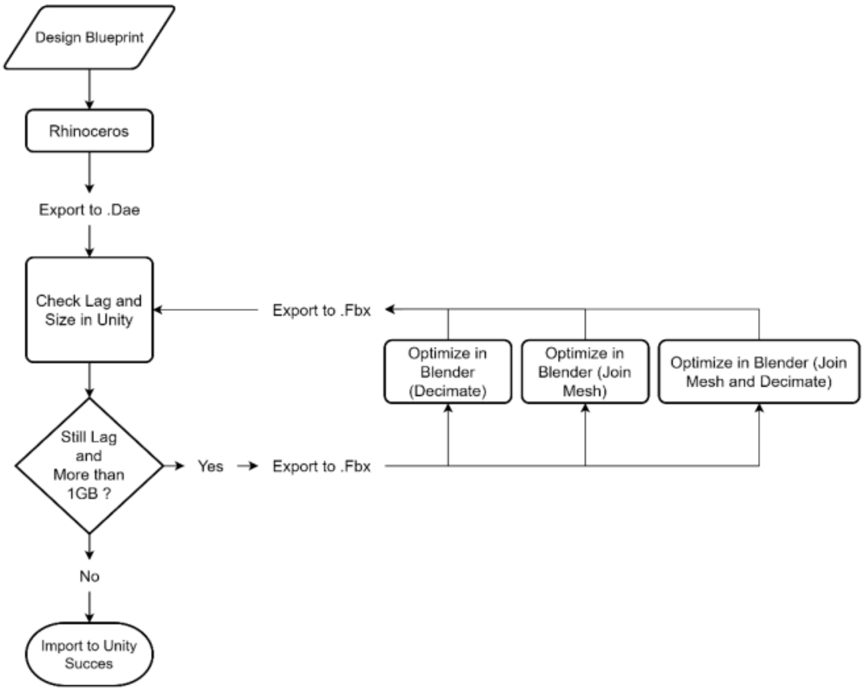


Figure 53 Optimization Process for 3D Virtualization
Made by the author: Sbai Oussama

The future of virtual environments focuses on integrating new technologies such as AI and machine learning (Zhou et al., 2024). This will automate and improve various elements of the realistic texture generation based on photographic examples on input, and even predict lighting conditions for specific shots. Machine learning algorithms (Zhou et al., 2024), for example, can provide analysis of large datasets of environmental variables to suggest optimal design strategies as urban planning simulations. Similarly, AI can be the driving force behind creating dynamic interactive environments and environmental reconstruction. In that case, new tools can enable real-time terrain adjustments based on user interactions as parameters change.

IV.3 Interaction and Navigation.

Interactive elements transform virtual spaces into dynamic environments that allow users to engage and manipulate their surroundings actively. They include a range of technologies, such as VR controllers, gesture-based systems, and haptic feedback mechanisms, and help to enhance the sense of presence and interactivity (Russo 2021). virtual architectural walkthroughs allow users to adjust design elements such as wall colors, lighting, or furniture layouts in full continuity, fostering a deeper connection between users and the virtual environment and making the design process more participatory and intuitive.

Gesture-based systems that use advanced motion tracking technologies to create a good interactive experience in the virtual environment are critical to ensure a good level of user involvement in the historical representation (Amin, D. and Govilkar, S. 2015). However, they are not the only ones, as the most commonly used methods at the moment are clickable or text-based methods. which satisfying some primitive needs such as orbiting the architectural space and changing the configuration of its elements but remain limited compared to motion tracking systems that use cameras and sensors to capture the user's physical movements and translate them into digital actions in virtual space. A hands-free interaction that not only improves accessibility but also allows for a more natural and fluid engagement with the environment, updating the visualization with each change of the physical body within the virtual space.

IV.4 Floating messages.

Floating messages and annotations provide an additional interaction layer by providing contextual information about specific environmental elements (Hussein, H.A., et al 2023). For example, during a virtual visit to a historical monument, hovering the mouse over a statue or framing a marker can reveal the object's origin, material composition, and cultural significance. This feature enhances the user's understanding without overwhelming the visual space. Further, it enriches these experiences by integrating multimedia elements such as audio, video, and animation that guide the user through a cohesive narrative (Diestro M. et al 2021). This immersive storytelling transforms virtual environments into powerful cultural education and conservation platforms, especially in museums, where interactive exhibitions can be created, and visitors can virtually 'touch' and explore artifacts too fragile to be physically handled.

Chapter V. Augmented Continuum.

V.1 Filling the Gap (Ex-stabilimento Fiat, Italia 61, GreenPea, Palazzo del Lavoro).

Urban space tends to have a dynamic between use and liveliness and abandonment. Dark alleys and neglected buildings are a spatial and experiential void that, in some cases, prevents the dynamic evolution of cities and their cultural and social value. These voids in the city interact not just as unused real estate, but also as the promise of future trasformations. Augmented architectural visualization (AAV), which integrates digital content into the physical environment, provides a new mechanism to bridge these gaps, creating rich, augmented, and interactive environments. AAV can be the vehicle for this occurrence of unity. In a workfram where linkages, stimulate engagement, experimentation, and network building between spaces, user experiences, communities, and stakeholders.

Dark alleys and derelict buildings are some of the most common and stigmatized spaces in urban landscapes, often viewed as unsafe, ugly, and undesirable. Such spaces often turn into places of social disconnect, economic stagnation, and aesthetic degradation. Conventional methods for the revitalization of cities, such as physical restoration or redevelopment, are complex and resource-intensive processes that fail to fully appreciate the unprecedented potential for immediate digital intervention. With the addition of AAV, these spaces can be reimagined as platforms for cultural narratives, interactive art, and innovative design, offering a sense of social connection and community revitalization.

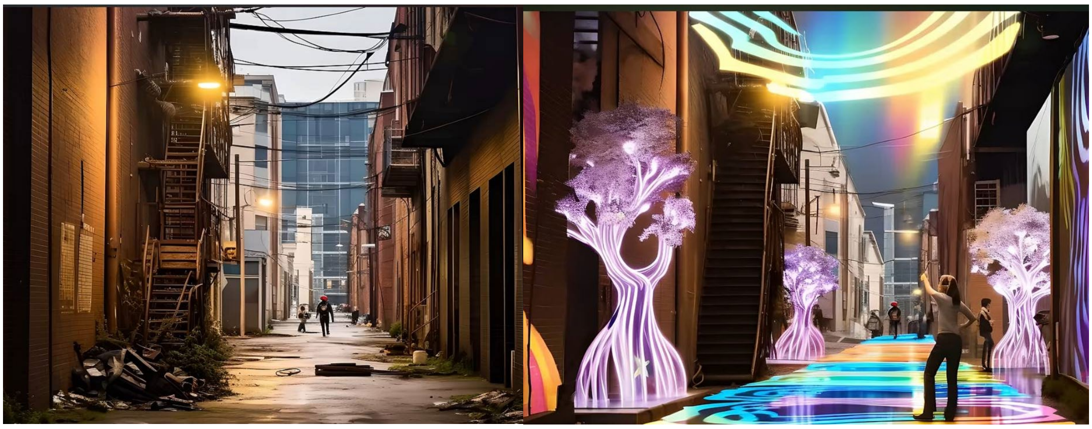
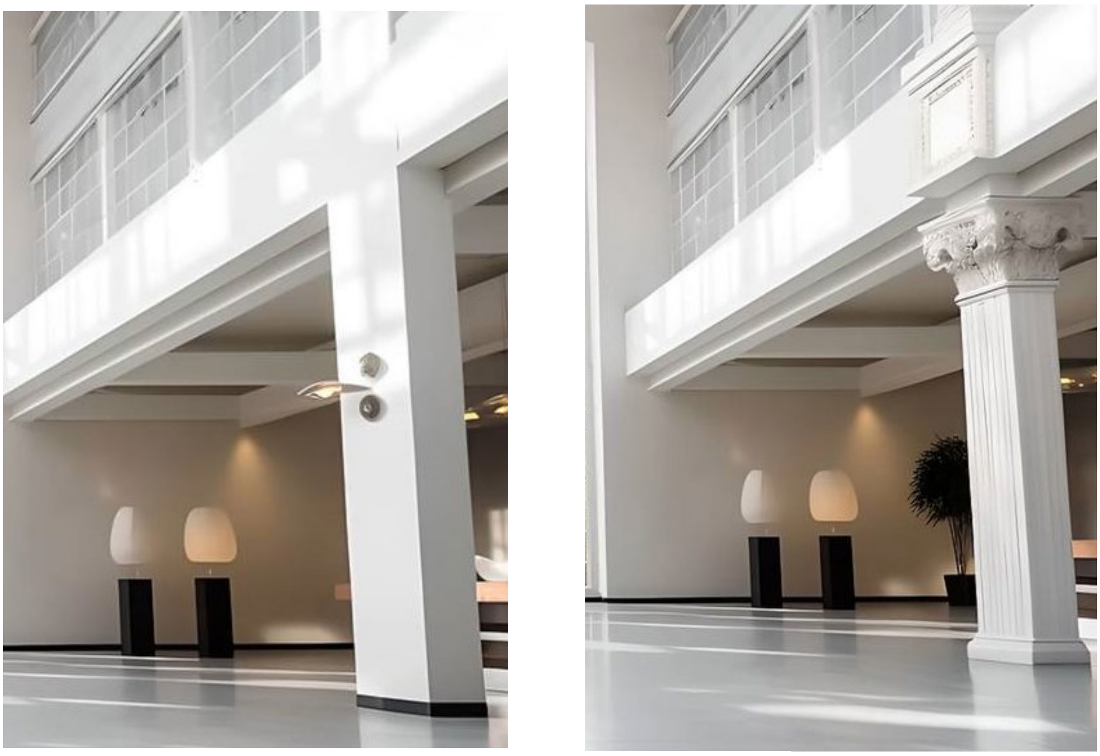


Figure 54 The transformation of the Back alleys to an Augmented world
Dami Li: Dami Lee, 2023: Virtual Reality is Not What You Think

Experiencing and observing European cities with their layered histories and architectural diversity, we can clearly see the significant challenges in maintaining cohesion amidst some fragmented urban fabric (Isabella Baldini, 2013). The juxtaposition of historical and modern structures often creates a physical and social dissonance that complicates the relationship between individuals and their environments. This fragmentation stems from centuries of evolving urbanization, where historical preservation and modernization compete for space and influence. The medieval core of many cities is surrounded by modernist expansions or industrial relics, creating stark contrasts in form, function, and accessibility. These fractures manifest not only in the physical landscape but also in the socio-economic dynamics of urban life, with historical centers often becoming isolated enclaves for tourism while surrounding areas convey the impact of urban sprawl and neglect. The digital augmentation of urban environments through technologies like augmented reality (AR) offers an innovative means to address these gaps, creating a dynamic interface between the physical and digital realms. By overlaying digital narratives and functionalities onto real-world structures, AR can bridge the divides between past, present and future; individual and space; public and private domains. This potential is especially critical in a context where urban spaces are increasingly expected to serve as multifunctional arenas that support cultural heritage, community interaction, and sustainable development.

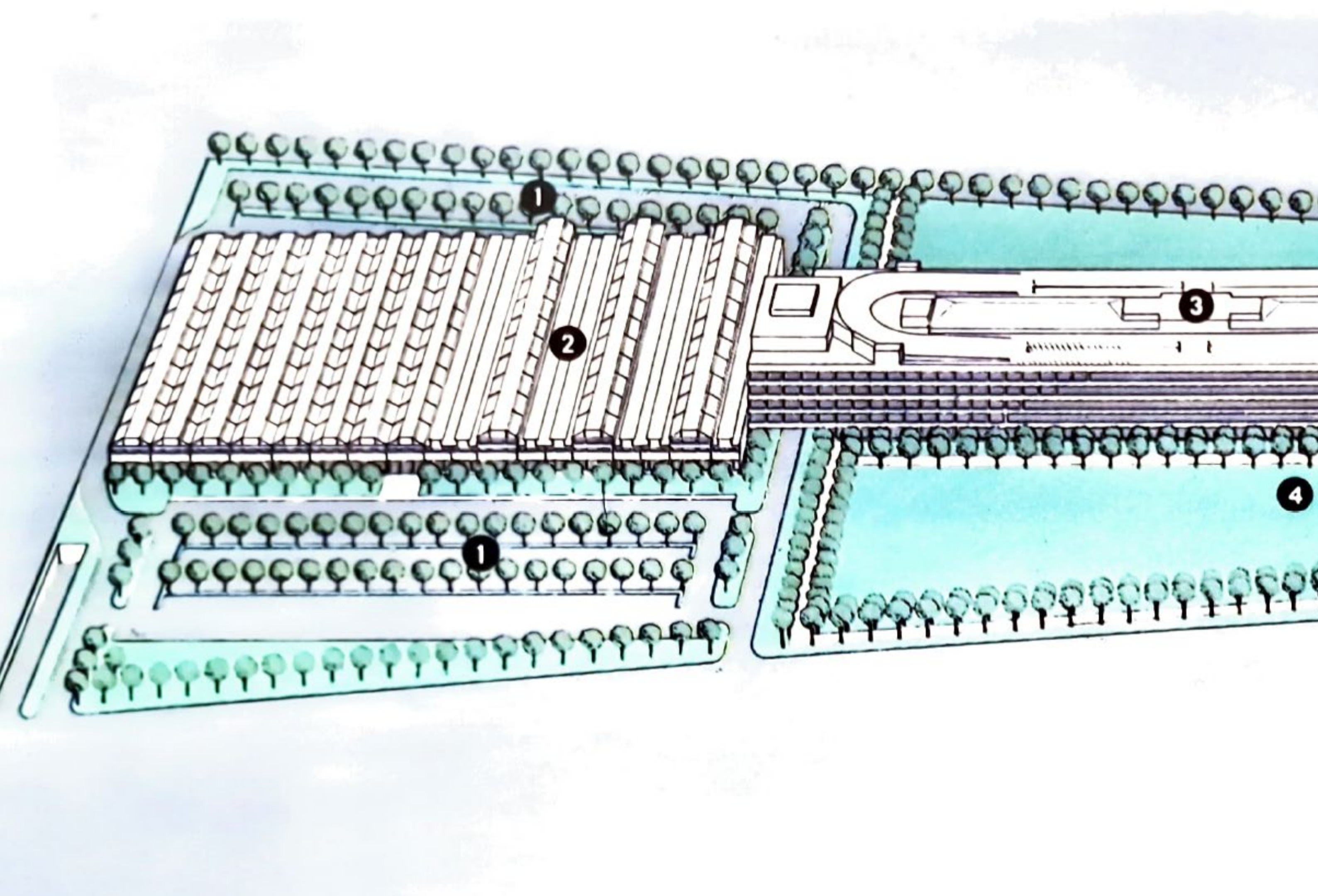


Real environment. *Virtual environment.*

Figure 55: AAV, illustration of potential personalization of space in the virtual world
Source: Dami Lee, Dami Lee, 2023: Virtual Reality is Not What You Think

Figure 56 From the Left to the Right: Palazzo del Lavoro, Palazzo della Regione, Centro 8Gellery ex Fab.Fiat, Green Pea
Made By The author: Sbai Oussama

The building that currently houses the 8Gallery bears witness to the change we are talking about in social, cultural, and historical terms: an icon of Italian industrial architecture. In 1915, Senator Agnelli took the decision that led to the construction of the factory. At that time, it truly represented the ‘new’: it met the future, and anticipated its concretization... (Bastianini, A., et al 1984). Built between 1917 and 1920 by Giacomo Mattè Trucco, the former FIAT Lingotto factory in Turin was cutting-edge for its time, not only for its industrial efficiency but also for being a cultural icon representing Italian technological progress and ingenuity.



Le Corbusier called it ‘one of the most impressive achievements of modern industry (Bastianini, A., et al 1984). After production ceased in 1982, the building underwent major reconversions and renovations led by architect Renzo Piano, who transformed the complex into a multifunctional center.

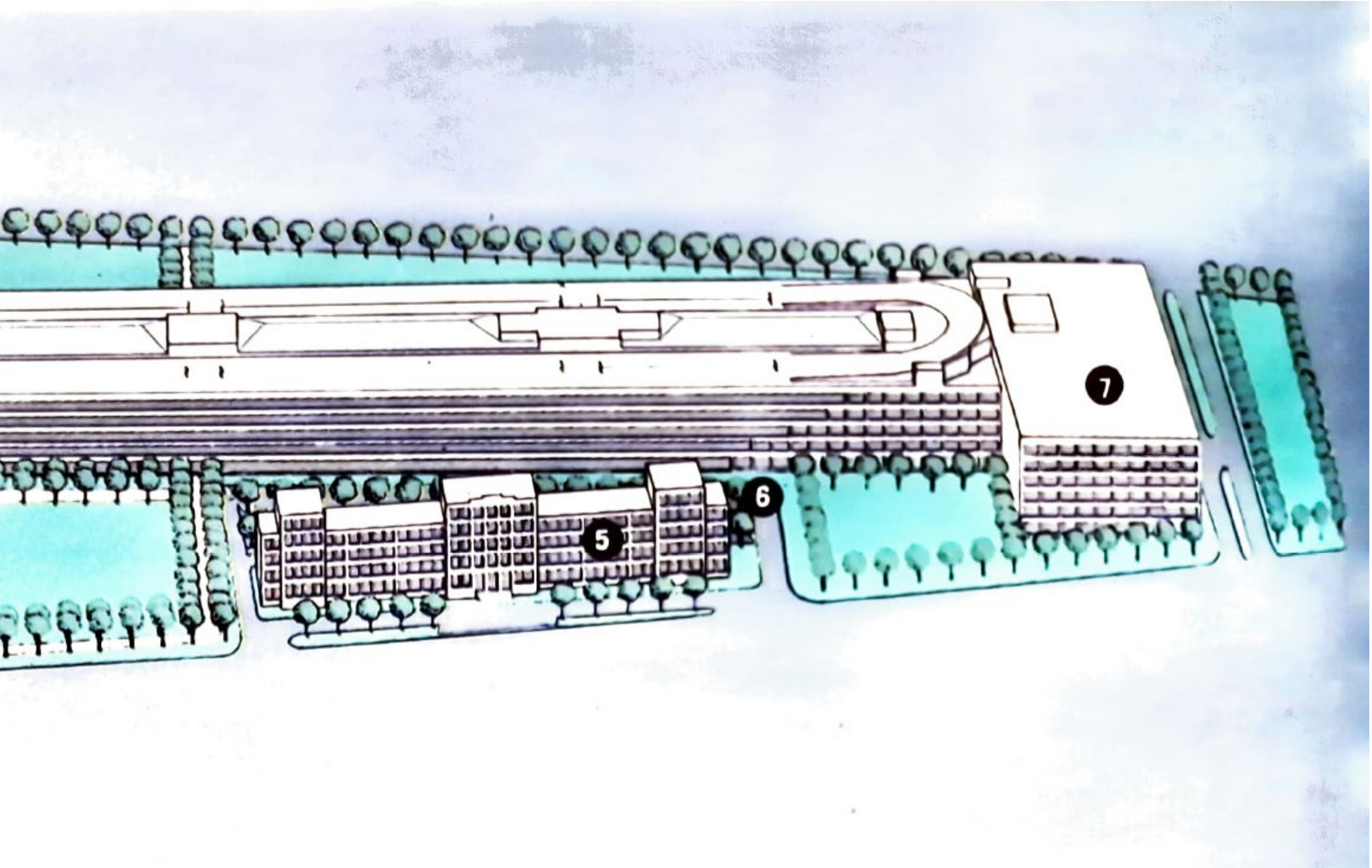


Figure 57: Project of Kevin Roche, presented in the book Venti Progetti per il Futuro del Lingotto.

Lingotto Complex: 1. Car parking of the press center. 2. Press center transformed to a museum. 3. The mall's transformed offices. 4. The Garden. 5. the office building converted into a hotel. 6. The hotel's Parking. 7. The mall's parking.

Today, in 2024, the building is surrounded by the Torre della Regione, a 42-story, 209-meter-high skyscraper designed by architect M. Fuksas in 2011, and the Green Pea shopping center, designed by Oscar Farinetti and inaugurated 2022, the first commercial space entirely dedicated to sustainability and respect for the environment. The aim is to promote conscious consumption by offering products and services that respect the Earth, air, water, and people.

This rich diversification creates a complex reading of urban space, disadvantaging historical structures compared to modern ones. In fact, one can observe people visiting a space culturally and historically very rich and enjoying themselves by creating new experiences but not grasping the historical value of these places. This relationship is even stronger when it comes to a shopping center like the Green Pea, which promotes an ecological transition in a technological way and in line with the social evolution of its users. In this case, the spaces are appreciated more because of the similarity of the modern structural language and, consequently, promote user attraction.

Under the supervision of Prof.ssa Rossella Maspoli and in cooperation between The Politecnico di Torino and ISMEL, -Istituto per la Memoria e la Cultura del Lavoro dell'Impresa e deli Diritti Sociali- An Exhibition has been launched in the corridor of the shopping center to promote its historical value. A project dedicated to promoting heritage awareness and appreciation through information banners containing text, historical images, floor plans, and structural diagrams. The aim is to tell the story of the former Fiat Factory in its different phases.

The project demonstrates the serious intention on the part of the organizations involved to find an appropriate way of communicating with the user that allows the structure to tell its story.

Information banners are an effective way of disseminating information, but when it comes to a historical narrative dedicated to a wide audience, few individuals have the time to stop to read and analyze the details. This type of interaction could easily be achieved with Augmented Reality tools that accompany the user from the beginning of the visit with customized paths, and as he or she explores the spaces, the storytelling continues in the background.

Figure 58 Exhibition in the corridors of the 8 Gallery shopping center about the history and transformation of FIAT ex-factory. Rossella Maspoli et al 2024.
Photos taken by the author: Sbai Oussama

AR, when applied to urban design and regeneration, might act as a connective tissue that binds the diversification of the architectural style together, offering to the public a more appreciable visualization and storytelling of the industrial heritage. AR also illustrates the ongoing transformation by offering an immersive experience that helps to understand and reinforce the relationship with the structures that constitute the urban landscape and shows how the city has developed, how it got to where it is today, and where that trajectory can lead in the future as a cohesive narrative.

CityScopeAR, for instance, is a project developed by MIT Media Lab and aimed at participatory urban planning through augmented reality demonstrated the possibility of enabling stakeholders to collaboratively visualize and experiment with proposed configuration to understand better the impact of design decisions (Ariel N., et al 2019) allowing citizens to help reshape the city and make sure the transformation in the urban landscape is respectful of the identities that are part of the city's fabric.

Palazzo del Lavoro, also known as Palazzo Nervi, is an emblematic building designed by the engineer Pier Luigi Nervi in collaboration with the architects Gio Ponti and Gino Covre and built between 1959 and 1961 for the celebrations of the centenary of the unification of Italy, known as Italia '61. The building covers an area of approximately 25,000m^2 and is characterized by a structure that was innovative for its time. The roof is divided into sixteen canopies, each supported by a central reinforced concrete column over 20m high, with a spoke of steel beams forming a square of 40m on each side. These elements are separated by skylights that allow natural light to enter, creating a bright and spacious environment.
The Palazzo del Lavoro is almost unknown today because it has been abandoned for years. Another building with a rich history that has witnessed the transformation of the city since the 60s, as the focal point of the great celebrations of the centenary, the Italian Union, and Expo 61.

Palazzo del Lavoro welcomed visitors from all over the world for Expo 1961, an exhibition dedicated to progress and modernity, but in 2025, with the increasing opening of modern spaces in a rapidly evolving society, the values that this building has represented for decades have been neglected, not only because of its state but also because of the lack of a vision for its reuse and the failure to reintegrate it into the urban life system of the Mirafiori Sud area, turning it into a symbol of decadence.

Figure 59 Palazzo del Lavoro, Mushroom columns and the internal space.
Source: https://www.boi.waw.pl/ February 2024

Aesthetically, even if it seems to be a simple work, it hides an extraordinary technical complexity, based on a square plant of 160m per side and a height of 25m. The entire structure is made up of 16 mushroom-shaped columns, each of which expands upwards to form a kind of star-shaped crown that supports the ceiling.

These cases should be understood within the broader conversation on AR and AI as a practical and theoretical framework for addressing urban fragmentation as part of a multi-dimensional effort in cultural, social, and technological terms.

If we want to imagine a Virtual/Augmented Reality experience in Palazzo del Lavoro, it would be an interesting call for its recuperation, through a reconstruction process following Prof. M. Russo's pipeline and using the suited tools analyzed in this research, we can offer a close view on different scenario for its recuperation.

Chapter VI. Conclusion.

The value of this thesis emerges from its attempt to motivate and promote the use of innovative technologies for project communication. Parting from the Campus Valentino project was a valuable experience where we had the opportunity to work and test some of the mentioned case studies like the Tadarch app, 3d modeling, physical building of the Campus Valentino Maquette, and the AR experience for design communication, which established the basis for this research, offering the opportunity to work and experiment closely with different communication tools, such as 3D printing, rendering, and augmented reality. The in-depth study of digital survey and documentation techniques highlighted the need for digital tools, while AI remains the key element for managing the historical architecture database.

The results of this research also define an increasing need for the adoption of new digital technologies in architectural communication, which offers numerous benefits, enhancing both the design process and stakeholder engagement through: 1. Real-time visualization tools that allow architects to interactively present designs with greater spatial accuracy and realism, bridging the gap between concept and execution, 2. MR that extends beyond static representations enabling users to experience immersive walkthroughs and interactive design modifications in real-world environments, 3. 3D printing, and computational fabrication, which enhance tactile representation, offering tangible prototypes that improve design validation and communication. Moreover, AI-powered tools that may be integrated into the different pipelines facilitate automated analysis, optimization of complex geometries, and data-driven decision-making, ensuring a more efficient and informed design process. By integrating these digital tools, architecture transitions from static visualization to dynamic, experiential, and data-enriched communication, fostering greater collaboration, accuracy, and engagement among designers, clients, and stakeholders.

While traditional renderings remain an effective method for visual representation, their limitations become evident when compared to Mixed Reality (MR). Architecture, as an art form based on the reading of space and creativity in its transformation, could benefit greatly from the advantages of these technologies. The sooner these tools are integrated into the architectural workflow, the better equipped the discipline will be to tackle future challenges and expand its communicative potential.

Why Invest in AR, VR, and AI for Architectural Communication and Cultural Heritage Preservation?

Even though the Metaverse is not yet fully developed or widely adopted by consumers, investing in AR, VR, and AI for architectural communication and CH preservation is not only strategic but is becoming more essential. These technologies are already revolutionizing many fields besides design workflows, providing immersive and interactive ways to explore, analyze, and preserve architecture. In cultural heritage, AR and VR enable virtual reconstructions of lost or deteriorated sites, allowing historians, architects, and the public to experience historical spaces that might no longer exist physically. AI further enhances this by automating heritage documentation, improving the classification and recognition of architectural elements, and facilitating predictive restoration. Furthermore, waiting for the Metaverse to mature before investing in these technologies would be a missed opportunity, as industries that adopt AR, VR, and AI early will be best positioned to shape the future of digital architectural experiences. Many tools developed for current AR and VR applications will form the foundation of future Metaverse environments, making their adoption and democratization a crucial step in preparing for the digital transformation of architectural practice, education, and heritage preservation.

In this thesis, an attempt has also been made to point out a clear and optimized path towards each of the purposes mentioned at the beginning, highlighting where the advantages and weaknesses of each framework meet. Some of the software presented in this thesis (UE, TWM, Rhino, Blender, Metamesh, etc.) was preferred based on the author's existing knowledge. However, other programs can provide similar performance, especially considering the rapid development of the computing industry.

Ultimately, this research underscores the transformative potential of digital and immersive technologies in architectural communication, advocating for a phygital (physical + digital) transition that bridges conventional architectural representation with cutting-edge interactive experiences. By embracing these tools, architects and designers can enhance project visualization, foster more profound engagement, and redefine how architecture is conceived, communicated, and experienced.

After the surveying phase(1) of creating the virtual experience, using the advanced surveying techniques already mentioned to provide high-resolution spatial data, the modeling phase(2) for geometric reconstruction, and the third phase of creating the virtual environment using the integrated ArcGIS database available in the latest versions of Unreal Engine. The next step is to import the terrain models, 3D meshes, geolocated textures, lighting, interactive elements, and other engaging feature configurations into Unreal Engine (some of them have to be created inside Unreal Engine). The UI is the final step before migrating the data to the virtual reality environments, where interaction panels and navigation tools must be added to the experience for fluid and intuitive storytelling. The project is then thoroughly tested for performance optimization and usability before deployment across desktop, mobile, and VR platforms.

In a questionnaire addressed to students and researchers in architecture, interior design, and graphic design, 60% of the participants did not know how artificial intelligence is used in design communication nor of advanced modeling, or Mixed Reality tools.

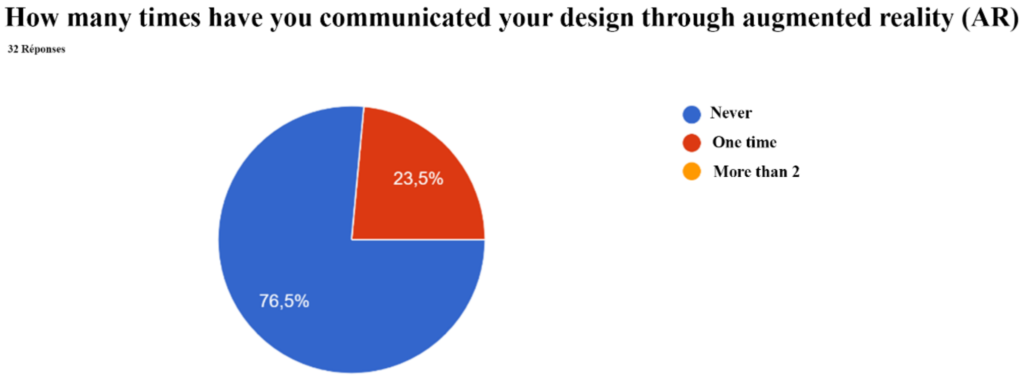


Figure 60 Question number 13 of the survey was answered by more than 32 students from Polito and the graphic design communities.
Survey Led by the author: Sbai Oussama

Only 23,5 % of the participants had the opportunity to work with AR in their projects, while AI was still ignored in most cases. Blender and Rhino were the 3D modeling software most used; however, Omniverse, as a fully interoperable platform constructed around the USD file type, was unknown to the participant. 3D printing questions instead had shown more awareness and operation due to its increasing accessibility and affordability.

From the results obtained, it is clear that there is a need to promote and facilitate access to these technologies, which, as emphasized in the thesis, may offer a significant contribution to the optimization of the modeling process and interaction with the project, represent the future of design communication, particularly for architecture and cultural heritage.

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