3D ArchiVHR – Good Practices

3D Architectural Virtual Hypothetical Reconstruction

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1. Introduction

Background: The CoVHer Project

European architectural and cultural heritage is immense. Yet part of this Heritage is invisible: prehistoric huts, ancient temples and forums, churches, synagogues, and mosques that have either been destroyed or never been built. Now the digital revolution offers the possibility to bring these monuments to a new life, through 3D reconstruction.

A new way of studying and representing the past has become increasingly important in the academic and cultural heritage domains and also in the entertainment industry (such as films and video games). This new way makes use of the so-called *virtual 3D reconstructions*, that is, 3D models based on figurative and textual sources of artefacts that no longer exist or have never been built.

Today, architects, art historians, restorers and archaeologists use this medium to study and represent the past. The large production of these studies and models has encouraged an international debate about the scientific reliability of these (re)constructions. Two important theoretical guidelines have been drawn up in this regard: the London Charter (http://www.londoncharter.org/index.html) and the Principles of Seville (http://sevilleprinciples.com/). These documents have fixed general guidelines on the scientific nature of Computer-based Visualisation of Architectural Cultural Heritage (CVCH) models. However, despite several studies which were dedicated to similar subjects, so far there are no shared standards or applied methods on this specific topic. There are European projects dedicated to the digital studies of CH as Horizon 2020 (i.e., Inception-project Horizon 2020 https://www.inception-project.eu/en), but not specifically dedicated to the topic of no longer existing/lost/destroyed and unbuilt projects.

Today it is not possible to distinguish a scientifically valid 3D virtual reconstruction from an amateur 3D model, because there is no academic level reference standard designed to evaluate its quality and scientific reliability. Thus, the Erasmus+ European project CoVHer (Computer-based Visualisation of Architectural Cultural Heritage) was proposed and funded to address these and other related issues.

The main objective of CoVHer is to define applicable/practical guidelines and operational methodologies aimed at the study, as well as the implementation, visualisation (including access) and critical evaluation of the 3D models, following the Charter on the Preservation of Digital Heritage (UNESCO, 2003). The aim is to define a clear methodology for the creation and documentation of the CVCH model.

The CVCH model can be used as an instrument for scientific dissemination as well as a three-dimensional reference document for scholars of CH. The latter objective, to build a valid CVCH model, must be accompanied by all the methodologies and references used. All this material should be stored in the clearest and most transmissible/accessible way. To pursue transmissibility and transparency, the actors in this field should discuss and adopt shared standards at the international level.

This is the reason why this project involved five universities and two private companies from different countries as principal partners. The Institute of Architecture at the Hochschule Mainz is a member of the Time Machine project (https://www.timemachine.eu/membership-overview/ and our actions are strictly connected to the FAIR data principles, see https://www.go-fair.org/fair-principles/).

In addition to scholars, architects, engineers, art historians, archaeologists, and restorers, the project is also aimed at proactively involving associated partners (e.g., museums, municipalities) and the public.

Sensitising the public to distinguish accurate from inaccurate historical reconstructions has become critical nowadays because the gaming and film industry makes large use of 3D models. Movies and games have a huge impact on the collective imagination that is not comparable with text or academic lessons. It is important to provide tools and increase public awareness of the scientific nature of these *reconstructions*. This will contribute to increasing the knowledge of the European architectural heritage.

CoVHer Objectives

The CoVHer project supports the digital capabilities of the higher education sector and fosters innovative learning and teaching practices. It aims to develop a shared glossary to foster the production of more consistent outputs of the scholars in the field of hypothetical virtual 3D reconstructions, which nowadays still do not share a common vocabulary. Another of the project's objectives is to define applicative/practical guidelines and operational standards aimed at the study, implementation, creation, documentation, visualisation, access, and critical evaluation of the 3D models of artefacts that no longer exist or have never been built, following the Charter on the Preservation of Digital Heritage (UNESCO, 2003).

The creation of a repository is also one of the objectives of the project, which is crucial for the sharing of scientific knowledge. Currently, there are several internet platforms or projects (i.e., Inception-project Horizon 2020 https://www.inception-project.eu/en) with digital collections of the European architectural heritage. The innovation of CoVHer's digital repository consists of being open access and also opened to 3D digital reconstructions of artefacts that were never built or have been destroyed, altered or damaged along History. The goal is to create a digital 3D repository that can transmit, together with the finished product (3D model), the essential information for the critical evaluation of the work. The platform, therefore, has two different and complementary vocations. The first is being a reference place for scholars (architects, engineers, art historians, archaeologists, and other field experts) where they can share, download and study 3D reconstructions and the sources used to build them, with an emphasis on scientific correctness. The second is being a public repository accessible to laypersons (non-experts) and will contribute to the valorisation of the European architectural and cultural heritage.

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Finally, the dissemination activity in the academic world and the public world is an important goal of this project. The CoVHer project targets the students and scholars of architecture, engineering, archaeology, restoration, history of art, professionals of CH and the public. The last of the objectives is to create teaching modules of university courses dedicated exclusively to the virtual reconstruction of CH.

Raising awareness among the academic world and the public on the possibility of scientifically reconstructing the past through virtual hypothetical reconstructions is a way to increase the cultural and social cohesion of European citizens.

In synthesis, CoVHer aims to achieve the following specific goals:

- define methodological standards and a common glossary for the construction/evaluation of 3D models of CVCH (Computer-based Visualisation of Architectural Cultural Heritage);
- create a repository of 3D models of CH (infrastructure for applying the standards and methods);
- disseminate the CoVHer ideas in the academic and public world of CH.

CoVHer Expected Results

The project will contribute to improving the digital capabilities of the higher education sector and stimulate innovative learning and teaching practices.

The principal project expected results are:

- redaction of a set of guidelines and methodologies to outline operational standards for generating computer-based visualisation of cultural heritage;
- creation of 3D computer-based visualisations/models of cultural heritage as case studies;
- creation of the dedicated platform/website as an open-access repository for scientific 3D models of cultural heritage;
- creation of open educational resources as innovative didactic modules;
- build an international network of high-level qualifications for the teaching/learning, study, construction, quality evaluation and visualisation of the 3D model of CVCH;
- tackle skills gaps regarding the study, quality evaluation, construction, and visualisation of 3D digital models of CH, in line with the renewed EU agenda of Higher Education [2017];
- contribute to providing architects, historians of art/architecture, and archaeologists with additional facilities and reference requirements for accessing the European market;
- contribute to establishing an international network and exchanges among scholars and students working on digital CH using innovative didactic modules;
- engage students and the public through the CoVHer open access repository and the online courses to make them more aware of the value and quality of the European cultural heritage while improving the sense of belonging to a common European cultural identity.

The Glossary Book and the Good Practices Book

The objective of the production of a common glossary and operational standard guidelines was synthesised in a series of two books: a Glossary Book (3D ArchiVHR – Glossary) together with a Good Practices Book (3D ArchiVHR – Good Practices).

The *glossary book* collects some fundamental terms (sorted in alphabetical order) for the topic of architectural virtual hypothetical 3D reconstructions of the past. The listed terms are the theoretical framework of the *Good Practices book*. The definitions presented in the first book are both technical and conceptual. The former are, for example, the definitions of NURBS or mesh, while the latter are, for example, the concepts of the scale of uncertainty or the Raw Model and the Informative Model.

The two books have to be intended as complementary tools. The first book (3D ArchiVHR – Glossary), like all dictionaries, can be consulted starting from any voice, sorted in alphabetical order, and the definitions do not follow any hierarchical or chronological order. The second book of Good Practices presents and illustrates more in-depth theories, workflows and practices from start to finish applied in different contexts. Therefore, the first book is aimed at scholars or amateurs who need to clarify further only certain concepts and terms according to their cultural backgrounds, while the second book is thought to be read from start to finish because it is structured in a more hierarchical way.

How This Book Was Conceived

The research presented here is the result of months of discussion between researchers and professionals in the field of virtual hypothetical 3D reconstruction, who have different approaches, cultures, nationalities (participants are from five different European countries), and backgrounds (architects, engineers, art historians, restorers, archaeologists, and other professionals).

The good practices and theories presented in this book were developed during the three years of the CoVHer project and were discussed with all the partners and also with external experts at conferences and multiplier events. Workflows were tested and improved thanks to several international workshops meetings and events involving scholars, students and laypersons who gave critical feedback.

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2. Introduction to the Idea of Computer-Assisted Reconstruction of Architectural Heritage

Authors: Juan Anton Barceló, Laura Mameli, Evdoxia Tzerpou

Seeing the Past in the Present

In a way, the *past* –what came into existence before us- is present here and now. Buildings and constructions erected years, centuries, and millennia ago live with us. We are surrounded by old buildings standing next to modern, contemporaneous constructions. Furthermore, archaeologists unearth vestiges of built structures from many different periods, from prehistory to the most recent past. The trouble is that all this architectural heritage from the past is, at present, altered. The remains of prehistoric, ancient constructions and historical buildings we see here and now are not exactly how they were once in the past. They usually are incompletely preserved and may appear modified by successive uses and constructions or even broken into pieces, destroyed. We cannot see *now* how they were *then*.

What we cannot *see* in the present but existed sometime in the past can be *imagined*. When seeing ruins or historically modified buildings, we can build mental images about the *possible* visual appearance, spatial properties, and other characteristics such buildings had the day they were erected. We can also "see" in our mind how people lived there, what they made in their interior or around them.

What we can *imagine* in our mind, we may also externalise by producing a drawing, an annotated graph, a picture, a mock-up, a computer program, etc. In any case, what we are doing is not reproducing what existed before us but creating a new entity in the present: *a model*, that is, a surrogate that substitutes the entity that existed in the past. It approximates what we *believe* existed and how it existed years ago. Just as surrogate models in engineering approximate complex systems, a picture, a mock-up or a computer program captures the essential features of the original building they refer to while reducing its complexity. This simplified version can be more easily communicated, analysed, or manipulated without losing the essence of the original mental image. By using physical models to *represent* our ideas, we allow for a more accessible and manageable representation of intricate mental processes in the same way as surrogate models in data science and engineering simplify complex systems for analysis and optimisation.

The idea of Reconstruction

Figure 1: The Past can be "imagined" and explained –image (images created by the author using Microsoft Copilot)

Depending on the way we have generated this new entity *representing* how we believe that past looked like, and the amount of new information added to the preserved remains, we should distinguish:

- Restoration. Returning what physically remains today of the architectural heritage element erected time ago to a known earlier state by removing accretions added throughout the years or by reassembling existing elements without the introduction of new data.
- Reconstruction. It is distinguished from restoration by the introduction of new data.
- Replication. The construction of a copy of an architectural heritage element.

In fact, when imagining the past by using images, computer programs or physical models, we are always in the *replication* domain because we are not using what remains today from the past. However, it is fashionable to say that the past cannot be *replicated* faithfully. For many scholars, "ruins" retain evidence of the history that produced them, *but only imperfectly,* which leads *to* the *speculative* reconstruction of ruins. *Speculative* means "engaged in, expressing, or based on conjectures".

It is easy to see that a speculative replicate of the past is out of purpose. An excess of imagination when generating an image of the original appearance of an ancient construction might lead to what some critics call the 'Disneyfication' of heritage sites, turning them into artificial tourist attractions rather than authentic historical landmarks. This can trivialise the cultural significance of the site and alter its meaning for local

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communities. In the same way, inaccurate images of the past may convey erroneous information about what happened, potentially misleading people about their history and cultural heritage, and leading to a distorted understanding of historical events, architectural styles, and cultural practices, and weaking the community's sense of identity and connection to their heritage. Wrong reconstructions might erode public trust in heritage professionals and institutions, making it more difficult to obtain support for future conservation efforts.

London Charter and the Principles of Seville

In recent years, it has been an effort among cultural heritage professionals to avoid the free invention of particular pasts. Cultural Heritage International institutions have published some advice and criteria for good practice to evaluate the achievements of past elements restoration, reconstruction and replication, and to ensure that any representation showing a particular cultural heritage element be, at least, as intellectually and technically rigorous as it is based on sound historical, artistic or architectural knowledge and allowed by communication methods used in the visualisation. Both the London Charter (https://londoncharter.org/) and the Principles of Seville (https://icomos.es/wp-content/uploads/2020/06/Seville-Principles-IN-ES-FR.pdf) have been suggested as guidelines for the correct visualisation of architectural heritage. These principles aim to ensure intellectual integrity, reliability, and transparency in the use of visualisation methods for cultural heritage. They emphasise the need to identify and evaluate the original preserved evidence and its direct relationship with the final replicate.

We can resume in 7 main principles the necessity of reducing subjectivity, bias and speculation in the process of imagining the past:

- **Principle 1: Interdisciplinarity**. Replicating the past cannot be addressed using a single form of knowledge but instead needs the cooperation of many different means and, consequently, of specialists (archaeologists, architects, historians, heritage interpreters, psychologists, sociologists, designers, digital media experts, engineers, computer scientists, etc.).
- **Principle 2: Purpose**. There are no universally valid replicas of the past. They are produced for a specific purpose or determinate goal, and such a goal will affect many of their characteristics. Therefore, different levels of detail, resolution and accuracy might be required.
- **Principle 3. Complementarity**. Replicating the past using images should not aspire to replace other approaches to understanding what happened before us. We still need written descriptions and oral narrations by witnesses of events having occurred before us.
- **Principle 4: Authenticity.** When replicating the past, it seems necessary to distinguish what is real, genuine or authentic from what is not, what has been added to obtain the visual appearance the past had once.
- **Principle 5: Historical rigor.** The historical reliability of any replica of the past will depend on both the availability of precise historical information and how

it is expressed and visualised. There is no valid recreation of the past without explicitly indicating the knowledge sources used to generate it.

- **Principle 6: Efficiency.** Using fewer resources to achieve steadily more and better results is the key to efficiency.
- **Principle 7: Scientific transparency.** Any recreation, restoration, reconstruction or replica of the past must be essentially verifiable, i.e. capable of being tested by other researchers and professionals, since the validity of the conclusions produced by such visualisations will depend on the ability of the results to be confirmed or refuted by other experts in the field. That means that we must explain the logic behind our re-creation or reconstruction, showing the different steps, from data acquisition to the validation and verification of the final model.

Reverse Engineering

It is easy to see that the reconstruction/recreation process goes in an apparent "backwards" mode, "reversing" the historical transformations the object or building has experienced since it was first created. Reverse reasoning, also known as backward reasoning, is a problem-solving approach that involves starting with the desired outcome or goal and working backward to determine where the outcome comes from. In our case, we begin with preserved remains, the archaeological record, and go backwards in time and formation process to understand which kind of building generated those remains and which physical forces explain the actual location of individual preserved parts.

This is the same situation in which an engineer observes a contemporaneous object and, in the absence of any other knowledge, tries to "reconstruct" the way it can be produced (or used) again. This approach has been called "reverse engineering" and defined as the study of a sample of a product, device or machine to discover how it functions or has been made. The very idea of "reversing" engineering would mean reversing all the necessary processes for the creation of a product, including all the steps from the capture of the initial idea to designing, manufacturing, assembling, use and maintenance of the product. Whereas *forward* engineering would move from high-level abstractions and designs to physical system implementation, *reverse* engineering, by contrast, would begin with a final product and go backwards by analysing its design and the interrelation of its entities. Its purpose is the recreation of a product or the creation of a product with respect to another product.

Reverse engineering implies backward inferences from the end state to the beginning state of some system. From the understanding of the historical construction process and successive deformation episodes we should infer vital information about the actions having constrained and/or determined the final appearance of preserved remains –their size and shape, their colour and surface irregularity, the physical and mechanical properties of the raw material they made of, their placement at a precise location the moment the original building was erected and used, etc. With reverse engineering, scholars start with the preserved remains, the final state of the building, and work through the formation process in the opposite direction of its causality, backwards, to arrive at the original building design specification. Given each successive state of the design system, we should infer the previous state by reconstructing the mechanism that produced the observed deformation.

In short, we start from a historical hypothesis about the original building to analyse its design and thus modify it to discover how it has been altered over the years. This would be a process in which the technological principles of the building would be uncovered through a structural analysis, which involves the study of its parts and components. The procedure may vary depending on the application, although the following three steps are the most common. The first is data extraction, which is based on studying the architectural remains to extract revealing information. The second step is modeling, where the collected data is used to make a conceptual model with the objective of using it as a design guide to visualise the original construction. Finally, a review is made that includes testing the visualisation obtained in the previous step.

Using Computers for Reconstructing the Past

Figure 2: Using computers to recreate the past (images created by the author using Microsoft Copilot)

The process of creating images reconstructing the original appearance of ancient constructions can be "automated" using computers. In this context, "automation" involves the use of computer programs and algorithms to generate images of the original appearance of ancient buildings, produced with minimal human intervention. The advantages of using computers in visualisation would include:

- Increased Efficiency: Automation can significantly reduce the time and effort required to reconstruct ancient buildings.
- Improved Accuracy: Automated processes are less prone to errors compared to manual ones, leading to more accurate reconstructions. Instead of using lengthy narratives or detailed pictorial descriptions, digits

(numbers) allow summarizing and condensing of information, making it easier to understand and communicate.

- Enhanced Detail: Automation allows for the creation of highly detailed digital models that would be difficult to achieve manually.
- Replicability is a feature of digital models that allows them to exist in an infinite number of versions, which are modifications of the original. Computers allow encoding the visual model in different formats, allowing different uses. Transcoding involves converting digital media from one particular encoding to another, often with the aim of compatibility, optimisation, or adaptation for different devices or systems. The computer-generated visualisation can then be explored in different contexts and in different ways: as visualisation, virtual reality, augmented reality, and mixed reality.
- Interrogability: By using the language of geometry and advanced forms of human-computer interaction, there is the additional possibility of "interrogating" the virtual model. We can ask for metrical, spatial or visual details, and the model answers provide additional information

Virtual Pasts

Figure 3: Beyond mere images, Computer models are virtual entities (images created by the author using Microsoft Copilot)

A virtual entity generated by a computer program is an abstract object that exists only within the digital environment of the computer system. It is not a physical object that can be touched or seen in the ordinary sense but rather a collection of data and instructions that are manipulated by the computer program according to certain rules and algorithms.

Nowadays, Virtual Reality can be defined as an artificial, computer-based, and viewer-centred experience in which the user is enclosed in an all-encompassing 3D space that is - at least visually - sealed off from the physical environment. On the other hand, expressions like Augmented, Mixed or Extended Realities (often – misleadingly –

abbreviated as XR) are commonly used terms to describe how computer-based technologies generate or modify an apparent reality. Academics and professionals have been inconsistent in their use of these terms.

Since the 1990s, the concept of augmented reality has evolved and expanded to include a variety of technologies and applications. Today, augmented reality (AR) is a technology that overlays digital information and virtual objects onto the real world, creating a composite view that enhances or augments the user's perception of reality. AR typically involves the use of a device such as a smartphone, tablet, or smart glasses, which uses sensors and cameras to track the user's position and orientation and display digital content in real time. This has led to conceptual confusion and unclear demarcations. Augmented Reality and Virtual Reality have fundamental differences and thus should be treated as different experiences:

Augmented Reality experiences can be described on a continuum ranging from assisted reality to mixed reality (based on the level of local presence). Augmented Reality is a hybrid experience consisting of context-specific virtual content that is merged into a user's real-time perception of the physical environment through computing devices. AR can further be refined based on the level of local presence, ranging from assisted reality (low) to mixed reality (high).

Virtual Reality experiences can be conceptualised on a telepresence continuum ranging from atomistic to holistic VR.

Time Travel

Seeing the past in the present can be understood metaphorically as a form of time travelling, a journey to a previous state of our world, when what is incomplete or altered in the present was complete and unaltered in the "past". Nevertheless, it should not be a fictional journey. "Imagining" the past does not allow us to invent behaviours or scenarios that did not occur in the past. Consequently, any visualisation of the past appearance of buildings should have an explicit relationship with what once existed.

The truth likeness of our re-creation will depend on the quantity of information, its reliability, and the decisions made when adding information content at a particular step in the re-creation process. *Verification* can be defined as the evaluation of whether or not the images which implement the solution to the reconstruction problem comply with requirements, specifications, or imposed conditions for the proper recognition of the solution as deducible from the problem statement. That implies making explicit the way new information has been added to the initial data (the "ruins"), where knowledge comes from, how it has been added to the successive modes of the reconstruction, and the reliability of structural (in)dependencies between perceived and inferred elements. This verification is then just the reverse of the reconstruction process: describing where primary information comes from, how the image of the ruins has been built, how we know that some information is missing, which kind of visual information has been added to complete those missing elements.

In a way, verification can also be understood in terms of the calculation of the visualisation *degrees of freedom*, that is, the number of independent variables or parameters in a system that can vary without violating any constraints

In addition to verifying, we should validate the imagined past created by the computer. Validating a particular built heritage re-creation implies studying whether it meets the needs of its intended users or serves its intended purpose in the real world. Verification is about checking that a product or system conforms to prior technical specifications and standards, while validation is about achieving the desired goals. A goal is a desired outcome or end result that one aims to achieve. It's often a broad, overarching target that provides direction and guides decision-making. A specification, on the other hand, is a specific condition or capability that must be met or possessed in order to achieve a goal. Requirements are typically more concrete and detailed than goals, and they often need to be met in a specific way. *Validating* a particular built heritage re-creation implies making it acceptable or approved according to some criteria. It does not mean that the re-creation is universally "correct", but it fits an explicit use. Validating re-creations of the past implies exploring the use of such replicas and the goals we had when beginning the re-creation process.

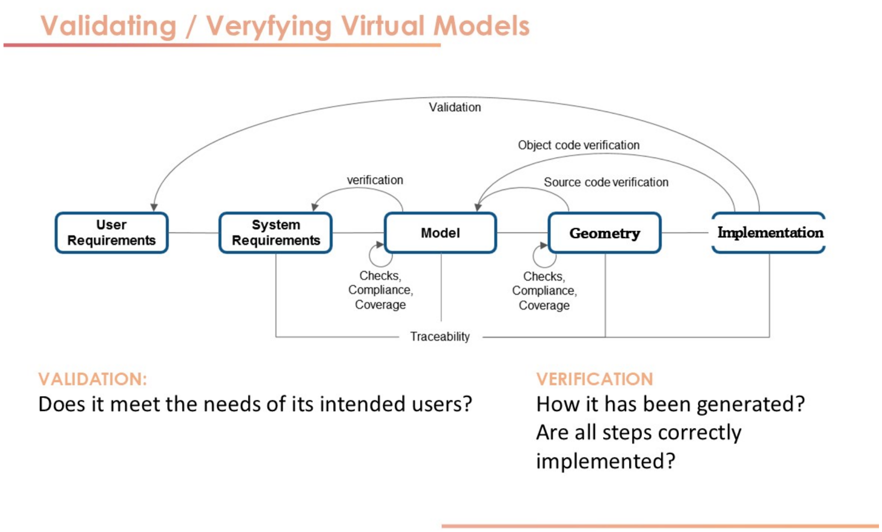

Figure 4: Distinguishing "Validation" from "Verification" (Image by the author)

The idea that a visualisation of the past should be deducible from initial data is fundamental to the truth-likeness of the reconstruction/recreation process. It involves using available information (initial data) to derive or infer new information (conclusions) through a process of logical deduction. This process is based on the principle that if certain premises are true, then a specific conclusion must also be true. Asserting the truth of a particular step in the reconstruction process involves a structured process of logical reasoning based on *established* rules and principles. The task of the verification process is to evaluate whether production rules are clearly stated and produce the expected result. It is also relevant to assert whether more than a logical rule can be applied: the higher the number of different reconstructions, the lower the reliability of the final visualisation.

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To "see" the original appearance of a building of which only a few remnants remain is tantamount to what philosophers of science refer to as an *inverse problem*: we see the *effect*, and we want to infer the *cause*. We see the actual state of the building – ruined and/or altered in the present- and we want to infer where preserved structures came from, that is, the original building, in the past. That means that to replicate/recreate the past, we should proceed in an apparent "backwards" mode, "reversing" the historical transformations the object or building has experienced since it was first created. This form of backward reasoning is a problem-solving approach that involves starting with the desired outcome or goal and working backwards to determine where the outcome comes from. In our case, we begin with preserved remains, the archaeological record, and go backwards in time and formation process to understand which kind of building generated those remains and which physical forces explain the actual location of individual preserved parts.

Going backwards implies reversing the *design process* by reproducing the technical and scientific knowledge of original designers and constructors. In short, we start from a historical hypothesis about the original building to analyse its design and thus modify it to discover how it has been altered over the years until conforming the ruins we can see here and now. It is a process in which the technological principles of the building should be discovered through a structural analysis, involving the study of its parts and components. The procedure may vary depending on the application, although the following three steps are the most common. The first is data extraction, which is based on studying the architectural remains to extract revealing information. The second step is modelling, where the collected data is used to make a conceptual model with the objective of using it as a design guide to visualise the original construction. Finally, a review is made that includes testing the visualisation obtained in the previous step.

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3. The Concept of Model

Authors: Krzysztof Koszewski

Why do we Build Models?

The answers to questions such as what models are and why we build them may seem obvious. However, a deeper understanding of the nature of models and their usage is crucial in virtual hypothetical reconstructions of the past. In the broadest sense, referring to the theory of modelling and simulation, models are certain approximations of the real world. Of course, this is not an approximation of the entire surrounding reality but a reflection of a fragment of it. We can call such a fragment a certain system Figure 5.

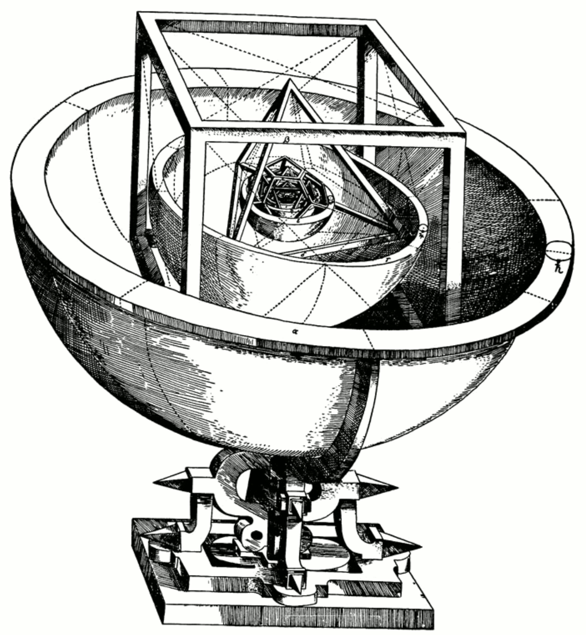

Figure 5: Solar System Model by Johannes Kepler.

We must isolate it from the whole reality because it is difficult or even impossible to model all of it. For this purpose, we define appropriate criteria that characterise the elements of our system and determine the relationships between them.

According to the theory of modelling and simulation, models—which means, as we said, appropriate approximations of reality—are built when there is a need to test systems (thus, mentioned fragments of reality) and experiment on them. In this way, we are able to check their behaviour under certain conditions Figure 6.

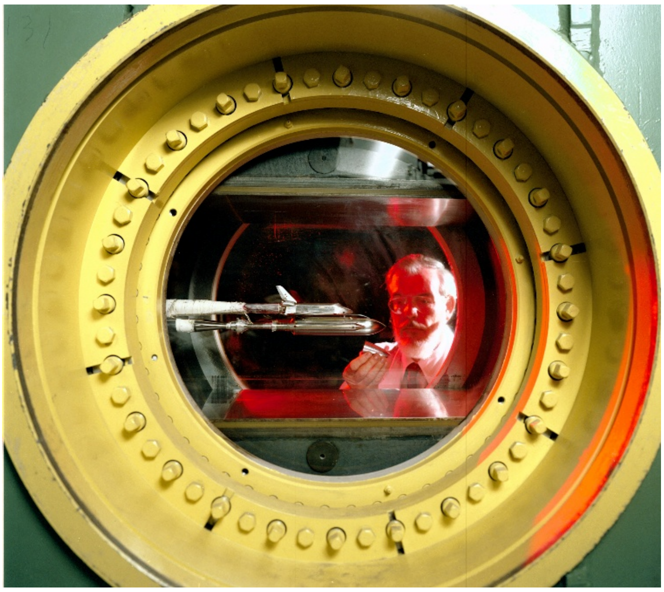

Figure 6: Marshall Space Flight Centre (MSFC) engineer observes the testing of a small Space Shuttle orbiter model, NASA.

We build models primarily when, for some reason, the real system cannot be used. This happens when the system is unavailable or, for example, when testing certain solutions would be dangerous or unethical [Banks, 2009].

To better understand the nature of models, let us look at a specific type of them – those created by architects Figure 7. Robin Evans once wrote that "architects do not build buildings, they create drawings of buildings." [Evans, 1989].

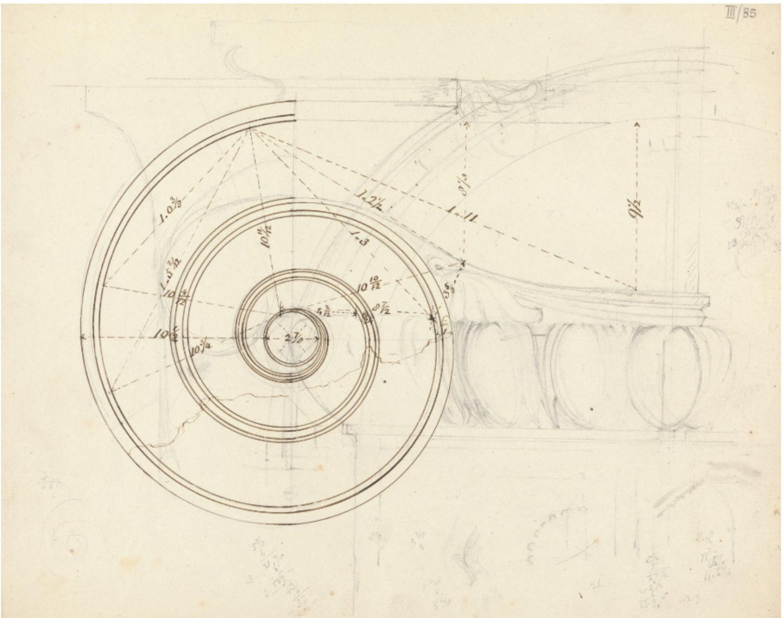

Figure 7: Example of architectural drawing by Robert Smirke the younger, Yale Centre for British Art, Paul Mellon Collection

And indeed, he was right, although in a broader sense, it can be said that it is not just about architectural drawings. Architects, while designing, in fact create models.

Based on these models, prepared in various ways and forms, buildings are constructed. Designing is thus a particular case of modelling, within which architects create a model in order to test a system that does not yet exist. In such sense, the designed building is a system containing all the necessary structural and functional elements Figure 8. On the other hand, its design is a model of this system.

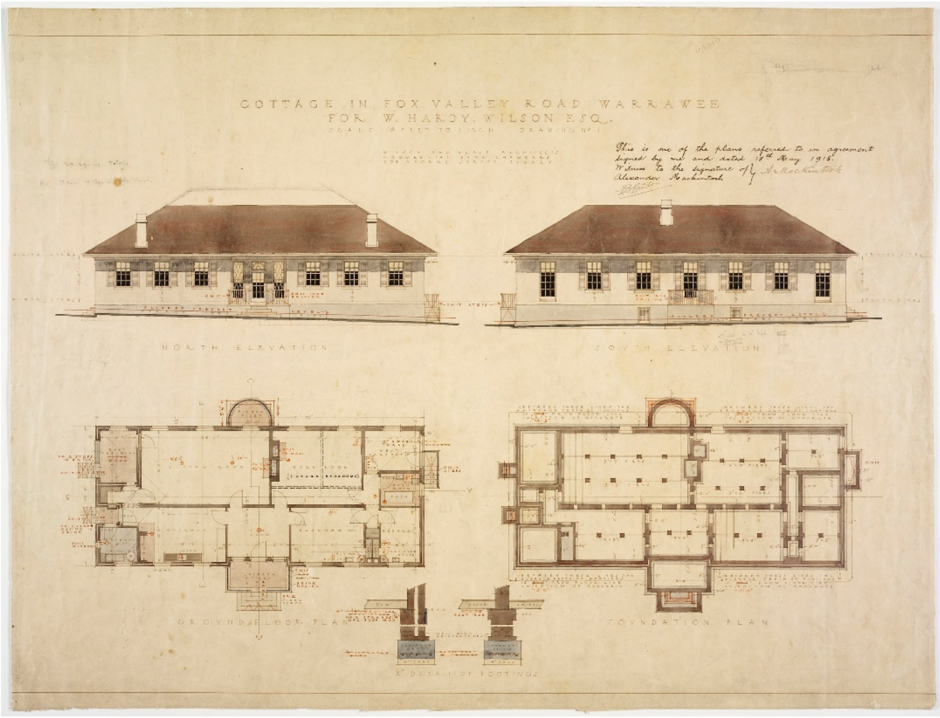

Figure 8: Example of early XX Cent architectural design: Residence "Purulia", Wahroonga, Sydney, 1916, by Wilson, Neave & Berry, State Library of New South Wales

It allows, to some extent, for testing the behaviour of the future building and boils down to the possibility of repeatedly observing the model under changing conditions. Such a model gives us the ability to assess and predict whether the resulting object will meet our requirements. It is worth noting that the possibilities of such simulation increase significantly when dealing with a digital model.

An architectural design, being an abstract idea, must be recorded in a way that allows conveying and understanding this idea. This is another function of models– recording and presentation. It is worth noting that such a model can be both a mock-up (which means a physical model Figure 9) and an elevation drawing or a building plan Figure 10.

Figure 9: Physical wooden model of the Trinity Cathedral of the Alexander Nevsky Lavra, Sankt Petersburg

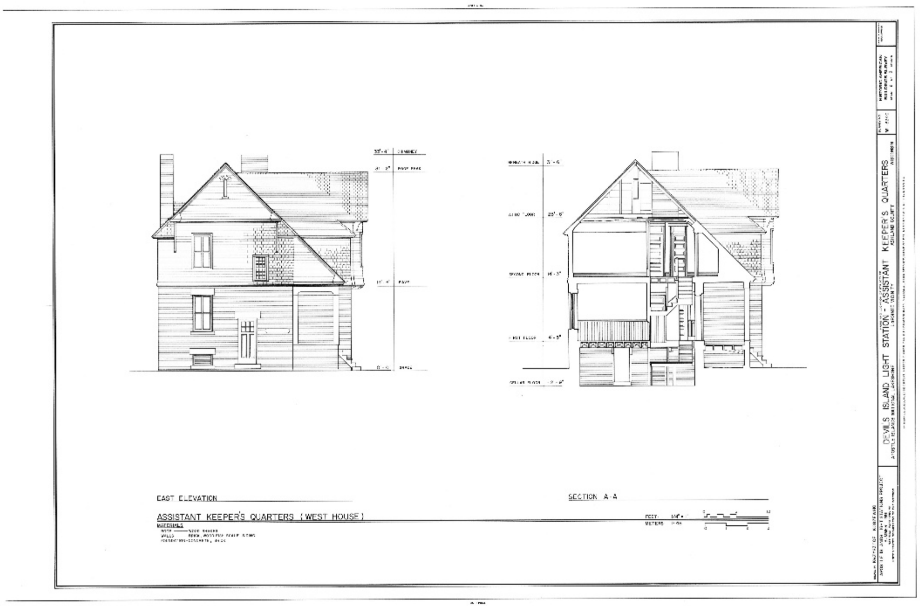

Figure 10: Survey drawings of the Assistant Keeper's Quarters at Devils Island, Apostle Islands National Likeshore, USA, Library of Congress, drawn by Krzysztof Koszewski

Finally, it can be a digital model recorded in a computer's memory. Very often, when talking about architectural models, we mean mock-ups, so physical, three-dimensional representations of a building to scale. Considering the cited features and functions of architectural models, a mock-up is just one of the possible types of models [Millon & Magnago Lampugnani, 1997].

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We already know that an architectural idea, a design, recorded in various possible forms, is a model. It is indispensable because the system (the building it describes), does not yet exist, so it needs a model to manifest itself. However, this is not the only case when the necessity of creating models occurs in architecture. Another situation related to the system's unavailability, resulting in the need to build its model, occurs when a building does not exist now but existed in the past. It is exactly the case of hypothetical reconstructions. We can also extend this set to buildings once designed but never built. Although we intuitively understand simulation as an attempt to examine something that may happen in the future, in mentioned cases, our activities of creating models can also be understood as leading to the simulation but of the past [Koszewski, 2021]. After all, one of the goals of building such hypothetical reconstructions is the desire to understand how these buildings functioned or, more precisely, how they could have functioned. Additionally, in these cases, we can speak about goals related to recording and presentation because a physically non-existent building is an idea that must be materialised in the form of a model in order to, for example, share it with others.

What is a Model?

Models of historic buildings and structures, including hypothetical reconstructions of those that no longer exist, is precisely the topic we address in this book. At this point, we should answer the question, summarizing what has been said: what exactly is a model, what are its features, and why do we create it?

A model is a representation of a selected fragment of reality (which may be called a system) reduced to a form that facilitates its understanding and highlights only those features that are helpful in formulating and solving the problem we are currently facing. Such a problem may be, for example, designing a new building or desiring to reverse-engineer a non-existent building in order to study how it functioned in the past.

What follows from this definition? Among other things, models always appear as certain simplifications to facilitate the understanding of a fragment of reality. Therefore, a model will never be (and, in fact, cannot be) an attempt to create an exact replica of something that exists or existed. The choice of significant features we want to represent in our model is extremely important. The criteria for this choice depend on the purpose of building the model. In the sense of the cited definition, a map, for example, showing certain features of a territory, is a model.

Figure 11: There is a limit to enlarging a map scale, it cannot become a territory itself

Let us concentrate on the example map Figure 11. Jorge Luis Borges describes the impossibility of creating a model containing all the features of reality in his short story, mentioning an empire where the art of cartography was highly advanced. The ambition of the imperial cartographers was to create the most accurate map possible, leading to developing a map on a real scale, which means 1:1. However, this map turned out to be useless because the territory represented itself much better, and the map, being its replica, did not facilitate anything [Jorge Luis Borges, 2013].

There are many classifications of models. One of the possible distinctions is:

- Iconic models – reflect the similarity of appearance
- Analog models – show similarity in operation
- Symbolic models – showing the principle, the idea of operation

If we relate this classification to architecture, we can say that an iconic model can be, for example, a mock-up, a visualised digital model, or a drawing. An analogue model is, for example, the hanging chain models by Antonio Gaudi Figure 12 or digital simulations of user behaviour during building evacuation, as well as any agent-based modelling in a digital environment. A symbolic model can be, for example, a functional diagram of a building Figure 13.

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Figure 12: Changing chain model by Antonio Gaudi

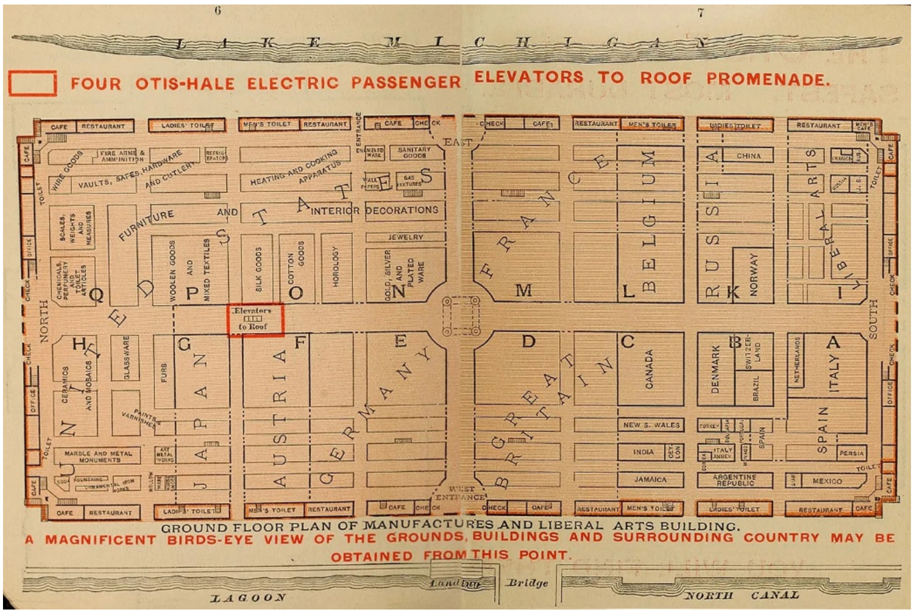

Figure 13: Floor map diagram of the Manufactures and Liberal Arts Building, World's Columbian Exposition in Chicago 1893

In the case of virtual hypothetical reconstructions of architectural heritage, which are the subject of our considerations, we are implicitly talking about digital three-dimensional models created in computer memory. It should be noted that such models, recorded as abstract digital representations, are available to users (for example, visually) thanks to computer interfaces or, in some cases, thanks to the ability to convert digital records into physical form, such as in the case of 3D printing. These models (Computer-Based Visualisation of Architectural Heritage) are subject to all the mentioned rules applicable to models understood in the light of the theory of modelling and simulation. Therefore, attempting to recreate a historical building in a way suggesting full realism will not mean creating a model. It will rather be a proposal of the author's subjective vision (or AI creation Figure 14), lacking the critical analysis resulting in defining appropriate criteria for selecting features we want to show to explain how the presented object could have functioned in the past.

Figure 14: AI-generated image of medieval city. Such an image can also be created by 3D modelling and rendering, but the level of reality does not allow for hypothesis

It is worth noting that virtual hypothetical reconstructions are usually iconic models, but with elements of analogue and sometimes symbolic models, since these last two offer effective ways to explain the performance of the object being modelled.

The Concept of Real vs Virtual vs Digital (And The Benefits of Going Digital)

The subject of this book is to discuss the methods of creating credible and plausible virtual models of the past. We may use various digital tools to achieve this goal. Firstly, however, we need to consider the terminology we are using to understand what we are dealing with and what we are doing.

So, what does it mean: virtual? The word "virtual" comes from Latin, specifically from its medieval variant. "Virtualis" was related to something that has potency or potentiality. The term evolved to mean something that has the efficacy or the essence of a certain thing without actually being it. In other words, virtual refers to the situation when the effect or experience of something is achieved without the thing itself or, more precisely, without the physical presence of this thing. So, generally, virtual means the non-physical equivalent of something. With advances in digital technologies, the term virtual was closely associated with digital representations and simulations Figure 15, which fit the mentioned descriptions.

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Figure 15: A woman wearing a virtual reality headset in a museum.

We may ask the question: does virtual nowadays mean the same as digital? Not necessarily. We can explain it, for example, using the case of the virtual image, which appears in a place where light does not reach, precisely like a reflection in a mirror (Figure 16). Indeed, there is no digital technology employed here. However, on the other hand, most virtual experiences are nowadays mediated by digital technologies.

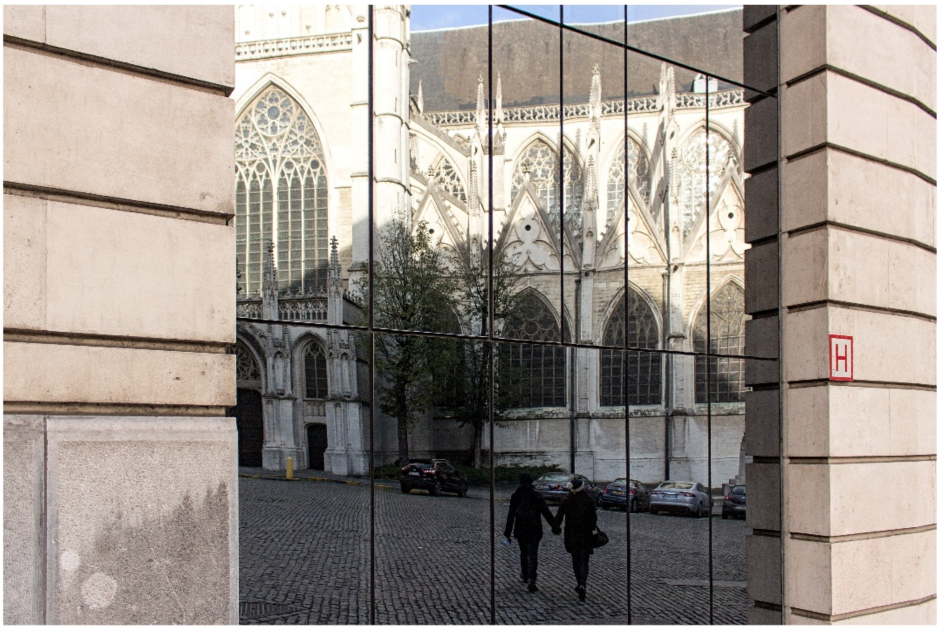

Figure 16: A reflection in a glass wall shows a virtual church, however, there is no digital technology used here.

Again, digital technologies are often used to achieve the effect of virtuality, but they refer to a much broader array of things created and stored in digital form in computer memory. All such data is encoded in binary form and is readable by computer machines, like an Excel spreadsheet, which contains data but does not attempt to invoke the effect of any physical thing (Figure 17).

Figure 17: There are many fields where digital technologies are used, but they do not invoke any virtuality

So, we already know that virtual and digital are not synonyms, even if the models we create are both virtual and digital. The second question is, why do we go digital? This seemingly obvious question is worth answering for the sake of critical thinking and awareness of the potential of the tools we are using. Digital models have features that make them particularly useful in the process of creating hypothetical reconstructions of the past. These features stem from the nature of new media. According to Lev Manovich [2001], they are:

- numerical representation
- modularity
- automation
- variability
- transcoding

The first of these features, numerical representation, is evident in the case of computer memory storage, allowing, for example, easy communication and reproduction of the model without loss of quality. This also means that new media objects, composed using numerical code, can be easily manipulated and programmed.

The second, modularity, means that media elements are broken down into independent parts or modules that retain their separate identities even when combined into larger wholes. This allows, for instance, fragmenting a model and assigning specific meanings to individual parts of it. This is known as semantic segmentation, which we will relate to later. The elements (modules) of the digital 3D

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model can be attributed to data beyond pure geometry. These can include information about the function of a given element, its provenance, or its dating.

Automation as a feature enables the acceleration of specific tasks through their algorithmisation, where we define the way model elements are created, leaving their generation and manipulation to the computer system. It also allows for creating models or their parts where we have too little data regarding a specific case, but based on analogy, we can define the rules for constructing these elements. Of course, this method, like the entire virtual hypothetical reconstruction, always carries a certain degree of uncertainty. Automation also facilitates more advanced operations like image recognition, data mining, or AI-driven processes.

Variability is a feature of digital models that allows each of them to exist in infinitely many versions, which are modifications of the original. These versions can be altered by modifying some of their parameters, and these changes are reversible, something that cannot be said of physical models. This makes digital models an ideal simulation tool, which is very useful in analysing different possible versions of the reconstructed object in the absence of specific data.

Finally, transcoding is a feature that manifests itself at the technological level (so the ability to save and exchange the model in various formats for different uses), but also at the cultural level, where the model can be a carrier of various concepts and meanings. Such flexibility facilitates exploring the model in different contexts and ways: as visualisation (Figure 18), virtual reality, and augmented and mixed reality. It can be a research tool, a means of popularisation, an element of a fictional world, or a scientifically justified attempt at hypothetical reconstruction. In some cases, transcoding can even lead beyond the digital world – based on the virtual model, we can create a physical mock-up using 3D printing (Figure 19), which will also be addressed in this book.

Figure 18: Visualisation of the virtual hypothetical reconstruction of the proto-town in Pułtusk, Poland, done by the team of Stefan Wrona. Image by Borys Wesołowski.

Figure 19: An example of transcoding possibility. 3D print of the model of the proto-town in Pultusk, Poland (shown in the previous figure), done by the team of Stefan Wrona. Model and print by Sławomir Kowal, photo by Robert Rzadkiewicz. Brown colour indicates huts reconstructed based on excavated relics, while white are pure hypothetical, based on analogies.

Features of digital models, such as variability and transcoding, allow created models to be as universal as possible. This means that after appropriate modifications, they can be used for various purposes and take different forms, in most cases retaining the possibility of being edited, manipulated, and customised over and over again. Features like numerical representation and modularity allow digital models to be informative, integrating various kinds of data. This is the kind of flexibility we need to create models of the past.

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4. Information Sources and Data Acquisition

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Introduction

On October 4, 2008, the ICOMOS General Assembly formally ratified the ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites, known as the Ename Charter. In article 2.4, it is reported that "Visual reconstructions, whether by artists, architects, or computer modelers, should be based upon detailed and systematic analysis of environmental, archaeological, architectural, and historical data, including analysis of written, oral, and iconographic sources, and photography. The information sources on which such visual renderings are based should be clearly documented and alternative reconstructions based on the same evidence, when available, should be provided for comparison".

To apply these criteria for good practice, it is necessary to distinguish between *Data* and *Information*. Data and information are fundamentally different yet interconnected. ***Data*** consists of raw, unprocessed facts or measurements that lack context, meaning, or organisation. ***Information***, on the other hand, is data that has been processed or interpreted to provide meaning or context, turning it into something useful. Data does not inherently explain its significance. It requires analysis and reasoning to extract value.

Digitising Images

What we need to start our visualisation of architectural heritage is visual data, which refers to immediate impressions received by the eyes before any conscious interpretation or cognitive processing takes place. Among them, we can mention:

- The brightness and shades of colour directly observed from the environment, influenced by the intensity of light and its wavelength.
- The direct perception of hues (red, blue, green, etc.), saturation (vividness), and tonal variations.
- The edges, contours, and boundaries of objects seen in the visual field without recognising what they are.
- Repeating or varied surface details, such as smoothness, roughness, or granularity, seen on objects.
- Initial impressions of depth from visual phenomena like overlap, size differences, or gradients before conscious interpretation.

To extract information from those raw data we need to organise those impressions into a meaningful structure able to quantify properties like location, size, distance, direction, separation and connection, shape/form, pattern, colour, tactile variation - albedo, uniformity, density, roughness, regularity, linearity, direction, brightness, deformation, reflectivity, opacity, transparency-, and many others. *Digitisation* is the process of converting the visual input captured by a machine (sensor, scanner, camera) into a *digital* organised structure, that is, as a string of discrete numeric symbols (*digits*). The most common form of digital data in modern information systems is *binary data*, which is represented by a string of binary digits (bits), each of which can have one of two values, either 0 or 1. Digital data can be contrasted with *analogue data*, which is represented by a value from a continuous range of real numbers. The word *digital* comes from the same source as the words *digit* and *digitus* (the Latin word for *finger*), as fingers are often used for counting.

Stereovision ("stereo-photogrammetry") was probably one of the first technologies to acquire 3D data from visual scenes. Such systems mimic depth perception found in nature in predatory animals with front-facing eyes. Upon comparison of images from two horizontally displaced cameras, the distance between two points that lie on a plane parallel to the photographic image plane can be determined by measuring their distance on the image if the scale of the image is known. Camera calibration is required since any lens distortion will adversely affect the depth measurements. In traditional photogrammetry, either the positions of the cameras or the position of some points that are visible in more than one image should be known.

In modern image-based algorithms for 3D estimation based on 2D geometries, matches are made between many points across many images without prior knowledge of the camera position. Once the appropriate number of matching points across all the images (the more, the better) the position of the cameras relative to each other can be estimated, and the location of any other point can be plotted in space, giving a dense reconstruction of the shape of the objects that were photographed. As the number of images from cameras at different positions increases, the time taken to assess the position of each camera becomes exponentially longer, which means that for very large image sets, the process can be impractically slow. The "Structure from Motion" approach allows for orienting huge numbers of images without any knowledge of the camera parameters, just knowing the order in which images were taken. The process begins by identifying in each photograph groups of pixels that constitute features that are likely to be discernible in several other pictures. Identified pixels are then matched across all the images in the sequence to produce a network of spatial relationships from which individual camera positions for each photograph can be reconstructed. The end result is a sparse cloud of 3D point locations that mark the successfully matched features. A much denser set of 3D points is created later by grouping the image sequence into sub-sequences of images covering similar parts of the surface and then looking for more detailed feature matches over a coarse search grid. Parameter choices, such as the minimum necessary number of matched features or the size of the dense search grid, affect the resulting number and quality of reconstructed points.

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The 3D point clouds generated via the above steps also contain the colour information from the original image pixels, as well as a degree of noise that might be due to unwanted additional objects in the photos, occasional atmospheric effects or variegated backgrounds. Such rogue features can be deleted or masked prior to matching and/or removed manually afterwards. In general, visual features are extracted without any prior information on the spatial scale or geographic location of the model it creates. This additional information should be added in a further step, either by marking points on the photographs prior to model construction or re-scaling and georeferencing the model afterwards. Recently, the same approach to 3D data acquisition uses video streams in what has been called *videogrammetry*.

Stereovision-derived methods are examples of ***passive sensors*** that detect and measure energy naturally emitted or reflected from an object or surface without actively emitting any energy itself. *Photogrammetry* is the science of taking measurements from photographs, especially to create 3D models or maps. It uses passive sensors (cameras) because it relies on capturing natural light that is reflected from the surface of objects. By taking multiple photographs from different angles, photogrammetry software can analyse the way light reflects off different surfaces and create a 3D model by triangulating the positions of objects based on those observations. This process involves passive sensors (cameras) observing how light interacts with the environment.

There are other passive-based technologies for converting structured data (images) into geometric models (information). In the case of *Reflectance Transformation Imaging (RTI)*, instead of looking for particular pixels, lighting information from the images is mathematically synthesised to generate the curvature profile of the original surface, having produced the range of shadows in the initial photographs. When the resulting transformed model is opened in RTI viewing software, each constituent pixel is able to reflect the software's interactive “virtual” light from any position selected by the user. This changing interplay of light and shadow in the image discloses fine details of the subject's 3D surface form. One of the main disadvantages of this approach is the fact that the surface reconstruction is only qualitative, and no metric information can be recovered.

Multispectral imaging is another form of passive-sensor visual acquisition method based on the detection of reflected or emitted electromagnetic radiation with wavelengths ranging between 10nm-1mm. Multispectral cameras are usually of lower resolutions than those of consumer-level digital cameras. The approaches explore multi-spectral modeling of heritage, including simple 2D-to-3D registration with common points in a geometric model produced by photogrammetric workflows. Photogrammetric tracking on pre-calibrated multispectral cameras and fringe projection systems for 3D digitisation used on the same scenes allow co-registering and projecting the multi-spectral data on 3D models of heritage surfaces, with accuracy better than half an image pixel.

Active sensor-based systems emit electromagnetic waves (laser beams, for instance) from a transmitter and capture the reflections of that wave on the endpoint.

Depending on the nature of the transmitter and the calculations on the reflected wave, we should distinguish between:

- Pulse rangefinders operate on the principle of measurement of the transit time, which is necessary for the transition of the impulse emitted from the device and its return. In international literature, they are referred to as *Time-of-Flight* or *ToF* scanners. Electronic time measurement starts during emitting, and it is stopped after reflection and return to the sensor. The speed of propagation of electromagnetic waves is 3.10^{-8} $m.s^{-1}$. Therefore, high requirements are given for the accuracy of transit time measurement. It is necessary to achieve a time measurement accuracy of 0,033 ns or less, and a distance measurement accuracy of ± 5 mm or less. Digital and analogue-to-digital timers are used for this purpose. Its resolution is generally quite low, but the general procedure is quite fast. Photonic Mixer Devices (PMD) are time-of-flight image sensors where each pixel can direct the charge from incoming photons to two or more storage sites within the pixel. The method illuminates the entire scene with modulated light, and the phase delay of the continuously modulated light is measured for each pixel to generate an intelligent pixel array that provides depth measurement without the need for scanning.
- Phase or "phase-based" rangefinders operating on the principle of measurement of ambiguity interval or phase difference resulting from emitted and returned signal. Phase-shift laser scanners emit a continuous laser beam. The range can then be derived from the phase-angle shift of the emitted and the received signal. A particular kind of phase-based rangefinders is structured light scanners, systems involving the projection of a series of parallel light strips onto an object. The light pattern can be fixed or programmable to achieve better accuracy or respond to ambient light conditions or the object's optical reflection characteristics. For instance, a modified High Dynamic Range acquisition technique can be used for recording data on shiny surfaces or for objects with strong differences in reflectivity; this could be the case of lithic objects. Based on the displacement of the stripes as viewed through a camera, the system can identify and retrieve the 3D coordinates on the surface of any object in view. The distance between the emitted and returned signal is determined from the resulting phase difference, provided that the distance must be greater than the length of the emitted modulated wave. Advantages include superior accuracy, but only at low ranges and in dark environments. This technology requires several patterns to be recorded, which may take a few seconds, hence, it is not suitable for dynamic scenes.

To cover an entire scene with measurements, i.e., to "scan" an entire scene, multiple laser shots have to be distributed over the area of interest, such as by deflecting the shots via a rotating mirror or even by rotating the entire scanner head. The precision and resolution of the resulting data point set depends on the camera

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resolution, the calibration, and the distance between the point under consideration and the rotation axis (and, therefore, its position on the image).

Additional Data on Visual Appearance

In addition to spatial and geometric data, further features can be recorded from preserved remains of architectural heritage. Colour RGB values can be assigned to each single point to facilitate navigating through the data, allowing for edge detection and region difference.

Beyond geometry, "texture" refers to features of a surface that have visual or tactile variation and contribute to distinguishing that surface from others interacting with it. In that sense, it is practical to distinguish strictly visual attributes (colour, contrast, brightness, reflectivity, opacity, transparency, etc.) from tactile features, that is, the small-scale geometry of the surface.

Texture attributes can be mapped onto the geometric model of a reconstructed surface. A surface texture is created by the regular repetition of an element or pattern, called surface *texel*, on a surface. In computer graphics, there are deterministic (regular) and statistical (irregular) textures. A deterministic texture is created by the repetition of a fixed geometric shape, such as a circle or square. Examples of deterministic textures are patterned wallpaper and bricks. *Texels* are represented naturally by the shape parameters of the specific shape. Statistical textures are created by changing patterns with fixed statistical properties. Most natural textures, like wood or stone, are statistical. Statistical textures are typically represented in terms of spatial frequency properties.

Measuring Material Properties

Visual and tactile appearance are the consequence of the particular materials the architectural elements were originally made of. Some aspects of the shape/form of particular parts are also constrained by the materials themselves and their physical, mechanical, friction and thermal properties.

The raw model should also contain this information. Obviously, beyond a mere list of the materials used and labels assigned to particular points of the model, we need to specify the detailed value of relevant parameters that may distinguish among different materials.

Physical properties are those whose particular values can be determined without changing the identity of the substance. Density, moisture content, permeability, and shrinkage are all important parameters used to characterise the various physical properties of materials.

Structural or mechanical properties of materials are the physical properties that describe how a material responds to an applied force or deformation. These properties are important for understanding the behaviour and performance of materials configuring the existing remains.

In some cases, additional material properties, like friction properties (static, kinetic, and rolling) or thermal properties (thermal conductivity, thermal diffusivity, thermal expansion coefficient, thermal shock resistance, specific heat, melting point, and creep resistance), can also be taken into account. For instance, thermal expansion is a measure of a material's tendency to expand or contract in response to changes in temperature. It is important for structural materials that are subjected to temperature variations, as it can cause dimensional changes and stresses in the material. Thermal expansion can be measured using the coefficient of thermal expansion, which is a measure of the material's expansion per unit temperature change.

Guidelines for Good Practice in Visual and Non-Visual Data Acquisition - Accuracy and Precision

Geometry and spatial properties should be correctly extracted from images of preserved architectural remains using appropriate cameras or sensors. It is important to take into account the differences between active and passive scanning because they are based on different theoretical and technological assumptions with relevant implications in accuracy and precision. In passive-sensed photogrammetry, the camera vision field determines the size of the digitizable area, which makes this method ideal when we should digitise large architectural elements or even entire buildings, a task that can be difficult or even impossible using some kinds of active sensors. Another advantage is the ease of acquiring geometrical input about the internal structure of the digitised element, such as the voids and cracks characterizing a particular wall, by taking multiple images from different angles. Nevertheless, the simplicity of usual photogrammetric equipment may be partially contradicted by the complexity of the computation required for the processing of a high number of still images. As the number of images needed for good accuracy and precision increases, the number of matching points across all the images also increases. Given that the position of the cameras relative to each point should be estimated to plot such points in a geometrically correct space, the time taken to assess the position of each point in each image becomes exponentially longer, which means that for very large image sets, the process can be impractically slow.

Active sensors, like pulse and/or phase-based rangefinders, make it possible to obtain spatial coordinates of millions of surface points at faster time rates. This is an obvious advantage when digitizing complex objects with many changes in basic curvature. Furthermore, the points cloud generated by a laser scanner has an absolute scale: each point represents the actual position of the corresponding point in space with some measurement uncertainty. Nevertheless, the amount of high-precision information generated by an active sensor system can also be considered a drawback. You require advanced hardware for processing huge point clouds with hundreds of millions of data points, and the edition of the resulting data set to check for errors in the digitizing process is more difficult than in the case of georeferenced images to be used by passive sensor systems.

Passive-sensor based systems (like photogrammetry) generate point representations with only relative scale, that is, in reference to neighbouring points, and not in relation with a unique centre of gravity. The resulting point cloud should

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scale after acquisition by aligning it with reference points obtained using an active sensor, a digital theodolite, for instance, by placing several targets in space around the object to be digitised and measuring the distances between these targets in space in advance. Then, only after image orientation, can these targets be detected on several photos from different points of view in order to locate their position in the resulting projected space. The distances between identified targets are given the same values measured in advance on the real scene.

Active sensor-based devices allow the direct measuring of a far higher number of points, which implies that photogrammetry tends to produce less accurate visual input of irregularly shaped architectural elements. For high accuracy and precision photogrammetric input, the user should be very careful with camera positioning, movement and optical settings. Errors in the proper calibration of passive sensors produce not only the impossibility of raw data acquisition but errors and bias –noise- in the acquired input.

In the case of profilometers and other equipment to measure material properties, measurement tools should be calibrated properly to ensure accurate measurements. Furthermore, in most cases, resulting values are not direct magnitudes but relative values that should be read in relation to standardised tables.

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5. Different Types of 3D Models

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The Raw Model, the Informative Model, and Raw Data

The Raw Model (RM) is a 3D model obtained using semi-automatic procedures that provides a digital version of a real object. Therefore, the Raw Model consists of three-dimensional data in the form of a point cloud or a mesh that sometimes conveys colourimetric data (through textures or vertex colours), meaning that it may also include surface information about the material and colour. The collected data is thus only metric and colourimetric and not interpretative.

The Informative Model (IM), on the other hand, is a 3D model that, in addition to dimensional (and eventually colourimetric data), presents processed information such as semantic enrichment, critical geometric analysis, historical data, symbolic analysis, etc. The Informative Model is almost always associated with one or more authors who have interpreted and created new information. Even if in the future computers might be able to interpret a raw model and produce a semantically structured model enriched with additional geometric or historical information, it will still be an informative model, the only difference is that in that case, the author of the hypothetical process of interpretation would be a machine. The two types of 3D models not only differ conceptually but also technically. The Raw Model is always discrete (e.g., point cloud or a mesh). In contrast, the Informative Model can also be described using the continuous representation method (e.g. NURBS model). The Raw model can never be continuous because in that case a critical interpretation of the geometric shape of the object would be needed (even if performed automatically by a computer it would still be an interpretation).

Raw data (RD), in our context, refers to the unprocessed data acquired from reality necessary to create the Raw model (e.g., the photos for a photogrammetric campaign).

First Case Study: The Reconstruction of the Critical Digital Model of the Roman Theatre of Urbisaglia

Here, we present an emblematic case study showcasing the different types of 3D models and raw data used. In this context, the focus is not on the specifics of the reconstruction and the work carried out but on outlining the types of data and digital models used.

The first case is a study for the virtual reconstruction of a Roman theatre located in Urbisaglia [Bassoli et. Al 2022]. The study started with the most important available source, namely the archaeological remains still present on the site. A survey campaign was then conducted, primarily using laser scanning technology. In this case, the raw data consists of individual scans and photos used for the surface colour data of the architecture. The Raw model is the 3D model of the coloured, cleaned up, scaled and aligned, point cloud representing the current state of the archaeological site. This Raw model thus becomes the main reference source for the hypothetical reconstruction of the theatre.

Subsequently, the architectural survey was completed through the critical redrawing of the plans, elevations, and sections of the archaeological remains based on the Raw Model. The architectural survey is not a Raw model but a critical representation because it contains and conveys processed information that requires the involvement of one or more authors.

The architectural survey can also be a 3D model. In this specific case, the Informative model consists of a digital model that critically interprets and communicates the ground truth data. From the survey as the main source of the ground truth and other historical sources, such as the archaeological remains of earlier theatres and reference historical texts, the hypothetical model of the Roman theatre of Urbisaglia was created. This 3D model is a Critical Digital Model as complete as possible that reconstructs the hypothetical configuration of the Urbisaglia theatre in a specific historical period.

Second Case Study: The Reconstruction of the Digital Critical Model of the Canova's Exhibition in Santo Spirito in Bologna

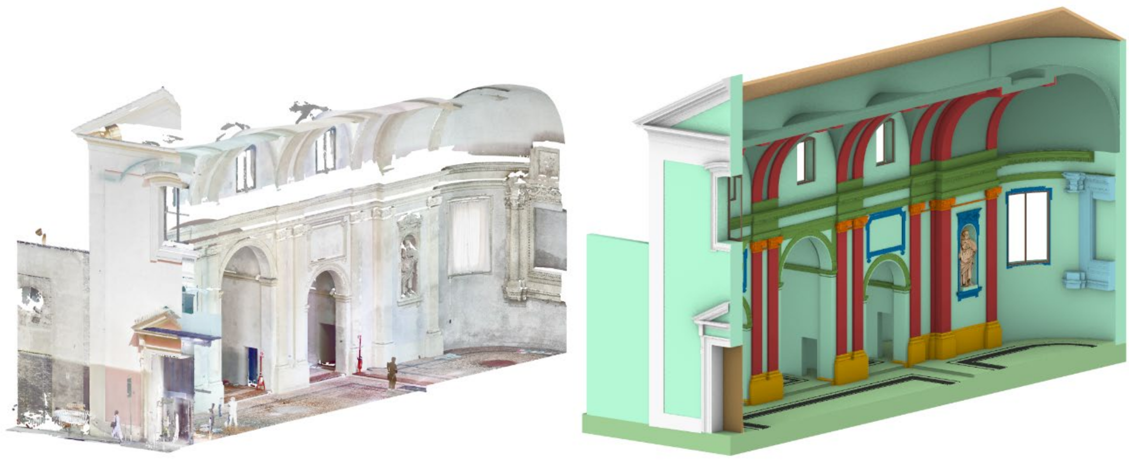

Figure 20: Spirito Santo Church hypothetical reconstruction. (Left) raw model, (Right) informative model

To understand better the differences between various types of models we present synthetically the case study of the hypothetical reconstruction of Canova's exhibition in 1816 in the Spirito Santo church in Bologna [Apollonio et. Al 2021]. This reconstruction aimed to reconstruct, as close as possible to its author's will, the event of the art

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exhibition organised by Canova when he came back from his mission in France to retrieve art stolen during the Napoleonic looting, which interested Italy in the previous twenty years.

The reconstruction started with the laser scanning and photogrammetric survey of the church that came down to us. The unprocessed scans and the photographic sets from the acquisition campaign are the raw data. The individual point clouds from laser scanning and the photos were automatically processed to produce a scaled dense point cloud and a textured mesh, these are the raw models (Figure 20). The church was then remodelled entirely with the NURBS mathematical representation method by cross-referencing historical sources. The semantically segmented rectified ideal model is the Informative model. The reconstruction of the event as closely as possible as its author's will is the Critical Digital Model because it aims to reestablish not only the configuration but also the atmosphere as completely as possible and by losing as little information as possible from the sources, while still aiming to add as little subjective hypotheses as possible (Figure 21).

Figure 21: S. Spirito Canova's hypothetical reconstruction of Canova exhibition

Master Model and Minimum Requirements Model

The master model concept proposed by Apollonio et al. [2012], was designed to establish entry requirements and validate the quality of 3D models before archiving and publication. Developed for archiving and managing 3d models from survey campaigns in the Pompeii Archaeological area, the master model aimed to minimise archival space and maximise the quality and reusability of 3D models stored. This approach ensured that only the models with the highest quality available were stored in the repository and not lower-quality models because they could have been derived from the better-quality ones. This allowed, not only to save archival space but also to set a benchmark for models uploaded by others and define the expected quality for external users, so the master model in this context was at the same time a minimum requirement model and a target quality model from which other could be derived.

Defining a target quality and setting minimum requirements of reality-based 3D models is much easier compared to informative models because they are mainly based on dimensional parameters (such as the number of polygons for geometry, the density of pixels for textures, the maximum acquisition error, etc.).

The master model concept may not be applicable to hypothetical reconstructive informative models due to the lack of an objective "best model" from which to derive others. However, the concept of minimum requirements models remains applicable and essential for maintaining scientific standards in research environments, functioning similarly to an editorial template for academic papers.

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6. The Methods of Digital Representation and 3D Modelling Techniques

Authors: Fabrizio Ivan Apollonio, Federico Fallavollita, Riccardo Foschi

The Continuous Method of Mathematical Representation

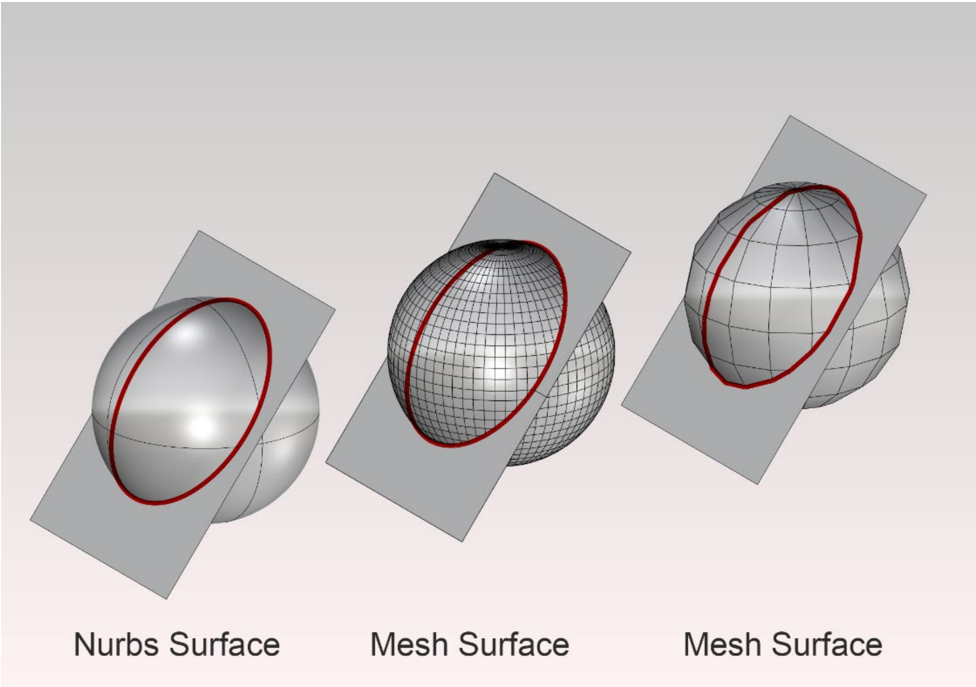

Figure 22: (left) sphere represented through a continuous NURBS surface, (right) sphere represented through a discrete polygonal mesh.

The digital representation methods can be classified in many ways, but the most important classification for the field of hypothetical reconstructions distinguishes the following two: the continuous representation and the discrete representation.

The continuous representation method describes shapes in digital space through mathematical equations in a smooth continuous manner, i.e. all the geometric properties (such as tangency, curvature, etc.) of curves and surfaces are described accurately on each point. An example of mathematical representation is the NURBS method which describes shapes through parametric equations (through the parameters u and v). This type of mathematics was born for the representation of complex shapes in the automotive and aeronautics industries and, later, was introduced in the field of architectural drawing. [Migliari, 2009].

The continuous representation method, thanks to its accuracy and precision, is generally used in technical drawing for meticulous control of the shape. Furthermore, the possibility to define the forms through curves and surfaces allows to preserve the design freedom while having accurate geometric control of the shape. In the context of digital architectural reconstructions, this method is used above all by scholars interested in studying the geometry of the architectural elements accurately, for example when studying the profiles of the classical orders, or the vaults. In these cases, the use of polycentric curves instead of ellipses, or the use of ruled surfaces instead of developable cylindrical surfaces, change the result and thanks to the mathematical representation method these choices can be carried out and controlled accurately and critically.

CAD drawing programs are generally oriented mainly toward a specific representation method; namely, they were created to absolve specific modelling tasks with tools that have a specific vocation. For this reason, in the field of digital representation, there is currently no software that is best in class for carrying out from start to finish the whole process of architectural drawing: from the initial sketch drawing to the final executive drawing, including project drawing and rendering. Thus, architects need to master many software packages in order to perform all the needed tasks. However, despite the main focus/vocation of software packages, most professional CAD modelling applications nowadays, also support the discrete representation (i.e. numerical or polygonal representation), even if it is not their main representation method of choice. This is because it improves interoperability between different software packages.

Furthermore, due to hardware and software limitations, modern graphics cards can only render discrete geometries. For this reason, for visualising a mathematical surface at some point in the visualisation process there is always a hidden or explicit step where the mathematical model is converted into a discretised polygonal model. Even when working in the interactive viewport what is visualised is not the real mathematical continuous model but its discretised version. However, the discretisation is not visible at first glance thanks to the Phong algorithm, which interpolates the luminous intensity of the various flat faces of the mesh and returns the illusion of a continuous surface. This trick, however, is revealed by looking at the silhouette or intersections between objects, which are still visualised as polygonal lines.

To help discern between the continuous and discrete representation methods, we can make an analogy with vector images and raster images. On the one hand, in raster representation, the resolution of the image is defined at the beginning of the creation process and the image cannot be zoomed-in or scaled up indefinitely without loss of quality; the same thing happens in the mesh representation; once the resolution of the surface tessellation is defined and applied, it generally cannot be increased later (at least not without complex algorithms and/or relevant manual work). On the other hand, in the vector representation and, in general, in the

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continuous representation, there is no concept of resolution and curved shapes can be zoomed in or scaled up freely without loss of quality or continuity.

To give an illustrative example, if we construct a simple sphere using a continuous method, for example through NURBS equations, we obtain a spherical surface that preserves the mathematical characteristics of the sphere at every point; in other words, it is possible to calculate the curvature or the tangent plane at any point on the spherical surface. If we cut the sphere with a plane, we obtain a curve that is a circumference (Figure 22).

Vice versa, if we construct a sphere using a discrete method, for example through a polygonal mesh, we obtain an apparently spherical surface that does not retain the mathematical characteristics of the sphere; this is because the shape is made up of a finite number of points and polygons that approximate the surface of the sphere via a polyhedron. If we cut the mesh sphere with a plane, we obtain a polyline curve that is a polygon approximating the circumference. The degree of approximation and definition of the shape is directly proportional to the number of points and polygons used in the tessellation (Figure 22).

The Discrete Method of Numerical or Polygonal Representation

The discrete representation method represents forms in space only through points, edges, and polygonal faces; a typical example is the polygonal mesh representation (also known as numerical representation). The degree of approximation of a curved surface through a mesh model is inversely proportional to the density of the tessellation. Tessellation in computer graphics is the representation of the surface using triangular faces (or even quadrangular or polygonal). The greater the number of faces and/or vertices, the better the approximation. When zooming in and looking at the mesh surface, the tessellation will always be revealed, no matter how dense it is.

As mentioned, generally, in a 3D mesh model, it is not always possible to increase the tessellation density retrospectively if the original surface from which the mesh was generated is not available anymore. And it is generally hard to convert a mesh model into its NURBS automatically because the mesh model does not have the mathematical properties such as curvature and tangency; on the contrary, it is always possible to convert a NURBS model into a mesh model because it is just a matter of placing points on the surface and connecting them with triangular faces.

Due to these characteristics, the discrete method is generally preferred, for example, in organic modelling, rendering, animation and 3D printing, where the accuracy is important only up to a certain tolerance, and the concepts of curvature and tangency are not of primary importance. There are several CAD drawing computer programs that mainly adopt the discrete representation method and are widely used in the architectural field. The reason is that this method is generally easier to handle by computer graphics because it is a method that is based on a very simple shape description: points in space and flat polygonal faces that join these points.

Furthermore, the accuracy of these applications is such that the approximation of the discrete representation method can be neglected; in the architectural construction field it is not always necessary to have a perfect geometric description of the shape and the ease of managing an approximate but sufficiently accurate description allows for various advantages: for example the possibility of accurately and immediately obtaining the executive drawings from the original 3D model, or to obtain higher quality real-time rendered images. However, in some cases where higher accuracy or control of curvature and tangency matter, these software packages do not provide a solution; thus, CAD applications based on mathematical representation must be used.

Explicit and Implicit Representation (3D Digital Representation Method)

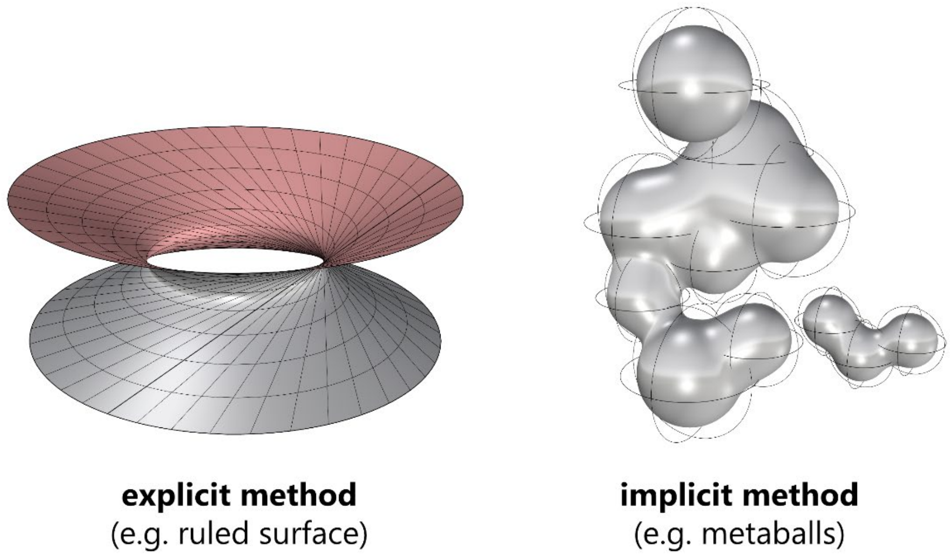

Figure 23: Comparison between explicit and implicit representation methods

In the context of 3D modelling, the terms explicit and implicit refer to the form of the mathematical functions used to describe the digital objects. An explicit function can be written in its general form y=f(x) (where y is an explicit variable), while the general form of an implicit function is f(x,y)=0 (where neither x nor y are explicit variables). If there is an explicit form there is always an implicit form of the same function, the opposite is often not possible [Pottmann et al., 2007].

In practice, explicit representation methods describe the shape directly by defining its outer boundary, while implicit representation methods describe the shape indirectly through mathematical equations or functions that define the relationship between the 3D space and the geometry of the object. Examples of models that make use of implicit representation are the metaballs or lattice models, while examples of models that make use of explicit representation are the mesh and NURBS models (Figure 23).

Explicit representation is the basis of most CAD 3D modelling applications, only a minority use implicit representation for specific tasks. Explicit representation is capable of describing xyz coordinates at every point of the surface accurately and can generate exact replicas of the geometries. However, some trade-offs come with these advantages. Firstly, a 3D model defined exclusively with explicit functions is much heavier than a model made with implicit functions because each patch of surface which concurs to the definition of the boundary of the object has its own mathematical formulation, this can cause performance challenges when working on complex models made with many surface patches. Explicit representation defines only the boundary of the objects and usually does not provide information about the inside volume. Explicit representation is the most used method in the context of virtual hypothetical 3D reconstruction because it is suitable for visualisation, data exchange between different applications, and replication of the 3D models.

Boundary Representation (3D Digital Representation Method)

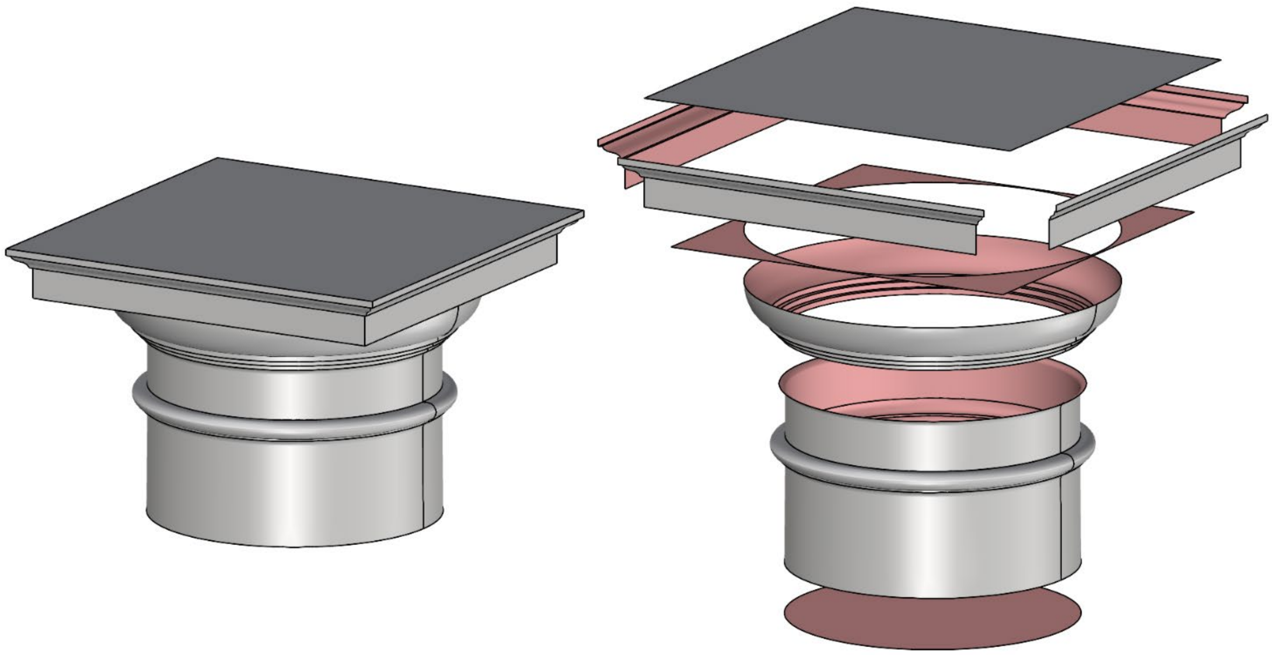

Figure 24: NURBS doric capital represented through boundary representation method. Left closed poly-surface, right model exploded into surfaces.

Boundary representation (or B-rep) is a 3D digital representation method where the 3D shapes are represented by defining their outer limits (Figure 24). Boundary representation can have slightly different meanings depending on the specific software, the references or the contexts. Sometimes, it is defined as the method to represent closed solid geometries by defining their outer boundaries, other times it also includes opened or non-manifold poly-surfaces (Grasshopper for Rhinoceros). B-reps can be both NURBS or meshes [Leary et al., 2021, p.134] but some applications assign the B-rep status only to NURBS models. In order to avoid misconceptions we refer to the initial most general definition.

Algorithmic 3D Modelling (3D Modelling Technique)

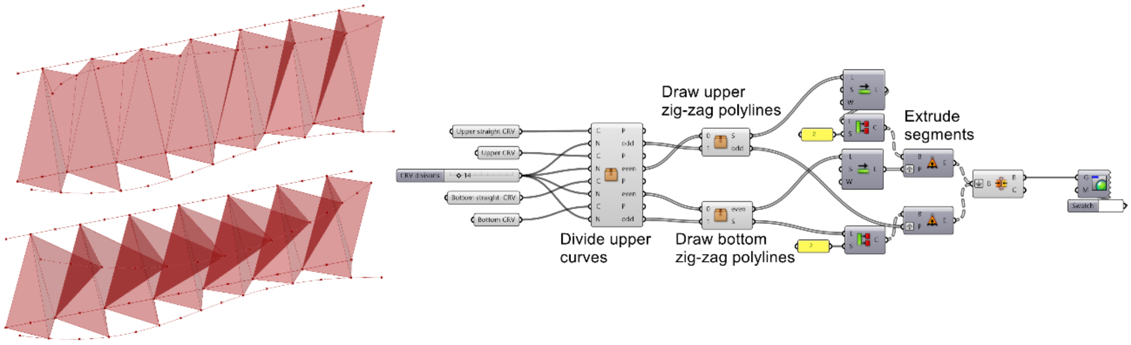

Figure 25: algorithmic modelling (Grasshopper)

Algorithmic 3D modelling is a 3D modelling technique where the three-dimensional shape is generated through the definition of an ordered set of non-destructive actions/ operations/ steps/ commands that are memorised, and each step can always be accessed and modified to update the final output (Figure 25). The actions can be in the form of strings of text, mathematical formulas, or nodes connected with wires. This approach is midway between traditional 3D modelling and computer programming. Even if someone tends to differentiate algorithmic, generative, and procedural 3D modelling, in this context, we intend them as synonymous because the distinction between them is blurry. Sometimes algorithmic 3D modelling is also used as synonymous with parametric 3D modelling; however, in this case, it is better to differentiate them because nowadays in the field of 3D modelling application, these two terms started to have specific meanings. In algorithmic 3D modelling, analogously to parametric 3D modelling, the operator can update the input parameters anytime and get an updated output automatically; but differently from parametric 3D modelling, algorithmic 3D modelling always provides access to all the steps in between, which can be changed without undoing all the latter steps.

In conclusion, algorithmic/procedural 3D modelling is a technique where 3D models are generated using algorithms/procedures and mathematical rules rather than manually creating and manipulating individual vertices, edges, and faces. It involves defining a set of rules and parameters that determine the shape, structure, and appearance of the 3D model.

Algorithmic 3D modelling offers a high level of flexibility and parametric control over the generated models. Artists can modify the input parameters and rules to quickly explore different design options and iterate on their creations. Additionally, procedural models can be easily updated or modified, making them well-suited for dynamic or interactive applications.

Boolean 3D Modelling (3D Modelling Technique)

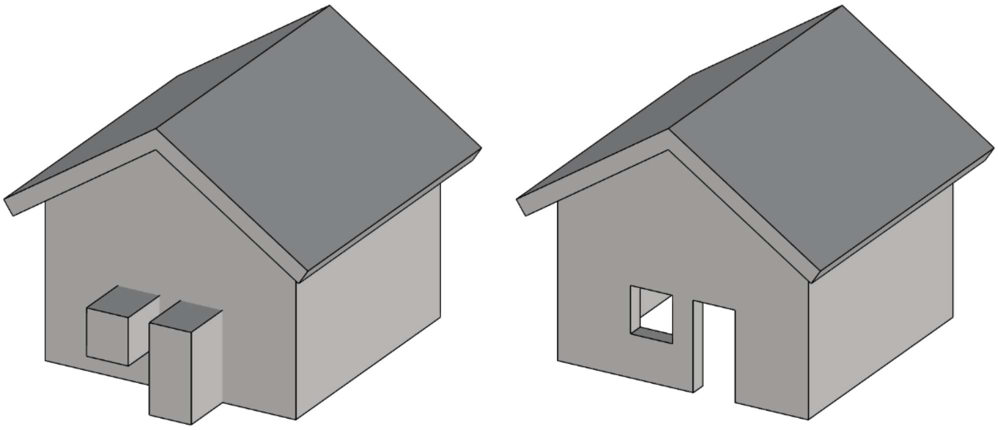

Figure 26: Boolean modelling examples. The door and window are made by subtracting two parallelepipeds from the wall.

Boolean Modelling is a 3D modelling technique where the 3D digital objects are created through the addition, subtraction, and intersection of other primitive solid geometries (Figure 26). In Boolean Modelling, the geometries must be watertight solids, however, some advanced 3D modelling applications allow the users to perform similar operations between open and closed surfaces or poly-surfaces. The naming comes from George Boole, the mathematician who theorised mathematical logic, which is the foundation of addition, subtraction, and intersections of shapes.

Digital Sculpting (3D Modelling Technique)

Figure 27: Sculpted characters and easel for paintings.

3D digital sculpting is a 3D modelling technique where the 3D shape is created by using the digital reproduction of those tools typically used by sculptors (Figure 27). 3D sculpting applications usually work with polygonal discretised geometries (meshes). This technique is a subfamily of the direct hand-made 3D modelling technique and partially overlaps with the polygonal 3D modelling technique.

Direct Handmade 3D Modelling (3D Modelling Technique)

Direct/handmade 3D modelling, in the 3D digital graphical context, is probably the most popular 3D modelling technique to generate a three-dimensional shape with a computer. It consists of generating the 3D model by using the tools provided by the software while constantly interacting with the model in the virtual viewport with the mouse and keyboard. Each change in the model is destructive, meaning that the model cannot be updated by changing the input parameters. For example, the CAD modelling of a house, the 3D mesh sculpting of a character, and the low poly polygonal 3D modelling of assets for video games can be performed through 100% direct handmade 3D modelling.

Parametric 3D Modelling (3D Modelling Technique)

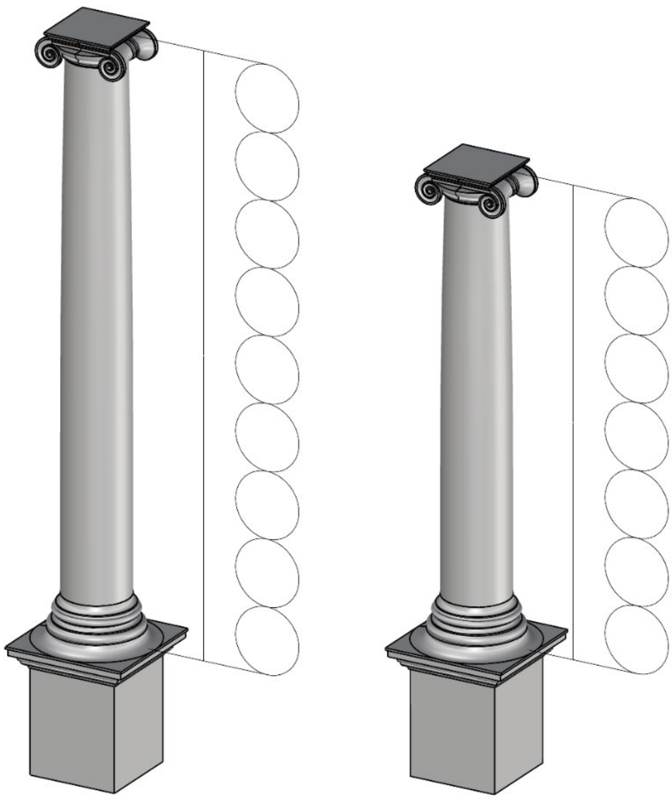

Figure 28: Parametric variations of an ionic column. The model changes automatically by changing some input parameters.

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Parametric 3D modelling is a 3D modelling technique that consists of generating a three-dimensional shape step by step while keeping some of the input parameters exposed and modifiable. This feature makes the process partially or totally non-destructive (Figure 28).

Parametric 3D modelling can be considered a subfamily of algorithmic/procedural 3D modelling, and sometimes these terms are interchangeable, however, they are not strictly synonymous. In parametric 3D modelling, it is often possible to change some of the input parameters, but the modifiable parameters depend on which of them are left exposed by the creator of the software. furthermore, differently from algorithmic 3D modelling, the procedure is not entirely (or not always) exposed/visible and accessible. Another difference is that usually in parametric 3D modelling, the users interact with the model directly in the 3D viewport similar to what happens in direct handmade 3D modelling, on the contrary, in algorithmic 3D modelling usually the users interact with the algorithm in a dedicated viewport and the 3D model is generated and visualised in a different viewport.

Reality-Based 3D Modelling (3D Modelling Technique)

Figure 29: Point cloud of the Church of Spirito Santo in Bologna. From the point cloud, it is possible to semi-automatically build the 3D reality-based model of the church in the form of a mesh.

Reality-based 3D modelling is a 3D modelling technique that starts from surveyed data and ends with the creation of a point cloud/3D model (textured or untextured) that digitally reproduces the object of the survey (Figure 29). The reality-based 3D modelling technique can be carried out with various tools and technologies (e.g., laser scanner, photogrammetry) and it can be partially or totally automated by algorithms which process the data automatically and extract spatial information onto which the model is built. Manual interaction from the user is minimal compared to the more traditional direct hand-made 3D modelling. Raw Models (RM) are always generated with reality-based approaches.

Subdivision Surface 3D Modelling (3D Modelling Technique)

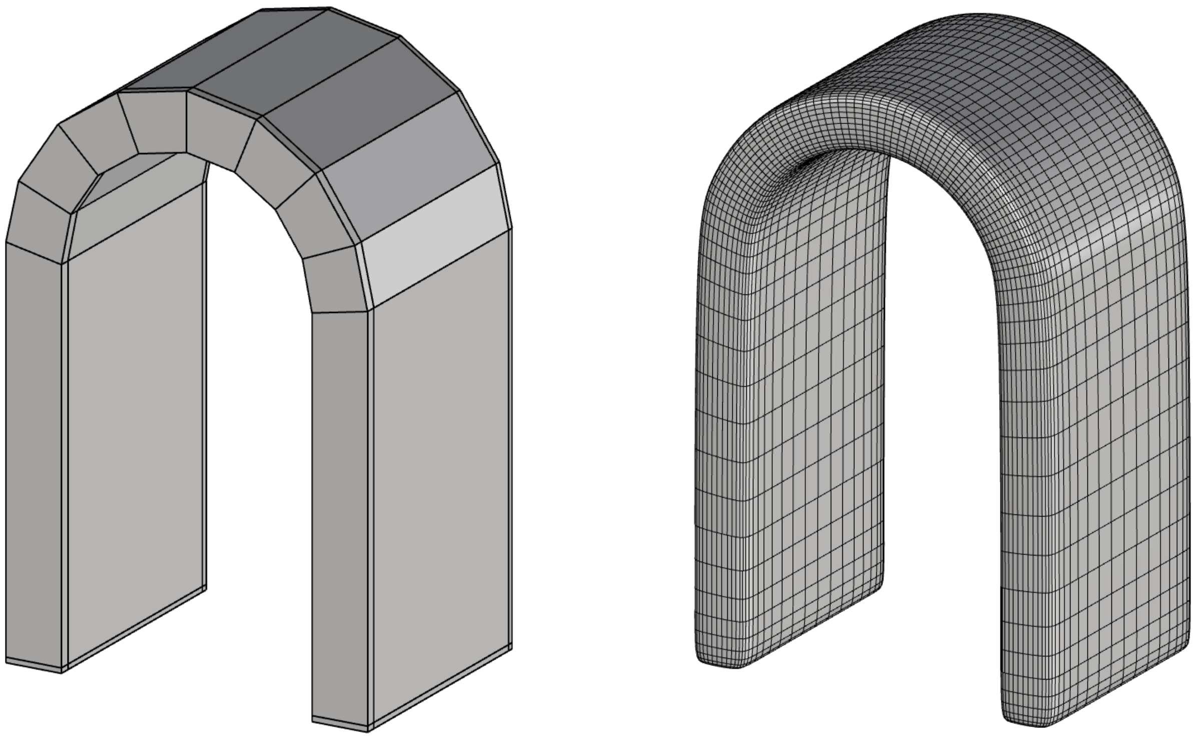

Figure 30: Example of subdivision surface model. Left, low poly control cage, right subdivided model.

In the field of 3D computer graphics, the subdivision surface (SubD) 3D modelling is a 3D modelling technique that starts from a coarser mesh, which is called control cage and converts it into a smoother geometry (a denser higher resolution mesh) (Figure 30). It is a recursive iterative process, and the resolution of the output model depends on the number of iterations of the algorithm. This modelling technique is useful for making complex organic shapes by manipulating a small number of points. This technique is usually applied to meshes, but some NURBS-based applications integrate systems capable of generating analogue results with NURBS.

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3D Digital Representation Methods and 3D Modelling Techniques Taxonomic Scheme

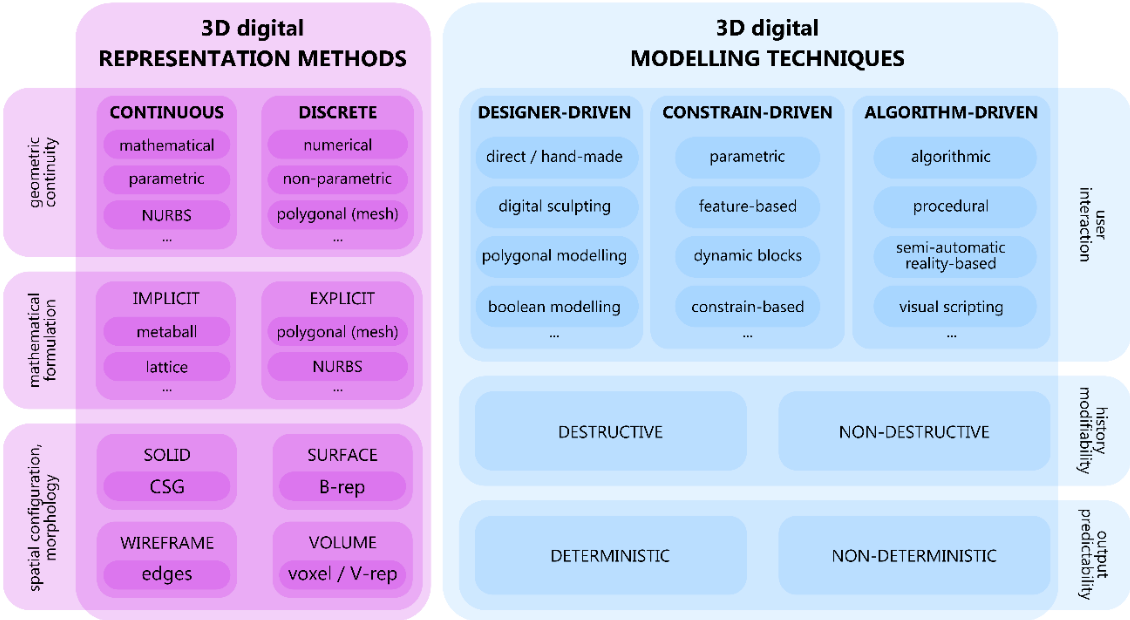

Figure 31: Simplified taxonomic scheme of the 3D Digital Representation Methods and 3D Digital Modelling Techniques [Fallavollita, Apollonio and Foschi - 2024].

The scheme shown in Figure 31 aims to clarify the relationship between the various representation methods and the 3D modelling techniques in the field of hypothetical reconstruction of architecture explained in the previous sections.

We focus on the representation methods first. They are organised into three main subfamilies, which are differentiated based on different concepts: geometric continuity, mathematical formulation, and spatial configuration and morphology.

The first family considers the geometric continuity of the models, and it is subdivided into the continuous and discrete subfamilies. NURBS modelling is one of the most known examples of continuous representation methods. The NURBS representation is mathematical and parametric because it is based on mathematical formulations that use the u and v parameters to control the shape. The polygonal representation (which generates mesh models) is non-parametric because it does not use u and v parameters, but it is based on points described with coordinates and topological relationships, which is why it is also called numerical representation.

The second family considers the mathematical formulation, and its subfamilies are the implicit and explicit representation methods. Implicit representation methods describe the shape indirectly through mathematical equations or functions that define the relationship between the 3D space and the geometry of the object; while explicit representation describes the shape directly, by defining its outer boundary (explicit functions are the basis of most CAD based 3D modelling applications, only a minority use implicit representation for specific tasks). Examples of models that make use of implicit representation are the metaballs or lattice models, while examples of models that make use of explicit representation are the mesh and NURBS models.

The third family considers the spatial configuration or morphology of the model, and it is subdivided into four subfamilies: Wireframe; Surface, Solid, and Volume. These types of representation methods consider the 3D space occupied by the model in different ways, as shown in Figure 32.

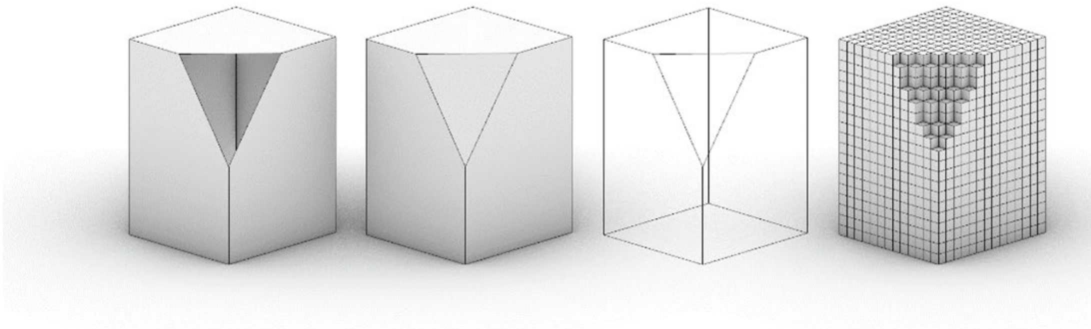

Figure 32: (From the left) surface model, solid model, wireframe model, volumetric model (image from [Münster et al. 2024]).

Of course, these subfamilies overlap with each other (for example, the implicit representation method is continuous and parametric too, and the polygonal representation is both discrete and explicit), but for clarity's sake, the scheme does not represent overlapping between subfamilies. In the field of hypothetical reconstruction of architecture, the most important representation methods to remember are the continuous and the discrete. Learning the differences between these two representations and learning when it is better to apply one or the other is of crucial importance to maximise the quality, accuracy and reusability of the results.

The 3D digital modelling techniques are subdivided into three subfamilies, which consider user interaction, history modifiability, and output predictability.

The former categorises the modelling techniques by considering how much and in what way the users need to interact with the software in order to create a 3D model, and this family is subdivided into three subfamilies: designer-driven, constrain-driven, and algorithm-driven.

The family considering the history modifiability differentiates the techniques into destructive and non-destructive. In destructive modelling, at each iteration, the model changes without the chance of changing previous operations, while in non-destructive modelling, some parameters remain modifiable up to later stages of the 3D modelling process. Examples of non-destructive modelling techniques are procedural, parametric, and algorithmic modelling, while an example of destructive modelling is direct/handmade 3D modelling.

The family that considers output predictability is subdivided into deterministic and non-deterministic modelling. The former allows the operator to foresee in advance the results of the 3D modelling process given that the inputs are known, while the latter can give different results despite starting from the same inputs. Genetic algorithmic 3D modelling, for example, is a non-deterministic 3D modelling technique because it integrates into the algorithm some level of randomness by design.

Analogy Between Traditional with Digital Representation Methods and Drawing/Modelling Techniques

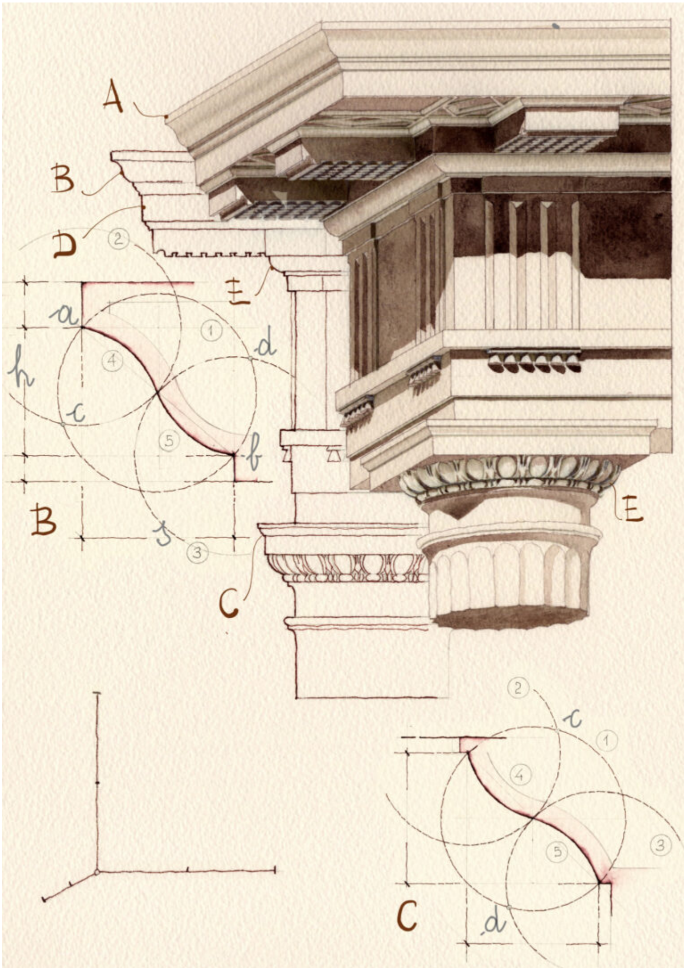

Figure 33: Hybrid drawing of the Doric order with the watercolour technique of R. Migliari [Migliari, n.d.]

3D digital representation methods and 3D modelling techniques can be mixed according to the needs. The same is true for the traditional representation methods and the traditional drawing techniques.

The traditional representation methods of descriptive geometry are: the perspective, axonometric or double orthogonal projections, and the traditional drawing techniques, for example, the watercolour for the chiaroscuro, and so on. Most of the traditional drawing techniques can be used to draw scenes or objects represented through the representation methods of perspective, axonometry and so on (Figure 33). In the same way, in the digital realm, for example, the algorithmic 3D modelling technique can be used to generate discrete polygonal meshes or continuous NURBS surfaces, depending on the workflow used.

The last issue concerns the aesthetics of these figures; probably the best way to restore expressive strength and the quality of "sprezzatura" to digital drawings is to combine traditional techniques with digital methods as in Figure 33, in which the 3D mathematical model of the architectural order was then hand coloured with watercolour.

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7. From Incomplete Remains to Complete Buildings. The processes of reconstruction

Authors: Juan Anton Barceló, Jan Salazar, Evdoxia Tzerpou

Introduction

The past has arrived to us partially destroyed, broken into pieces, incompletely preserved, modified by successive uses and constructions. The remains of prehistoric, ancient constructions and historical buildings we see here and now are not exactly how they were once in the past. It is difficult then to play with them, to teach them or to explain them scientifically. Beyond mere speculation or conjecture, we have already suggested that the task of imagining the past should be considered as the process of solving a scientific problem, starting with the empirical evidence of the ancient built structures and working backwards to the original state of the building. At each step of the reconstruction process, we should infer its previous state. Each step is then the result of a particular activity decided by an expert.

The process should be transparent and explicit so that each action transforming a previous state of the reconstruction is documented and its suitability and efficiency towards the final visualisation well established. Completing the original building from its incomplete preserved remains should be considered a formal cognitive process. As a deductive system, asserting the reliability of each step should be based on accepted rules and principles whose effects are known. In this chapter, we enumerate and explain well-known geometric rules that allow the addition of new (geometric) information to the preliminary incomplete data. Given that those procedures are well known in formal terms, and its efficiency has been proved in geometry, its application in the reconstruction process increases the verifiability of the final visualisation.

Anastylosis

The easiest and most self-explanatory logical rule for completing what appear to be incomplete is piecing together the different parts of the whole that remain.

Figure 34: Piecing together he different parts of the whole that remain. (Images created by the author using Microsoft Copilot).

Anastylosis is the technical word currently used to refer to the process whereby a damaged archaeological/architectural item is restored using only the original preserved elements. It may be based on techniques similar to those used for solving puzzles, that is, aligning pieces by minimizing the distance between their adjacent regions. In other words, based on statistically and geometrically based matches.

The automated reassembly of broken sherds relies on finding equivalent fractures on faces to be joined. According to Papaioannou et al. [2017], the reassembly is governed by 4 principal rules:

- A fragment can be linked to as many other objects as the number of its borders marked as broken.
- The bond between two fragments is unique.
- Fragment pairs that have similar features (shape, colour, texture) must be favoured.
- Fragments that do not belong to a valid reconstructed object must be isolated.

Digital anastylosis can be logically formalised in terms of an automatic process involving the identification of fragments from a broken entity, the search for corresponding parts within a fragment collection and finally, the clustering and pose estimation of multiple parts that result in a representation of (partially) reassembled objects.

In general, this is a three-stage process involving:

- Classifying fragments
- Detecting the borders of each fragment,
- Aligning corresponding borders of different fragments

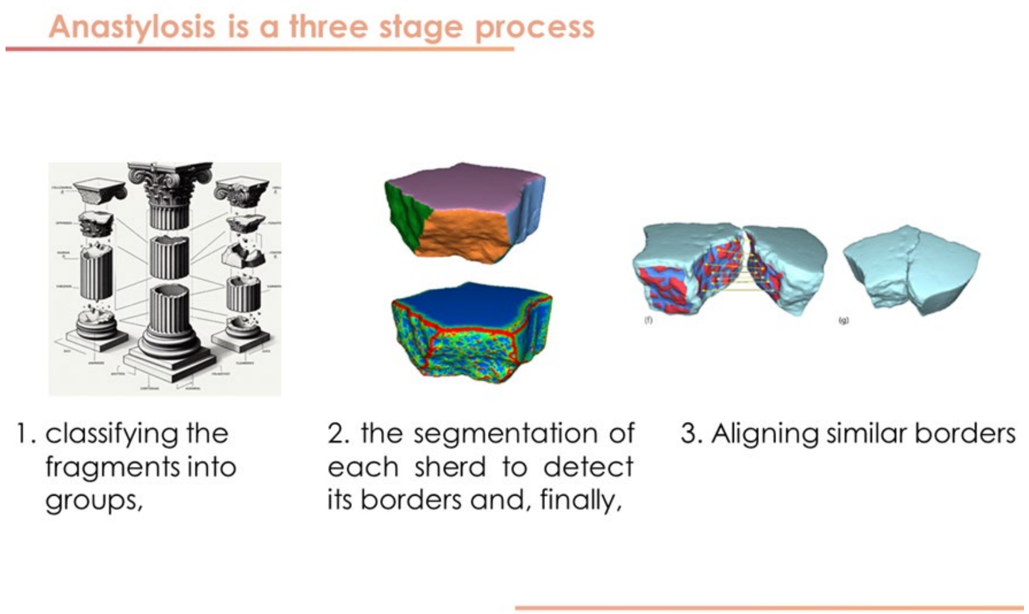

Figure 35: The three stages of the digital anastylosis task

Fundamental for the correct matching of preserved pieces is the very idea of fracture surface. It refers to the surface that forms when a material breaks or fractures. In the context of refitting elements of a broken ancient column or architectural element, understanding the fracture surface is crucial for accurately reassembling the pieces. Different types of breakage or building collapse produce characteristic features on the surface of broken fragments. By carefully examining and describing the fracture surface, archaeologists and restoration experts can better understand how the object was damaged and how its pieces fit together.

To detect fracture surfaces, we should partition a 3D object into multiple regions or segments, each of which corresponds to a distinct part of the object or its surface. In the context of fracture analysis, the goal of 3D segmentation is to isolate the fracture surfaces and borders from the rest of the object so that they can be analysed in detail.

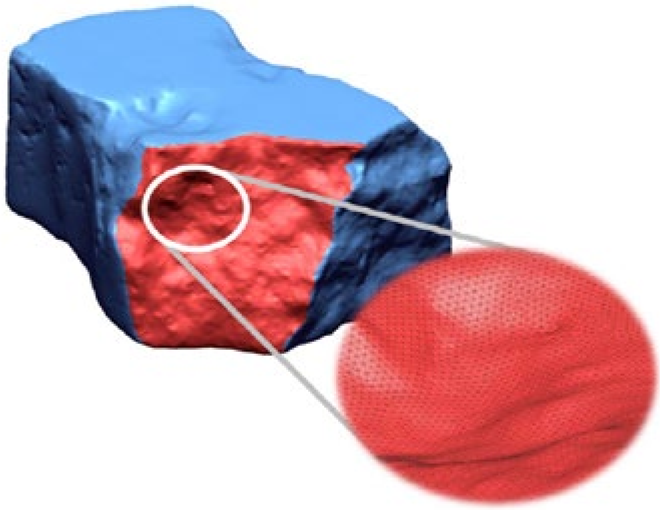

Figure 36: Characterising the fracture surface of a preserved fragment

We finally arrive at the final step of the anastylosis process: piecing together broken pieces. To join fragments and reassemble the whole entity they come from, we need to look for those fragments whose fracture surfaces coincide. In the process of finding adjacency fragments, the essence of comparing all fragments one by one is an iterative calculation in which the feature matching degree is obtained, and if the matching degree is greater than a certain threshold, the two fragments containing the two sets of features can be judged as adjacency fragments.

Automatic methods compute the reassembled position of each fragment by identifying corresponding geometric or appearance features between different fragments. Hence, the crucial step is to provide a robust yet expressively powerful shape descriptor to identify matching features coming from different fractured regions. A subjective, verbal description of the fracture surface is not enough, nor is a simple geometric description of its two 2D contours. We need a full 3D characterisation in terms of the Fracture Type, the Textural Features of the related fracture surface, and its spatial pattern and alignment. Additionally, we can also consider the effects of Surface Energy and the Surface Mechanical Properties.

Geometric completion

When preserved fragments are not enough to re-create the original architectural element those fragments may come from, we need additional information about the element. This is the usual way in art restoration, where existing gaps in a painting can be smoothly filled with information from preserved areas of the image. That is to say, it is a visual completion of what has remained based on hypotheses of the original visual appearance of the whole picture. This is referred to as image inpainting. This is a sophisticated process that exemplifies the application of visual reasoning in art restoration. Empty areas in an image, those that have lost painting traces, can be filled

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with details coming from well-preserved areas of the same image. That means existing information is extended to complete the painting.

3D completion methods follow the same approach using advanced techniques to infer the missing parts of some built structure to what has been recognised as "incomplete", adding the necessary geometry and ensuring that the missing information seamlessly blends with the existing one.

This approach combines principles from computational geometry, statistics, and machine learning to extract meaningful patterns, shapes, and relationships from available incomplete geometry. In practice, geometric inference involves estimating underlying surfaces, reconstructing shapes, identifying symmetries, and determining spatial configurations in the presence of noise and/or incomplete data. The techniques often involve algorithms for clustering, fitting, interpolation, and regularisation to derive accurate and robust geometric interpretations.

Architectural heritage completion is based on the assumption that architectural elements typically have a specific geometric structure or pattern that can be used to predict missing parts. The process of geometric inference involves analysing the shape/form and structure of the remaining parts of an architectural element and using this information to make logical deductions about the missing parts. It can be done manually by a human expert or automatically using computer algorithms. This problem is inherently multi-modal since there can be many ways to plausibly complete the missing regions of a shape/form. It leverages mathematical models and algorithms to predict the shape, structure, and spatial relationships of the absent components.

The simplest method for shape/form completion is interpolation. It coincides exactly with inpainting in fresco or mural restoration in that it is an operation of filling the gaps with information coming from neighbouring areas. In mathematics, interpolation is a type of estimation, a method of constructing new data points within the range of a discrete set of known data points. Essentially, it involves constructing new data points within the bounds of a discrete set of known data points. The objective is to predict the values of an underlying mathematical function at intermediate points. Functions used for interpolation are designed to provide a smooth transition between the known data points.

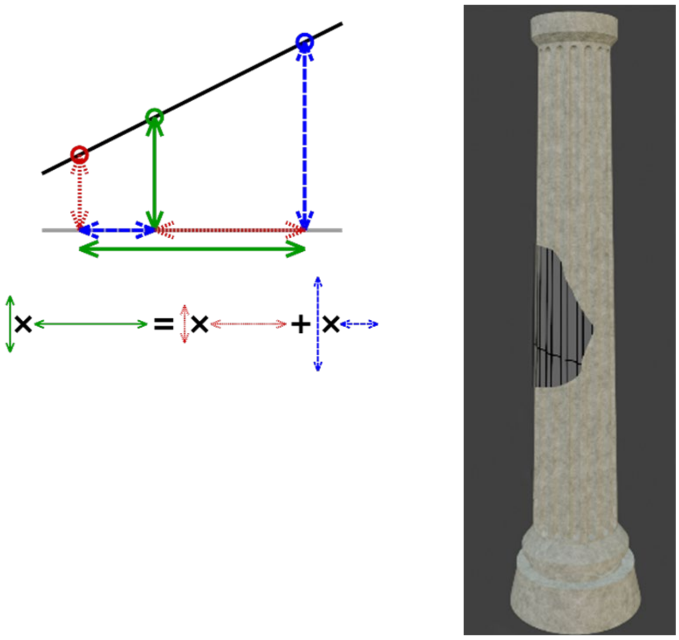

Figure 37: Geometric interpolation

The primary distinction between linear and non-linear interpolation lies in the nature of the function used to perform the interpolation. In linear interpolation, the function used to estimate the unknown value is a straight line between two known values. Non-linear interpolation involves using functions that are not straight lines to estimate values between data points. These functions can vary in complexity from simple linear interpolations to more complex forms like polynomial or spline interpolations, depending on the number of curves and changes in direction of the object's contour.

Interpolating the 2D contour of a complete original architectural element can be visualised as drawing a smooth curve that passes through a set of points on a graph. When the sinuosity of the object's silhouette is high, we need polynomial or spline-based interpolation methods. In the first case, a polynomial is fitted to the entire set of data points. In the second case, we can fit piecewise polynomials (usually cubic) between each pair of data points. These polynomials are constructed in such a way that they not only pass through the data points but also ensure smoothness at the joins (the points where the polynomial pieces meet).

Once the 2D contour of the complete architectural element is known, and its geometry can be represented by an appropriate 2D or even 3D function polynomial of system of equations, we can overlay the contour of preserved fragments and infer what it is missing for the complete shape. Illustrative examples have been published by Kurdy et al. [2012] and Giovannini [2020], among many others. We need to know the correct positioning of the preserved fragment, and then some lines can be interpolated, joining the contours of different fragments positioned at different distances. Such positioning is usually carried out in terms of size or scale comparison; once we know the shape contour, we can look for the location within this contour that best coincides with the size of the existing fragment.

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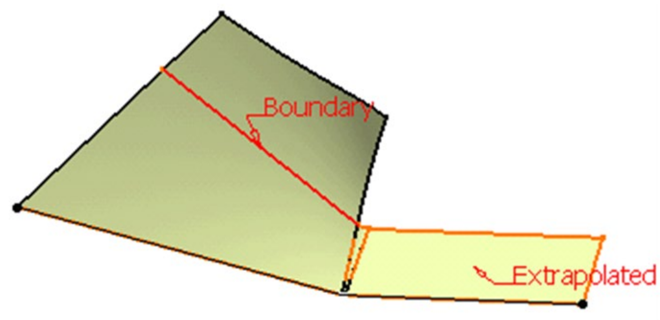
Beyond 2D contours, we can interpolate surfaces. Surface interpolation is a technique used in computer graphics and mathematics to estimate the values of a surface at points between known data points. It involves creating a smooth surface that passes through a given set of data points or vertices. This smooth surface can be represented mathematically using more complex functions than in the case of 2D interpolation. When the architectural element is better represented using a surface or a volume, for instance, a vault, we can use surface reconstruction methods to visualise the preserved parts of and complete the firm of the missing parts.

Another method for geometric completion is extrapolation. In human experience, when we project, extend, or expand known experience into an unknown domain, we talk about "extrapolating" a situation. In mathematics, extrapolation is a type of estimation based on estimating a value beyond the original observation range based on its relationship with another variable. Image extrapolation extends pixels beyond image borders. In a geometrical context, it involves extending or projecting a geometric pattern or relationship beyond the observed data points. It is like continuing a trend or pattern into areas where you don't have direct observations. Mathematically, geometric extrapolation often involves using algorithms that predict new vertices or surfaces by analysing the curvature, direction, and distribution of existing points. It is a much more challenging task since there is much less information available; while the boundary of the missing region is known in interpolation methods, in image extrapolation, we only know one border. We cannot extend a given information to infinity! This less-constrained problem means the method needs to extrapolate both textures and structures in a convincing manner.



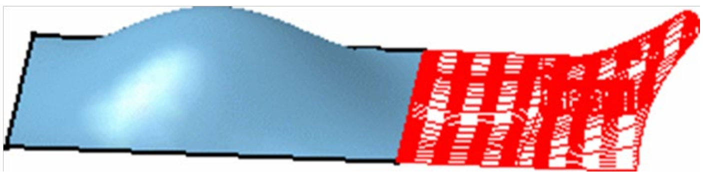


Figure 38: Geometric extrapolation

When reconstructing surfaces from a set of points, geometric extrapolation helps to fill in gaps, creating a continuous surface that aligns with the known data. A classical geometrically based method for 3D polygonal extrapolation is *extrusion*. This is a geometric operation where a 2D shape is extended along a specified path to create a three-dimensional object. This technique transforms a 2D contour into a 3D shape by adding a third dimension. For example, extruding a circle along a straight line produces a cylinder, while extruding along a curved path can create more intricate shapes like pipes or handles. The extrusion process typically involves defining a 2D point of departure and a path along which this shape will be extended. The resulting 3D object maintains the cross-sectional properties of the original 2D shape while adopting the dimensional characteristics defined by the path. This can be achieved using various software tools and algorithms, ensuring that the extrusion maintains geometric continuity and desired properties like thickness and smoothness.

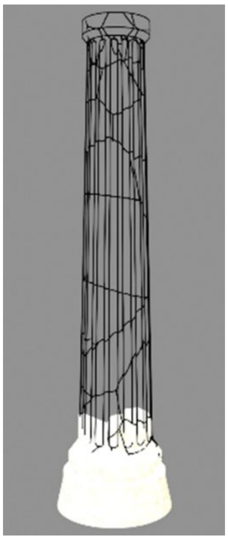


Figure 39: Completion of a fragmented column by extrusion

In some ways, extrusion can be equivalent to 3D printing. It allows the fast prototyping of different design iterations and modifications to walls and living spaces, allowing for rapid testing and evaluation of various architectural patterns and their impact on space usability and aesthetics. The resulting 3D models can be used for functional testing, such as assessing the structural integrity of walls and other elements under different conditions. This helps in understanding the visibility and performance of various architectural patterns, enabling simulations of environmental factors like lighting, ventilation, and acoustics within living spaces, helping architects optimise design for comfort and sustainability.

Extrusion was used in the early days of Virtual Archaeology to re-create building structures from floor plans by extruding the 2D layout upwards to form walls and volumes. The 2D initial floor plan -determined by the architectural/archaeological survey documentation of the building's original foundations- determines the plan or cross-section of the final extruded geometric model. A line-segment marks the starting and ending points of the extruded form in space. The reconstruction algorithm, in its simplest form, works as follows. The scanned exterior geometry is extruded by a uniform thickness to the inside of the to-be-reconstructed element to create the interior geometry; by connecting the newly created interior and existing exterior, a manifold mesh is formed and its resulting material volume can be calculated; the process is iteratively repeated until the resulting material volume meets the desired target material volume, within a given margin of error between the current volume and the target volume; the wall thickness is continuously refined until the algorithm converges. To avoid geometric overlaps while offsetting the exterior, the manipulation of a distance field can be chosen over creating an offset along the vertices' normal direction. Canciani et al. [2013] present an updated overview of how to integrate geometrically modelled sections and profiles of 3D scanned architectural elements, represented using line segments and/or circular arcs linked to their related extrusion path to create a 3D model of what had probably existed but has not been preserved until today. When the element to be reconstructed has a complex shape and is made of many different individual elements, the construction of a three-dimensional model will rely on a sequence of many nearby sections.

Modern 3D modelling software allows the possibility of setting parameters to determine whether a section or profile represented using B-splines or any other parametric surface method can be extrapolated to reconstruct a complete surface (NURBS). Kelly & Wonka [2011] have introduced a methodology where the concept of a generalised extrusion is applied on a building through a set of profiles. Once the extrusion has been applied, the result is a complete mass model for a new building, which can be enhanced with elements such as windows and doors [Moyano et al., 2022].

The limitations of extrapolation and extrusion to reconstruct ancient objects and buildings are pretty obvious, as there is no way to infer from the observed remains the distance in 3D space that the original 2D shape should be moved. From a 2D floor plan or a cross-section we cannot deduce the height of a wall, nor how an unknown roof may have closed that building. Added ornaments and construction imprecisions often lead to irregularities.

In some cases, the intrinsic uncertainties of geometric extrapolation can be reduced. This is especially true in the case of axially symmetric objects, like wheel-made pottery containers or cylindrical columns, which are rotationally symmetric. Many architectural elements, such as windows, doors, and arches, have a symmetrical shape that can be used to infer the missing parts. For example, if only half of a window is present, the missing half can be inferred by reflecting the remaining half across a vertical axis of symmetry. In other words, a fragmented architectural element can be recreated in terms of the digital twin of the existing building features.

Symmetry is a powerful psychological signal for human visual perception, and the computer vision field has also discussed the computational benefits of symmetry. If one can get the information about the symmetry of an object or architectural element, that information could be used to replicate portions of the object until completing it [Jain et al., 2023].

Figure 40: completion by symmetry (image generated by the author using Microsoft Copilot)

It is important that there are different kinds of symmetry, and each one can be associated with a different method of shape/form completion:

- Reflective symmetry occurs when one half of an object or shape is a mirror image of the other half. Some monuments, the Taj Mahal for instance, show reflective symmetry along a central axis, where the two sides of the main structure are mirror images of each other.
- Rotational symmetry exists when an object looks the same after a certain amount of rotation around a central point. It is also referred as inversion symmetry: it occurs when every point of an object is mapped to an opposite point through a central point, creating a mirror image. Medieval Cathedrals Rose Windows usually exhibits 2D rotational symmetry, where the circular design looks the same after rotations of certain angles around the central point. The dome of Florence Cathedral exhibits 3D inversion symmetry where elements on one side of the central point are mirrored on the opposite side.
- Translational symmetry occurs when an object can be shifted (translated) along a certain direction and still look the same. A tiled floor pattern that repeats periodically in horizontal and vertical directions.
- Glide reflection symmetry combines a reflection over a line with a translation along that line. Some Mayan temple carvings show glide reflection symmetry, where motifs are reflected and then translated along a line, creating a continuous and dynamic visual effect.
- Radial symmetry is a type of rotational symmetry where the object is symmetric about multiple axes passing through a central point. Rome

Pantheon's dome exhibits radial symmetry, with the coffered ceiling panels arranged symmetrically around the central oculus.

- Scale symmetry occurs when an object retains its shape after being scaled (enlarged or reduced) by a certain factor. Fractal patterns, where similar structures repeat at different scales. Spiralling minaret in Muslim architecture usually exhibits scale symmetry, as the structure maintains its shape while gradually decreasing in size towards the top.
- Helical symmetry combines rotational symmetry and translational symmetry along the axis of rotation. Muslim minarets also exhibit helical symmetry, with its spiral ramp combining rotational and translational symmetry as it winds around the central axis.
- Spherical symmetry occurs when an object is invariant under any rotation around its centre. The Globe Theatre, London, although not perfectly spherical, has a design that aims for spherical symmetry, allowing for an evenly distributed view of the stage from all angles within its circular structure.

In the case of 3D form completion, we can also use the external contour to reconstruct the 3D external and internal surface, provided such contour is parallel to the symmetry axis.

Also based on the idea of symmetry, we can convert complete a simple 2D image adding depth just by rotating the 2D contour. In geometry, a solid of revolution is a three-dimensional object that is formed by rotating a two-dimensional shape around an axis in three-dimensional space. The resulting solid is called a "solid of revolution" because it is generated by revolving the original shape around the axis. The axis of rotation can be any line in three-dimensional space that intersects the two-dimensional shape being rotated. The most common axes of rotation are the x-axis, y-axis, or a line parallel to one of these axes. The shape of the solid of revolution depends on the shape of the original two-dimensional figure and the axis of rotation. For example, if a circle is rotated around its diameter, the resulting solid of revolution is a sphere. If a rectangle is rotated around one of its sides, the resulting solid of revolution is a cylinder. If a more complex shape, such as a parabola or a sine curve, is rotated around an axis, the resulting solid of revolution can have a more complex shape as well.

This approach to geometric completion derives from the classical Pappus centroid theorem relating surface areas and volumes of surfaces and solids of revolution: the volume V of a solid of revolution generated by rotating a plane figure F about an external axis is equal to the product of the area A of F and the distance travelled by its geometric centroid. The condition of rotational symmetry allows researchers to assume a coherent final point in the extrapolation procedure, given the necessity to close the volume defined by the surface of revolution. Once we prove the incomplete element may be considered a part of a revolved surface, it is possible to compute the approximated axis of revolution. By rotating about its axis of symmetry a long enough segment of the longitudinal profile, we obtain a virtual "volume of revolution" that easily completes the shape of the container introduced by the preserved fragment. The set of points through which the longitudinal profile of the fragment rotates, define the geometric model of the reconstructed virtual object. Jain et al. [2023] show how the rotational Symmetry of columns can be used for a semi-automatic approach to solving the problem of incomplete data due to occlusion and insufficient coverage in surveying symmetrical architectural objects.

Although this approach is a promising direction, there are still some drawbacks:

- The original element (a wall, a column, an arch, etc.) may not be a perfectly symmetrical entity.
- The element itself can have experienced slight deformations because of the ancient breakage or deformation event, or it experienced successive alterations from its original deposition until the moment of its reconstruction: its sections are probably not exactly circular, or maybe they are not perfectly concentric to each other.
- Surfaces of the preserved incomplete element may have been made from a coarse material, deteriorated with time and weathering, and having lost their original geometric properties; different axially symmetric features in pottery are probably not coaxial.

Analogical Recreations

In too many cases, the number and size of preserved fragments and remains of ancient buildings and constructions will not be enough to restore the original shape and visual appearance of the building. Furthermore, it seems possible that the number of fragments and the doubts about their correct positioning do not allow the application of shape/form completion methods. In those circumstances, there are still some possibilities for the objective reconstruction of the original construction: comparing badly preserved remains with a well-preserved *similar* object. It is an example of case-based reasoning.

Analogy is a type of reasoning involving resemblance and similarity between different elements to better understand or explain them [Keane 2012, Godden and Grey 2021]. It involves finding similarities or relationships between pairs of objects. An analogy is composed of two elements: the target and the source.

- The target is the concept that the analogy seeks to clarify or explain. In our case, they are the fragments to be reconstructed.
- The source is the better-known of the two elements. In our case, it is a well-known, well-preserved ancient construction (or an image/drawing/model of it). We use it as a point of reference for understanding the target by drawing parallels and highlighting similarities.

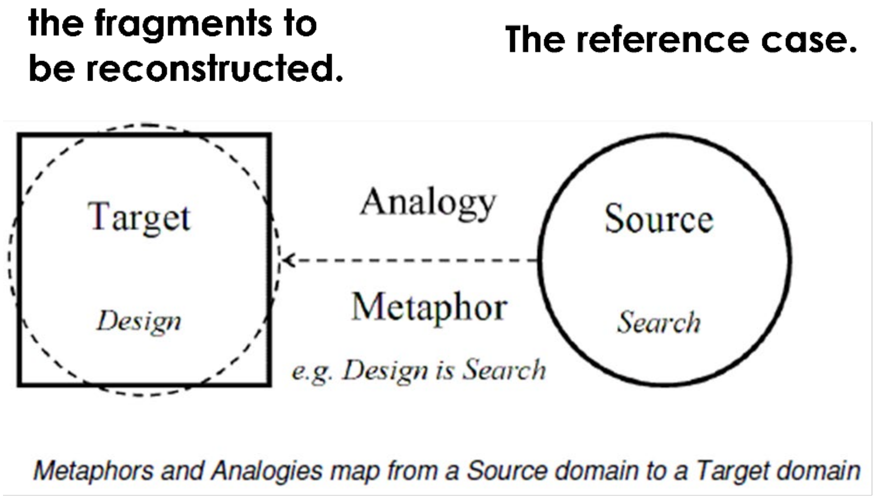


Figure 41: analogy

Since the early days of Edward Freeman [1846], or even before, analogy has been used in architectural restoration to establish a correspondence or similarity between two different pairs of objects or concepts, often based on shared relational patterns. For example, if a ruined building had a distinctive archway or vaulted ceiling, and it has been found broken or altered, it would be re-constructible based on an analogy with another well-preserved building to which it resembles. On the other hand, if the ruined building was originally constructed during the Gothic period, knowledge can be transferred from other Gothic buildings in the region or in other parts of the world. Here, resemblance is established in terms of style. By studying other buildings with similar style, it may be possible to gain insights into the design principles, construction techniques, and decorative motifs that were used during the Gothic period. These insights can be applied to the reconstruction of the ruined building, helping to ensure that the new structure is faithful to the original design.

The two main types of analogies used are:

- Direct Historical Analogies: Archaeologists compare the archaeological evidence with historical or ethnographic records from the same cultural tradition or geographic area. For example, structures from a well-documented historical period in a region might be used to interpret similar, older structures from the same area.
- Cross-Cultural Analogies: When direct historical analogies are not available, archaeologists may compare their findings with ethnographic or historical data from different cultures that are considered to have similar environmental, technological, or social conditions. This is more common for prehistoric or otherwise undocumented cultures.

Architects, archaeologists, and experts in Cultural Heritage have been using analogies intuitively to understand past remains by relating them to familiar buildings and constructions. This process has traditionally relied on the wealth of personal experiences and individually acquired knowledge, often without a systematic approach. Such analogical judgments are then influenced by the individual's unique context, emotions, and cultural and professional background, which is what imposes subjectivity in the comparisons. On the contrary, computational systems use formal algorithms to generate and apply analogies, relying only on structured data and predefined rules [Gentner and Forbus 2011, Mitchell 2021, Jiang et al., 2022]. These systems depend on explicit representations of knowledge, such as databases and ontologies, to draw analogies. The results may be less flexible as they are constrained by the algorithms and data they were programmed with. Once an analogy is generated by a system, it might not easily adapt to new contexts without reprogramming or additional input data. The advantage is that we can verify the quality and relevance of the resulting reconstruction because it depends only on the quantity and quality of the data they have used.

Analogical reconstruction is based on the existence of resemblance, and it is important to avoid subjectivism when affirming “similarity”. It is a measure rather than a characteristic: the similarity between two objects increases with the number of common features and decreases with the number of distinctive features [Tversky 1977].

When looking for well-preserved ancient buildings “similar enough” to the ruins we intend to reconstruct, it is important to distinguish between attribute-based and relational similarity because they can lead to different results and have different applications. *An attribute is a characteristic of an entity, whereas a relation is a connection between two or more entities. In logic, we can define an attribute as a predicate with one argument and a relation as a predicate with two or more arguments. Attribute-based similarity is based on the comparison of particular features, assumed to be independent among them, and it involves finding the* same physical properties between elements. Relational-based similarity, on the other hand, is based on the existence of something connecting the elements being compared. For example, if we are comparing two buildings, we might look at their *functional* relationships (the *same* activities took place in them), *temporal* (both are contemporaneous) or *spatial* (both are at the *same* location). If the two buildings were erected for the same purpose at the same place and in neighbouring locations, there is some similarity between them, even in case they are dissimilar in shape/form or in visual appearance. This leads to a distinction between attributional similarity and relational similarity. Two things, *X* and *Y*, are *attributionally* similar when the attributes of *X* are similar to the attributes of *Y*. Two pairs, *A:B* and *C:D*, are relationally similar when the relations between *A* and *B* are similar to the relations between *C* and *D*. Attribute-based similarity might be more appropriate for comparing physical objects such particular architectural elements like walls, arches or windows, while relational similarity might be more appropriate for comparing complex buildings.

Similarity should be always calculated with respect to a particular subset of attributes or relations because the selection of attributes and relationships factoring the calculation may change with the context. To solve this “selection problem” we suggest distinguishing a minimum of six different fields or domains to enumerate descriptive features of architectural heritage elements: *size, shape/form, visual* *appearance (colour, texture), mechanical properties, spatiotemporal location*. That is, two architectural elements can be similar in size, but not in shape and be, even, dissimilar in colour or texture. Two elements can be similar in spatial location (they can be at the same position, or very near), and they can be dissimilar in time (different moments of construction). In any case, we should take into account that similarity can be calculated over both perceptual and functional attributes, and over abstract features or relation.

Template matching

Template matching is a high-level machine vision technique that identifies the parts on an image that match another image used as a reference ("template"). The idea is then to compare the "image" of the fragments with the template "image" of the known case and look for matches in between. If there is a match, then the template is used to complete the missing parts in the input.

The key question is how to match source and target, that is, the task of finding correspondences between present remains and a referential case. Imagine we have some images of the present ruins of an ancient church, and a series of images of churches of different times. Feature matching refers to finding matching attributes and correspondences between two similar images, based on a search-distance -similarity-algorithm (see last section on analogy). The process can be divided in two stages: the first stage includes feature extraction such as points, lines, edges, corners and regions on each image, which can be linked to descriptive properties in the form of architectural features. The second stage corresponds to the search for homologous points, lines or regions between source and target. The idea is, then to analyse the topology of data in source and target, to detect common feature patterns, and matches with features within localised patterns. The accuracy of matching features depends on the similarity, complexity, and quality of the image. In addition, feature selection plays an important role.

It is important to take into account that the raw geometry of the preserved remains should be cleaned and pre-processed to remove any noise, outliers, or artefacts that could affect the template-matching process. This can include removing redundant points, smoothing the surface, or normalizing the point cloud. It is of topmost importance the scaling of both target and source. When looking for matches between the existing element and a meaningful template, it is important to ensure that both are in the same scale and size

There are different ways to achieve this. One approach is to normalise the image of a fragment or preserved element and the image of the well-preserved building used as a reference (template), in such a way that they have the same scale and orientation. In that sense, the centroid and principal axes of the fragment and the reference building should be aligned, or the fragment should be enlarged or reduced to match the size of the building used as the template. Another approach is to use a reference object of known size or scale as a guide to ensure that the fragment and the complete shape are in the same scale. Debailleux [2015*]* shows an interesting example based on the calculation of statistical descriptors between pairs of pictures of wooden frame structures. The fractal dimension, the Hausdorff distance and the geometrical ratio are evaluated and then combined as a single original parameter, facilitating comparison of various structures, notwithstanding any modifications which may have been made.

After feature detection and description follows the feature matching. This second stage in template-based reconstruction refers to the problem of determining the parts of an image to which parts of another image correspond, i.e., the segments in the image of present remains that are the same in the image of the particular case that can be uses as reference. The matching procedure should find and match identical elements in both target and source.

In many cases, a correspondence can be found by just overlaying the fragment over the simplified contour of the building used as reference (the "template). Alternatively, if we are comparing 3D forms and not only simplified 2D contours, we can use an opensource software like CloudCompare [https://www.danielgm.net/cc/]. It is a 3D point cloud (and triangular mesh) processing software, originally created by Daniel Girardeau-Montaut. It was originally designed to perform comparison between two dense 3D points clouds (such as the ones acquired with a laser scanner) or between a point cloud and a triangular mesh. It relies on a specific octree structure dedicated to this task. Over the years, it has grown with contributions from various developers and the support of a large user community.

In more complex cases, when the shape/form of the reference case cannot be reduced to a simple contour, or the point cloud of the 3D model is too complex, we need to extract meaningful segments in the image -identified in terms of architectural elements- as patches, to normalise them in order to achieve invariance to image transformations, and computing the descriptor vectors associated to keypoints, whose distance is used to establish the candidate correspondences. Finally, we will filter the surviving matches by means of methods like the spatial global or local constraints, as those exploited through RANdom SAmple Consensus (RANSAC). This is an iterative algorithm used for estimating the parameters of a mathematical model from a set of observed data that contains outliers. The basic idea of RANSAC is to iteratively select a random subset of the data, fit a model to this subset, and then determine how well this model fits the entire dataset, including both inliers (data points that fit the model) and outliers (data points that do not fit the model).

Procedural-Generative recreation

The term generative modelling or procedural architecture reflects a paradigm for representing the shape, form and geometry of architectural elements as the result of a sequence of operations rather than a static set of low-level shape primitives. It is an iterative design process that uses algorithms and computational methods to automatically generate architectural models and structures based on predefined rules and parameters

This approach combines elements of generative design and procedural modelling to create complex geometrical forms and layouts without manually designing each

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component. It implies the definition of a set of rules, constraints, and parameters that guide the recreation of the original appearance of the architectural heritage element. In so doing, we can generate alternative solutions by changing factors, variables and parameters. The process involves continuous evaluation and optimisation of generated designs to meet specific criteria. This approach is particularly useful for creating large-scale or highly detailed architectural models, such as entire cityscapes or intricate building facades

By leveraging computational power, generative procedural architecture enables the recreation process to explore a wider range of design possibilities, optimise solutions, and create more responsive and adaptive architectural designs.

On the other hand, procedural-generative techniques have great advantages since they make complex models manageable by allowing for the identification of a shape's high-level parameters; they are extremely compact to store as only the process itself is described not the processed data; they make the analogy of 3D modelling and programming explicit; and lead to much better results concerning model-based indexing and retrieval tasks.

Procedural building generators are programming languages that allow the creation of visual models by iteratively refining an initial shape or geometry and creating more and more detail. They are conformed by formal grammars implementing a set of production rules in a formal language. The production rules describe how to create valid strings from the alphabet of the language and according to the syntax of the language. A shape grammar is a type of production system that generates geometric shapes and consists of a set of rules that operate with shapes and a generation mechanism that selects and processes those rules. A shape rule defines how an existing shape can be transformed into another shape. In that sense, the reconstruction or recreation will be generated through the definition of a procedure, that is, an ordered set of computer commands that are recorded, accessed repeatedly to add geometric and visual elements to some raw input, modifying and updating successively the final output, according to new input. The commands call for operations, expressed in different ways: strings of text, mathematical formulas, nodes connected with explicit links, and so on. In so doing, diverse components of original raw model may be transformed by applying a finite set of computational actions filling the missing parts in the geometrically modelled raw data and generating a synthetic visualisation of the reconstruction, without intervention of the user, except for the initial input. The output will be referred as procedural content.

The first application of procedural visualisation of architectural cultural heritage was the work of Stiny and Michell [1978] trying to reproduce the logic of Palladian architecture in Renaissance times. Classical Roman architecture and its rigorous system of orders and proportions is, indeed, the architectural style most commonly cited by proponents of the mathematical logic of architecture. Müller et al. [2005] were among the firsts in attempting to create a shape grammar based on the writings of the ancient Roman architect Vitruvius, in his *Ten Books on Architecture*, encoding rules for procedurally defining the make-up of Roman settlements. Their initial results allowed the procedural generation of classical Roman Houses, which include many of the architectural elements found in Roman civic buildings. However, talking about the problems of applying Vitruvian theory in the field, we should realise that such a regularity rarely occurs in practice. It is inevitable that the virtual reconstructions will contain some uncertainty and some hypothetical elements.

In the last two decades, procedural modelling has been applied to re-imagine Classical Roman buildings expeditiously with impressive results. The architectonic proportions described by Vitruvius are implemented in rule sets and applied to give the best practical approximation of the appearance of the temples or any other Roman times building. The user has to enter only the few initial parameters, and the remaining parameters are then calculated proportional to the known parameters, generating a full ancient architecture model with all of the architectural elements automatically aligned

This approach to computer visualisation of ancient buildings in its hypothetical original appearance concentrates on structural and semantic features of modelled artefacts. User-defined behaviour related to the attributes and geometry of a feature can be defined in a particular syntax language that allows the execution of this behaviour.

Nevertheless, it is important to take into account that architectural procedural rules rarely existed in a static state for long and have been constantly re-written as the need for new parameters arose. A universal construction logic rarely occurs unadulterated in practice. Although formal shape grammars aid in the efficiency of scene generation, there are some drawbacks to the way in which shape-grammar based procedural languages enforce a hierarchical structure upon the rules.

Among those drawbacks:

- The development of shape-grammar rules can be subjective, leading to potential biases in the reconstruction process.
- Rules and Shape grammars may be insufficient, not capturing the full complexity and variability of architectural styles.
- Information provided by user: initial data and parameter vu can be incomplete limiting the accuracy and applicability of rules and shape-grammars
- Shape-grammar based procedural languages may not provide an intuitive or interactive way for users to explore different design options or make modifications to the reconstructed models

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8. Artificial Intelligence Methods for the Computer Reconstruction of Architectural Heritage

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Artificial intelligence

According to the EU Artificial Intelligence Act-Regulation 2024/16891, "Artificial intelligence system" (AI system) means a system that is designed to operate with a certain level of autonomy and that, based on machine and/or human-provided data and inputs, infers how to achieve a given set of human-defined objectives using machine learning and/or logic- and knowledge-based approaches.

Generative Artificial Intelligence (AI) programs are specialised AI systems that can create new content or data that mimics existing patterns, such as text, images, audio, or even code.

The question is then whether such a non-human system can generate by itself images of the past, recreating or reconstructing past states of buildings in a reliable way.

The Dream of an Intelligent Machine. Beyond Science Fiction

This "magic" is possible thanks to a kind of computer algorithm called "Neural Network" that is able to associate huge quantities of data. In any case, forget about the name. Although it was created originally trying to imitate the animal brain, it is a computer algorithm, more related to statistics and number processing than anything occurring in our brain. But it works effectively!

Artificial neural networks are made of "artificial neurons", which are computing units that receive a number (input), for instance, a measure of a column or an arch, process it and send in response another number.

Such artificial neurons are organised into "layers". The input process information is introduced by the user, the hidden or intermediate layer processes such information, and the output displays the result of calculations.

For instance, we can describe the arch of an ancient church using some geometric measurements. This information stored in a database is read by the input layer. The output will show some general characteristics of the building the arch comes from: its style, material, decoration, function, etc.

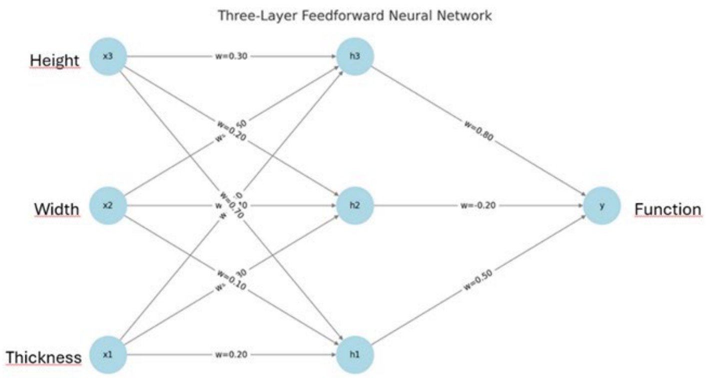

Figure 42: Neural units and computations are organised into layers

We can go well beyond the use of discrete features and numeric variables and use raster images both for input and output.

In theory, each pixel in the input image would correspond to a single neuron in the input layer, and the same for the output layer. The problem is that if you intend to process a high-resolution image, you would need a neural network with millions of neurons, both in the input and output; the number of intermediate neurons would also increase, and the number of interconnections would make everything difficult to manage, even with the most performant computer.

There is a way to simplify this problem. Using an image processing operation called convolution. Think of an image as a grid of numbers. A filter (also called a kernel) is another smaller grid, often with values like -1, 0, or 1, and it helps detect or enhance certain features in the image (like edges or blurriness). The filter "slides" over the image, one pixel at a time. At each position, the filter overlaps with a small part of the image. For each part of the image that the filter overlaps with, multiply the corresponding numbers (values of the image and the filter). After calculating the sum, the result becomes a new value for the centre pixel of the image area the filter just covered. This is repeated for every pixel in the image. The final outcome is a modified version of the original image, where certain features (like edges, sharpness, or blurring) have been enhanced or detected, depending on the filter used.

A convolutional neural network is an example of deep neural learning, that is to say, a network with many hidden layers and with an input layer receiving one convolutional vector for each image. The complexity of the thousands of pixels in the input images has been reduced to more manageable vectors expressing the edges and specific parts of the image that make each one different or similar to the rest.

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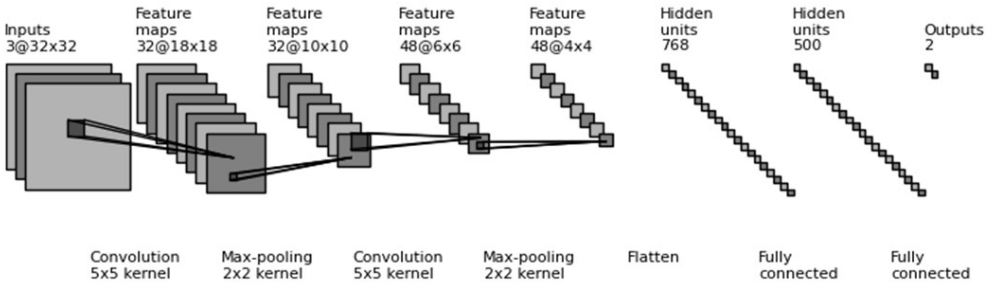

Figure 43: A convolutional Neural Network

Machine Learning

We should begin by gathering a large dataset of measurements, architectural plans, drawings, photographs, and textual descriptions, including both complete and incomplete structures. This dataset should ideally cover a wide range of architectural styles and periods to ensure the AI model can generalise well.

To be readable by the computer, gathered architectural data should be represented in a suitable format. For 3D data, this may involve converting point clouds or volumetric representations. For images, it may involve resizing and normalisation. In many cases, it implies a pre-processing preliminary step to extract relevant features, such as geometric descriptors and shape parameters.

A computer system learns by being trained on this data. It involves feeding the computer images and/or geometric models together with labels indicating the specific association to be learnt: this image is an example of a complete gothic church; this other image is an example of a complete Greek temple. The computer used hundreds, thousands, millions of input output associations and generalises rules for completion

To train neural networks we use an algorithm called Back-Propagation. This algorithm helps a computer adjust its predictions after seeing how wrong it was:

- Step 1: The computer makes a prediction (like guessing if a photo of part of a heritage building is an example of a roman or a gothic style arch).
- Step 2: It checks how far off its prediction is from the correct answer (this difference is called "error").
- Step 3: The algorithm sends this error backwards through the system, layer by layer, so the computer can understand where and how much to change in its "thinking" (its internal settings or weights).

The second part of the process of learning how to predict involves “fixing the mistake”. It is carried out using a Gradient descent algorithm. Once the computer knows how far off it was, it needs to figure out how to improve. Think of gradient descent like taking steps toward the right answer. At first, the computer looks at the error (how wrong it was) and figures out how much it needs to adjust. Then, it makes a small adjustment in the direction that helps reduce the error. This adjustment is like taking a small step in the right direction. The computer repeats this process many times:

after each adjustment, it checks its error and takes another small step toward improving.

Given the complexity of a deep learning software architectures, and the complexity of the task of reconstruction, it can be useful to use a *pre-trained* neural network, one that has proved its ability to classify general images, before using it to classify images of heritage buildings and use the results of that classification to reconstruct the ruins of another buildings. This is a form of *transfer learning* because it allows the transfer of knowledge from different domains. Instead of starting from scratch, we take a model that has already learned useful features from a large dataset and adapt it to another task, often related but may have limited data available. In this way, we can save time and resources, as it allows you to build upon existing models instead of training a new model from scratch. A pre-trained classificatory neural network can provide a strong starting point for the architectural cultural heritage reconstruction problem, having already learned a wide range of features that can be useful for the reconstruction task. Then, our network will begin learning a more specialised classificatory task once the weights necessary for distinguishing basic classes have already been learnt. AlexNet, VGG, ResNet, and YOLO are pre-trained deep learning models primarily designed for object recognition, classification, and detection tasks. Although these models are not specifically designed for reconstructing ancient buildings from ruins or architectural surveys, they can be adapted and used as a starting point or backbone for this purpose. Pre-trained models of deep neural networks are downloadable by any user and ready to be used for any complex classification task. Some models are implemented in MatLab platform, for Keras, or Torch, among many others.

Advantages of Neural Networks

The advantages of using this kind of “automated” associative memories to the problem of reconstructing the original aspect and structural properties of heritage buildings from the remains of them preserved in the present are obvious:

- *Pattern recognition*: Neural networks excel at recognizing patterns in complex data sets, making them well-suited for identifying architectural features and styles in ancient structures. For example, in image recognition, a neural network can learn to recognise edges, textures, and shapes without being explicitly told what to look for.
- *Generalisation*: Neural networks can generalise from training data, allowing them to predict missing information in fragmented structures. Supervised learning enables associative memories to complete incomplete patterns. When presented with partial input, the system can recover missing parts by following the learned associations. In the same way, associative memories trained through supervised learning can effectively remove noise from input patterns, recovering the original clean pattern
- *Adaptability*: Neural networks can learn and adapt to new data, making them capable of handling a wide variety of architectural styles and building types.

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- *Robustness*: Neural networks can be robust to noise and errors in the training data, which is particularly important when even well-preserved ancient buildings in the present may have been damaged or altered over time.
- *Integration of multiple data sources*: Neural networks can integrate information from various sources, such as historical records, archaeological findings, and 3D scans, to create more accurate and comprehensive reconstructions. There is, apparently, no limit in the quantity of data that can be used for training.
- *Objectivity*: Neural networks can provide more objective reconstructions compared to traditional methods, which may be influenced by the personal biases and interpretations of researchers and archaeologists. This is a consequence of using exhaustive training databases.

Applications in Architectural Heritage

Probably the first domain of application of AI methods and Machine Learning lies in the identification of architectural styles. Different methods, based on neural network technology can be used for the stylistic identification of ancient architectural remains.

Especially relevant for our purposes is the possibility of using the machine learning abilities of neural network for processing *big data*. The data needed for the computer visualisation of ancient architectural heritage can be considered within the category of "Big Data" because visualizing ancient architecture often requires high-resolution images, multi-level cartographies (Geographic Information Systems), 3D scans, geometric model, textures, mechanical properties, labelled in a complex way. These files can be very large, especially when dealing with entire archaeological sites or complex built structures. As new discoveries are made or as restoration work progresses, the dataset may need to be continuously updated with new information. Furthermore, techniques like LiDAR (Light Detection and Ranging) and drone photography can generate vast amounts of data quickly. These methods are often used to capture detailed information about archaeological sites. Consequently, the dataset may include a mix of structured data (like measurements and coordinates), semi-structured data (like metadata from images), and unstructured data (like textual descriptions and historical documents). The data may come from various sources with varying levels of accuracy and reliability, and significant effort may be required to clean, validate, and integrate data from different sources to ensure its quality and consistency.

Another area in heritage architecture reconstruction where AI-based programs may be very useful is "semantic segmentation". Before "reconstructing" the ruins, we should *identify* the different architectural elements, even if they have only been preserved partially, altered or fragmented. Semantic segmentation in 3D graphics refers to the process of assigning a label or class to each point or region within a 3D model or scene. This will help to define the functional components that we should identify in the ruins in the process of reconstructing the original building. For example, we may need to segment the building into different rooms or spaces (e.g., hall, corridor, entrance, etc.), or into structural or mechanical components (e.g., beams, columns, HVAC systems). A deep-learning method can be trained to identify the relevant features: a neural network can be trained to associate input features such as the location, size, orientation and geometry of the ruins with a formal definition of architectural elements. In any case, we should take into account that semantic segmentation is particularly challenging in historical and classical architecture, due to the shapes complexity and the limited repeatability of elements across different buildings, which makes it difficult to define common patterns within the same class of elements. Even if the shape is repeatable, perhaps for a given architectural style, the objects are still unique as they are handcrafted and not serialised. Another problem is that the objects are ancient and subject to erosion and decay.

The domain where we should expect more relevant applications of artificial intelligence and machine methods is in the domain of restoration and anastylosis. We have already studied how to consider the broken fragments of architectural elements as puzzle pieces (Anastylosis). Neural networks can be trained to look at these pieces and figure out how they fit together by understanding their shapes, colours, and patterns. In this way, the neural network acts like a smart assistant, using its training to assemble the puzzle quickly and accurately. The idea is to automatically recognise similar fragments that may fit together because colours or patterns may match or edges may align. The network will also learn about the overall picture the puzzle might form, which helps it decide the most likely arrangement.

Limitations of AI-based Recreation.

There are also problems and limitations in using AI-based methods for the automated recreation of the past. In general, universal generative artificial intelligence programs, like DALL·E, developed by OpenAI, or Copilot, designed by Microsoft, do not work for our specific purposes. They generate an imaginary reconstruction that does not fit with available data.

Those programs do not work because they have been created for a different purpose, linking texts to images, and they cannot link ruins to their completions

Although actual generative IA programs are useless for properly reconstructing past remains, they open the way to an alternative way to heritage reconstruction multiplying the power of traditionally based analogical reasoning and similarity-based reconstruction.

Nevertheless, there are applications that show the real possibility of "automatizing" the process of reconstruction using apparently "intelligent" programs.

The easiest way seems to be creating a classification of architectural forms, using geometric information, 2D images or 3D models of complete buildings of different periods for training, and once trained, classify fragmented items in terms of the classes generated, and use the information for that category to restore missing parts in the fragment. The more exhaustive the data set for creating architectural categories, the better. The higher the number and greater the diversity of categories will allow higher historical precision. We have already discussed how neural networks excel in

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classification tasks when the training set is huge, and the diversity of descriptions (numeric data, image 3D geometry) is also very great.

Maitin et al. [2024], offer an excellent practical example of AI-based reconstruction using deep-learning methods. Their work consists of a computer system that receives an image representing a Greek temple in ruins and can directly detect which are the missing architectonical elements, returning the same image with the restored temple. For this purpose, authors have used generative adversarial networks (GANs) that have been trained with only pairs of an image of the ruined temple (input) and its corresponding image with the complete temple (output). The dataset incorporates 30 buildings from this historical period that correspond to different configurations of the classical Dorian order Greek temple, with different numbers of columns and diverse organisation settings around the sanctuary wall. All these buildings have been modelled in 3D in their original state and progressively destroyed in three stages to enrich the number of possibilities for viewing and therefore analysing the ruined structure. The study focuses on the formal and volumetric aspects of the building and, therefore, has not incorporated added sculptural elements in pediments, metopes, and acroteries, nor the striking polychromies that covered the stone that made up the temple. In this dataset, care has been taken in the application of more realistic stone textures in conjunction with a global lighting system that provides more nuances to the areas in shadow and half-light, being able to distinguish many more elements. In addition, a realistic environment has been modelled using a 3D mesh, incorporating a terrain texture, which serves as a background for the images of the temples. The ground on which the plinth rests also has some irregularity that interacts with the model and the shadows cast from it. The presence of the landscape is fundamental to the analysis of the images as it will force the neural model to discern the figure (the building) from the background. From 3D rendered models, 360 images (512 × 512 pixels) have been obtained from different perspectives and angles of vision, capturing all the material and light nuances of the model. This has provided 43,200 images to feed the learning of the neural network.

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9. Best Practices for Constructing 3D Models

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Segment the Model Semantically

Despite the purposes that a virtual reconstruction might serve, there are best practices that should be followed to construct 3D models that aim to be reusable in a scientific context. An important aspect of studying architecture is the semantic approach, which can have different inclinations: symbolic, architectural, structural, philological, and functional. In our case, we refer to the semantic segmentation of architectural elements, such as: doors, windows, floors, vaults, roofs, pillars, columns, pediments, bases, capitals, and even decorative elements (like mouldings), etc.

Semantic segmentation allows for recognising, naming, and interrelating individual elements. The assessment of 3D reconstructive models in the scientific context is often done part by part. Therefore, the transmissibility of knowledge through the 3D model depends on how clear and consistent the determination and identification of the individual and specific architectural elements are. A good practice, therefore, is to organise the 3D objects hierarchically, in levels and sub-levels. Today, computers can aid this work thanks to the workflow imposed by drawing programs, which use layers to keep digital objects organised.

In the example in Figure 44, Ledoux's architectures have been reconstructed by identifying the elements that determine the architectural composition. Additionally, using different colours and structuring the layers with coherent names helps in understanding and conveying the 3D model as an object of study. The degree of granularity and semantic depth is a subjective choice. Generally, a greater degree of semantic segmentation corresponds to a potentially more granular enrichment and investigation.

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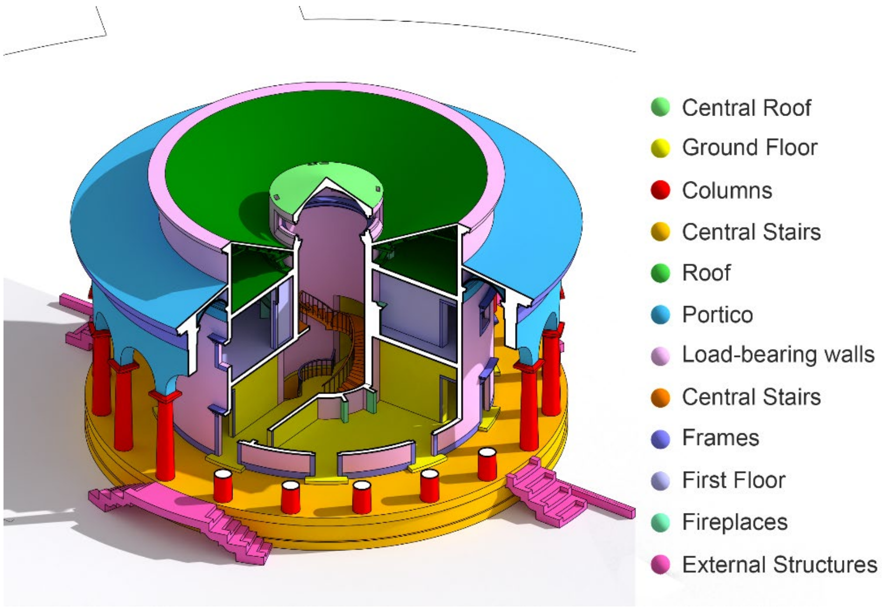

Figure 44: 3D model of Ledoux's Propylaea: semantic segmentation.

Choose the Proper Method of Digital Representation

There are different methods of digital representation (see lesson The Methods of Digital Representation and 3D Modelling Techniques). The two most used in the field of virtual reconstructions are the continuous representation method and the discrete representation method [Münster et. All, 2024].

The choice of the most suitable method is also tied to the choice of the CAD program that will be used to design the 3D model. Generally, CAD programs are predisposed to specific purposes, meaning they are designed to perform certain operations better than others. Therefore, it is important to select and use the software suitable for the predetermined goals, also because currently, there is no CAD program capable of fully carrying out all the phases of an architectural project: from sketching to executive drawings, including rendering, etc.

It is preferable to use software that implements the continuous representation method (e.g., NURBS) if one of the main goals of the virtual reconstruction is the rigorous and accurate study of the geometry of the object of study.

On the other hand, it is preferable to use software that implements the discrete representation method (e.g. polygonal meshes), if the goal is to control the shape of the object of study sculpturally or to produce renderings, video animations, simulations, etc.

In some cases, it is possible to opt to use both methods and have a model composed partly of NURBS mathematical elements and partly of polygonal mesh elements.

If in doubt using the continuous method (e.g. NURBS) is preferable because discretising a model made with the continuous method is much easier and can be done automatically, while the opposite is much harder and needs relevant manual work.

Use the Proper Reference Unit and CAD Tolerance

It is essential to identify the unit of measurement used to design the original project (e.g., the Roman or Vicentine foot) and, where possible, to identify the reference module (e.g., the diameter of a column equivalent to one and a half feet). If the unit is not explicitly declared in the documents, it can be inferred from the historical period and geographical area (see the lesson on Units of Measurement).

Despite the historical unit of reference, in the CAD environment, it is preferable to choose and set one of the contemporary measurement systems in use (metric or imperial); thus the measures must be converted accordingly. Furthermore, the specific multiple or submultiple of the chosen measurement system should be set in proportion to the size of the object of study. For example, for a Palladian villa, the optimal choice is the centimetre. Selecting the meter or millimetre would increase the likelihood of calculation errors in the CAD program because the 3D model would be too small or too large relative to the absolute tolerance.

Concerning tolerance, it is a value that expresses the level of accuracy of each software. Despite being much more accurate compared to hand drawing, computers are not infinitely precise, and thus it is important to set their tolerance properly in relation to the size of the 3D model to prevent the occurrence of errors. To have a grasp of such types of errors it suffices to think about three points A, B and C. Point A coincides with point B within its tolerance, and point B coincides with point C within its tolerance, however, point A and point C aren't automatically coincident because their distance might exceed their tolerance, the bigger the tolerance compared to the point distance, the bigger the risk of these errors to occur (Figure 45) [Migliari, 2009, p. 27], thus point snapping is not a transitive tolerance.

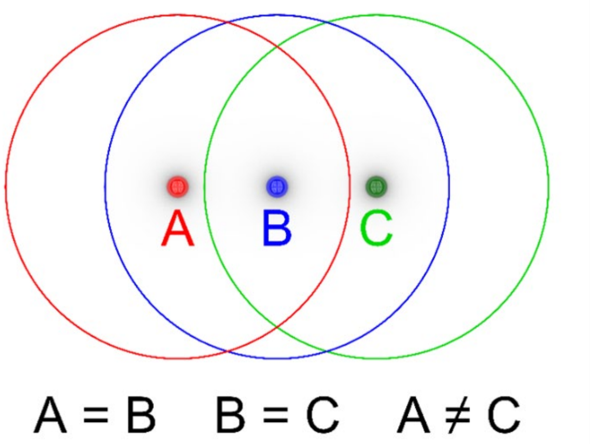

Figure 45: point snapping is not a transitive property due to tolerance.

Usually, software developers already properly set the predefined tolerance, for example, Rhinoceros predefined start-up files are sorted based on the expected size of the project. In general, if the software does not provide a series of predefined start-up scenes or does not allow to modify the tolerance manually, it is most often sufficient to choose the correct unit of measurement in relation to the size of the model and the tolerance should change automatically accordingly. For example, an architectural-sized model such as a Roman theatre that reaches a detail comparable to a 1:100 scale can be safely drawn using the centimetres, while an urban-scaled scene such as the city of Rome that reaches a detail comparable to a 1:10.000 scale meters should be used instead. Figure 46 shows the occurrence of snapping errors due to the improper sizing of the 3D model. To solve the error, the model must be remodelled from the beginning; scaling it after the occurrence of the error would not be resolutive.

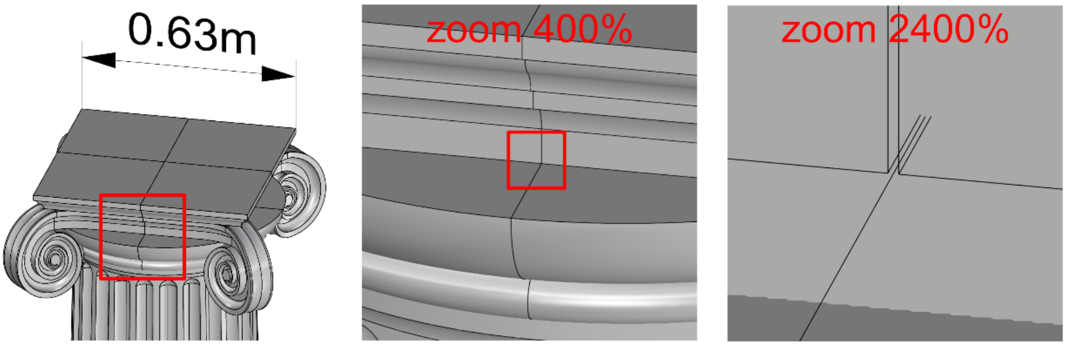

Figure 46: snapping error due to the improper sizing of the 3D model of an Ionic capital.

Determine the Scale of Representation and Level of Detail

The scale of representation is a concept that belongs to traditional drawing and the printing of technical drawings. For 3D models, however, we refer to Levels of Detail (LOD). For this reason, it is misleading to say that in digital representation, we draw at a 1:1 scale; it would be more accurate to say that we adopt the unit of measurement without reduction (or multiplicative) factors and draw the model according to a certain level of detail.

The reason is that the 3D model is generally viewed on a computer screen, and the concept of scale becomes difficult to determine because in real-time visualisation, we continuously change the field angle and point of view with zoom and rotations. Thus, in the field of 3D computer graphics, the concept of LOD was developed.

Currently, there are two slightly different concepts of LOD applied in computer graphics. The first concerns the level of visualisation complexity calculated in real time by the computer for the 3D model. The farther you move away from the model, the less complex the numerical representation of the 3D model becomes, and vice versa. This method is mainly used in video games to avoid overloading the displayed scene and thus make the gameplay smoother.

The second concept, however, pertains to the construction of the architectural 3D model.

For example, in the context of Building Information Modelling (BIM), the level of detail (LOD) does not refer to how densely tessellated is a polygonal mesh but refers to the amount of detail and information that is included in the 3D model of a building or structure at different stages of its development. The BIM LOD scales can differ from country to country and change over time, in the USA for example the scale goes from LOD100 to LOD500 and indicates the level of development and detail in a BIM model [Abualdenien, J., and Borrmann, A. 2022, p. 367]:

- LOD 100: (conceptual model);
- LOD 200: (approximate geometry);
- LOD 300: (precise geometry); LOD 350: (construction documentation);
- LOD 400: (additional detailing about fabrication, assembly, and installation);
- LOD 500: (as built).

These levels of detail help in defining the scope and accuracy of information contained within a BIM model and are crucial for effective collaboration and decision-making throughout the building lifecycle.

The level of detail could also be related to traditional representation scales. For example, if a 3D model has a LOD that allows it to be printed at a 1:50 scale with loss of detail, we could declare this reduction factor as the maximum representation scale. The 3D print scale thus becomes the benchmark to evaluate the LOD of the 3D model, analogously as it was the 2D print scale for technical bidimensional drawings.

Make a Plausible and Constructible Geometry

Unbuilt virtual architecture must be plausible and constructible if it aims to be a scientific reconstruction. Conceiving a virtual architectural 3D model that does not adhere to the laws of physics is a conceptual and practical error because it limits reusability. In fact, a 3D model with floating parts, intersecting or open solids cannot be 3D printed or used for advanced simulations and assessments. Overlapping solids with coplanar surfaces could cause classic rendering errors such as light leaking and Z-fighting.

In other words, the 3D model should always be conceived and created as a scale model that could be 3D printed or constructed using traditional techniques: 3D models should always be made up of solid elements that rest on each other and do not intersect. In some rare cases in 3D models, the intersection of solids is necessary. For example, when rendering liquids into transparent containers it is suggested to slightly intersect the liquid with the container to avoid seeing Z-fighting errors through the glass, but this does not usually concern architectural models.

Some CAD programs allow for automatic model proofing (e.g., solid intersection checking, open poly surfaces checking, invalid objects highlighting, overlapped objects selection, etc.). However, it is generally good practice to perform frequent manual checks during work to prevent such errors from occurring.

Aim for Interoperability

The final aspect concerns interoperability, which is the ability to share and reuse the 3D model for other purposes in other applications or platforms. There are different exchange file formats that can be used to bring the geometry from one software to the other. The most popular file types for polygonal models are: obj, gltf, fbx, stl, and the most popular for NURBS are: iges, and step. However, in the context of hypothetical virtual reconstruction, it is important that the shared 3D model preserves the geometric quality, the semantic structure, and the attached metadata and paradata of the original informative model. Some exchange formats capable of preserving metadata and paradata attached to the model are for example the IFC, and the CityGML, however, both of them sometimes have limitations in terms of preserving the geometric quality (because they do not fully support NURBS geometries), so in most cases, when sharing the 3D model it is better to export it with multiple file formats to minimise the loss of data (see the lecture on exchange formats for more info).

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10. Scale, Proportions, Measures, Level of Detail

Authors: Fabrizio Ivan Apollonio, Federico Fallavollita Riccardo Foschi

The Ancient Units of Measurement

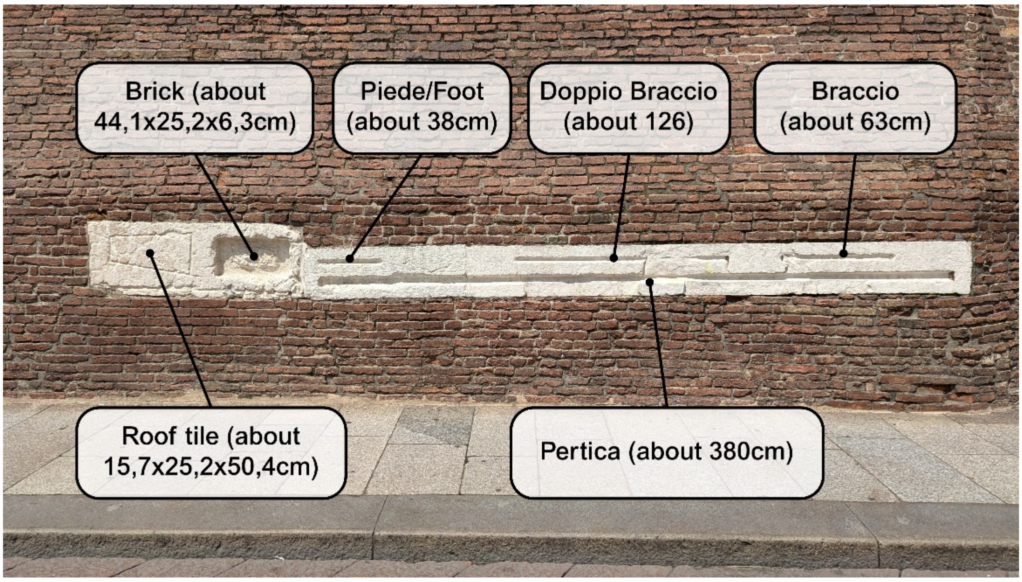

Figure 47: Ancient units of measurements sculpted on Palazzo d'Accursio in Bologna.

Dividing architecture into modules and measuring it in relation to their multiples and submultiples has been a fundamental practice throughout architectural history, serving both compositional/theoretical and constructive/practical purposes. Consequently, dimensioning and proportioning are crucial elements, especially in the context of hypothetical reconstructions, and must be considered from the initial stages of the project to the publication of the digital model.

In the scientific hypothetical reconstruction of historical architectures, it is essential to employ a methodology that is repeatable, readable, easily accessible, and shareable. By accurately determining the appropriate unit of measurement and proportioning of the model based on strict modularity, the reconstruction process can be rationalised and simplified, facilitating its production, documentation, and dissemination.

Although historical sources may not always explicitly mention the unit of measurement or module used, these can often be inferred by considering the historical period, the geographical context, the author, the architectural style or the construction system employed. For example, prior to the adoption of the metric system in Italy, the foot was a widely used unit, although its length varied slightly between municipalities. For example, the Bolognese foot measured approximately 38 cm (Figure 47) [Ministero di Agricoltura, Industria e Commercio (1877), p.119; Bologna Blog 2022], while just 100 km away from Bologna in Vicenza the foot was approximately 36 cm [Vajenti, 1810, p.72].

The Module of the Architecture

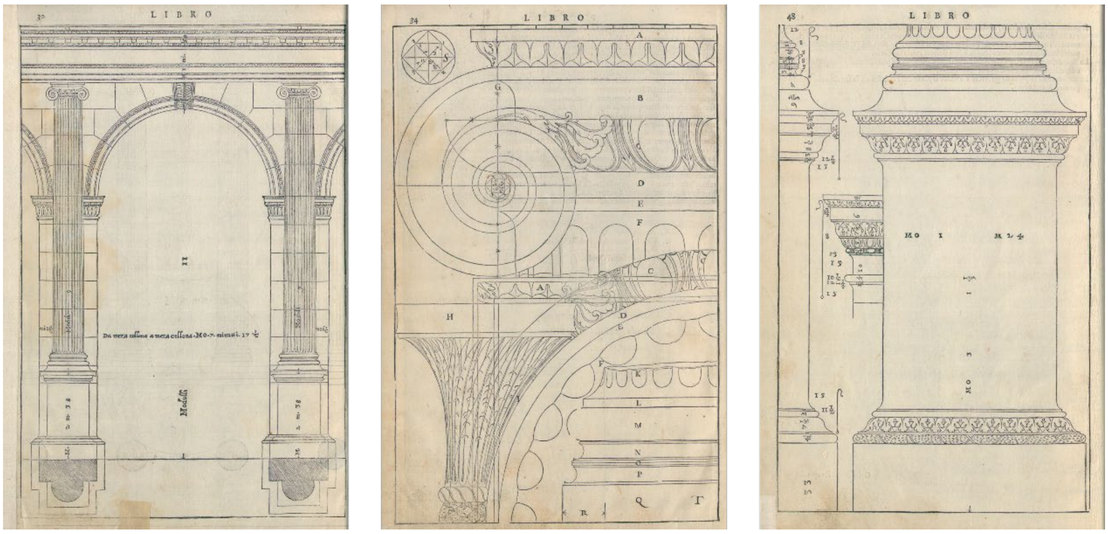

Figure 48: extract from 4 books of architecture by Andrea Palladio [Palladio, 1570].

There is a difference between the unit of measurement and the architectural module. The unit of measurement is "real scalar quantity, defined and adopted by convention, with which any other quantity of the same kind can be compared to express the ratio of the two quantities as a number" [JCGM 200, 2008]; usually, it is strictly related to civilisation and specific geographic area and it is often imposed by law. On the contrary, the architectural module is the reference measure, usually derived from one of the elements of the architecture itself or its multiples and submultiples, from which the entire architecture or its parts can be proportionally related; the module is not geographically determined, it is specific for each architecture and is particularly useful for determining proportional rules that do not depend on the size of the building. For example, renaissance treatise writers [Serlio, 1537; Vignola, 1562; Palladio, 1570] individuated the diameter of the column or pillar (measured in the first third of the shaft), and its multiples and submultiples, as the reference module used to describe and control the proportioning of the classical orders (Figure 48). Similarly, masonry structures can be modulated based on the dimensions of bricks and the bricklaying patterns. In fact, based on these two examples, we can describe how far two columns are, by simply counting how many of their diameters can fit between them, or we can describe how thick a wall is by simply saying how many bricks fit in its width, with no need to reference to the size of the building and the specific unit of measurement in use (meters, feet, braccia, etc.).

When the proportioning of a specific architecture is based on a specific module, it is possible to know its exact size by multiplying the measures expressed in modules by the measure of one single module expressed in the given unit of measurement. For example, if we know that two columns are 6 diameters away from each other, and the diameter is exactly one foot and a half, the two columns are nine feet apart.

But why is the module important? And why is the unit of measure not enough? In architectural design history, the proportion between the parts was often a priority for the designer (for example, in classical architecture), and not the decontextualised dimensioning of the elements. Furthermore, more practical reasons regards the fact that historic units of measurement are often approximated and are not always known or easily retrievable; and reference graphical sources are often deformed or drawn at a small scale, thus being able to proportion the whole architecture with a reference unit that is readable from the architecture itself (the module), would allow achieving more rationalised, accurate and more easily sharable and readable results.

The Scale of Representation

In architectural drawing, the scale of representation is used to determine the size of architectural objects or spaces based on their drawn reproduction on a bi-dimensional media (e.g., a sheet of paper). In comparison, the representation scale of 3D models has a direct analogy with the representation scale of 2D drawings; however, in digital 3D space, the concept of scale is not anymore strictly related to the size of the represented object because, through displays, digital objects can change in size based on the zoom level, on the contrary, the representation scale of 3D models is related to the concept of Level of Detail (LoD) which determines the maximum scale at which the 3D digital model could be printed without loss of detail.

So instead of saying “The model is in scale 1:1”, one could say “The model was built in cm without reduction or multiplication factor, and its LoD is comparable to that of a drawing in scale 1:100”.

Case Study of S. Margherita

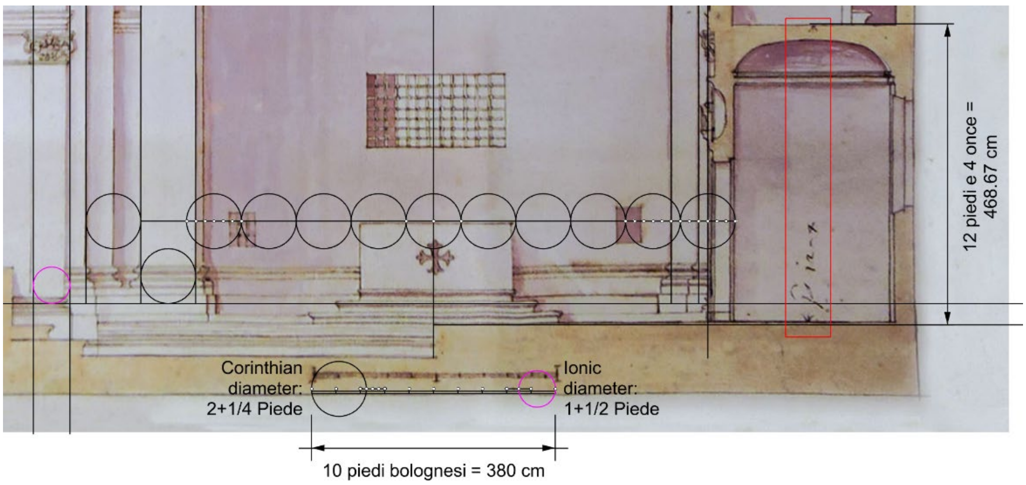

Figure 49: scaling of the authorial graphical sources based on the graphical scale.

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For illustrative purposes, we consider the case study of the 1685 project for the church of Santa Margherita in Bologna by Agostino Barelli. First, the drawing was scaled starting from the graphical scale based on the Bolognese foot (Figure 49), which was about 38 cm, deduced by considering the period and geographic area of the project. When scaling the drawing, it is important to use the biggest measure possible to minimise parallax error. The reference module was individuated in the width of the Corinthian pillar, which was hypothesised to be two feet and one-fourth of a foot (3 ounces), about 85.5 cm in total.

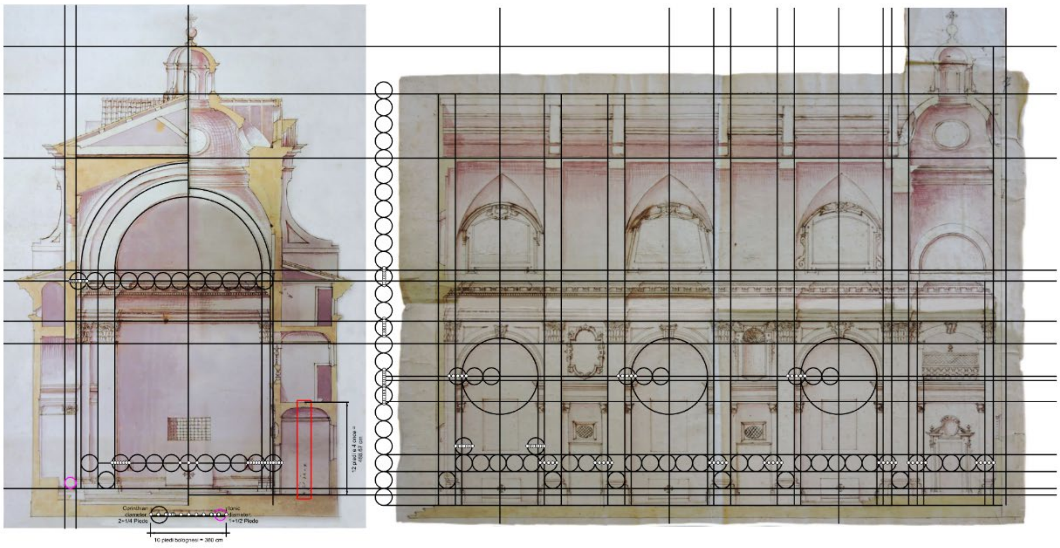

Figure 50: proportioning of the building by using the width of the Corinthian pilaster.

Based on this module and its multiples and submultiples, the proportioning of the entire architecture was then assessed (Figure 50); for example, the central nave corresponded to eight modules and four-sixths of a module, which corresponded to 19 feet and 6 ounces (approximately 7 meters and 41 centimetres). The proportioning and scaling were verified with some dimensions reported by the architect. In cases where neither the graphical scale nor any dimensions are available, it is possible to base the scaling on known elements, such as the risers and treads of a stair or the height of doors; however, this method is more uncertain and should only be considered when no other alternatives are available. Lastly, the whole project was vectorised critically, by retracing manually all the relevant lines making sure to straighten and rectify them according to the inferred modularity (Figure 51).

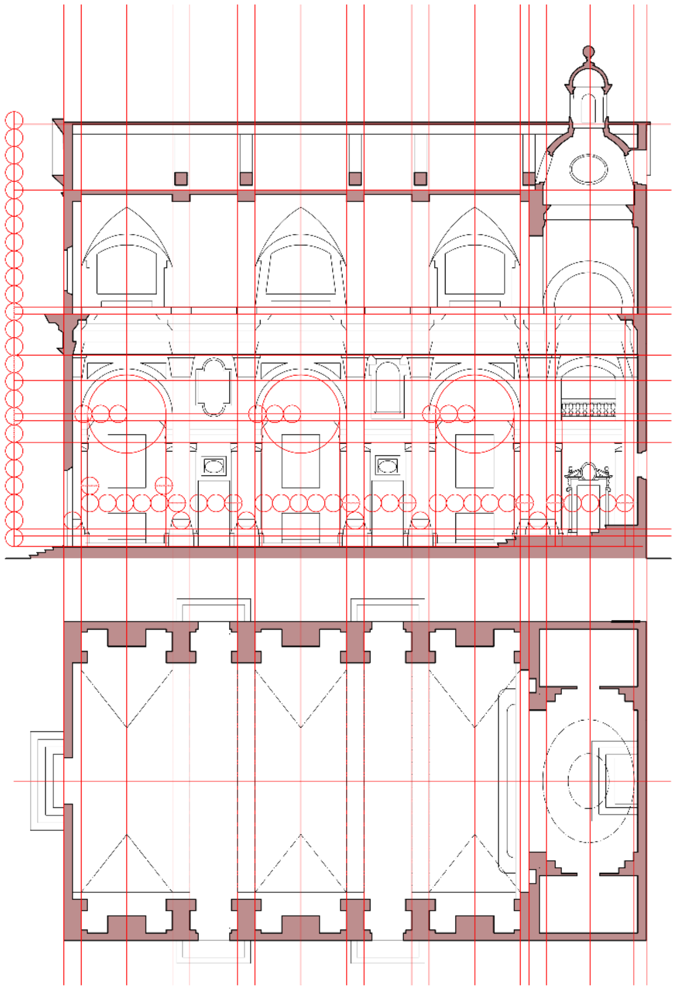

Figure 51: redrawn vectorised section and plan.

Proportioning architecture based on a module and not just the unit of measurement has not only a philological value but also a practical one. It allows for identifying a rule to compensate for potential alterations typically present in sources subject to deformation. Moreover, it helps simplify the redesign phases and make documentation more transparent. Adopting rigorous modularity and clearly communicating it will allow future scholars to repeat the procedure more easily and obtain comparable results. Naturally, it is not always possible to identify a module for every architecture; in this case, it might mean that in the historical period of reference, the modules were not used, or the architect intentionally preferred to work only with units of measurement. In that case, it will be sufficient to identify the unit of measurement and proportion and measure the architecture using only that.

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11. Semantic Segmentation and Semantic Enrichment

Authors: Krzysztof Koszewski, Karol Argasinski

Introduction to Semantic Segmentation

Modularity is one of the essential features of new media. This is modularity, which allows for breaking down into parts that retain their identity but still can be combined to create the whole. Such a feature, manifested in the discreet nature of the raw digital model, makes it possible to fragment this model and assign specific meanings to individual parts of it. This is called semantic segmentation. Why is it so important? And when is it used?

The concept of semantic segmentation is associated with digital image analysis and computer vision. In this context, it involves assigning appropriate labels to individual pixels, allowing these pixels to be grouped into representations of objects that can be captured in a semantic description. In other words, objects can be organised into structures to which meaning can be assigned. In a broader sense, the concept of semantic segmentation can be related to cognitive science, as it describes the systematisation and categorisation of objects during the perception process, which is necessary for understanding the content of the image. In fact, research on the mechanisms of perception, describing the recognition of objects accompanied by their categorisation, has become the basis for numerical image analysis and modelling these processes using digital systems. These, in turn, have found applications in machine learning for image recognition.

Let us return for a moment to the cognitive understanding of semantic segmentation. If this categorisation is necessary for understanding the content of the image, it is thus also essential for understanding our digital model. When we look at a point cloud on a computer screen, we perform its segmentation in the perception process. However, to make such a model understandable by machines, we also need to carry out this process at the level of the digital model itself.

Moreover, from an informational standpoint, our model cannot be limited solely to geometry. We should be able to encode all relevant information about the modeled object, including essential features regarding its nature. In the case of a historical monument, such features focus on its significance because it is precisely this quality that makes the monument a value we want to pass on to future generations. Without the semantic layer, culturally encoded in its physical form, the object monument will not possess the qualities that make it valuable. This is semantics that facilitates understanding the monument, without which we cannot appreciate or protect it.

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Imagine creating a model of a historic monument, for example, in the process of laser scanning. Certainly this model is to meet the expectations to encompass the original's essential features. In that case, it must be a carrier of the mentioned meanings, both as a whole and, particularly, as its elements. To appropriately assign this meaning, these elements need to be identified and distinguished precisely through the segmentation of the model. The key to conducting segmentation is assigning meaning to the elements of the model by referring to their semantic layer present in the real object. It is worth emphasising again that the very nature of the modeled object, as a historical monument, necessitates the creation of a meaning layer and assigning individual elements of the model to it. This approach identifies semantic segmentation not only as a method of encoding and representing knowledge but also as a constitutive feature of recording spatial information about the monument. Of course, a digital representation of an object limited to its geometry is not worthless, but its significance can be compared to a blurry analogue photograph devoid of any description. Most of the benefits derived from the characteristics of the digital medium are then severely limited, if present at all.

In summary, the semantic segmentation of a model involves dividing it into parts that can be given meaning and have significance as elements of a larger whole. An important task is to adopt relevant segmentation criteria as they are essential in adequately defining the components and result from the very purpose of creating a model.

Introduction to BIM

Now that we have a clear understanding of semantic segmentation, let's explore how we can build upon this foundation with semantic enrichment in architectural modelling.

Before diving into the specifics of semantic enrichment, it's essential to understand Building Information Modelling, or BIM. BIM is a comprehensive process that involves the generation and management of digital representations of the physical and functional characteristics of places. It is much more than a 3D model; it is an intelligent model-based process that provides insights and tools to plan, design, construct, and manage buildings and infrastructure.

Figure 52: Detailed Heritage BIM model of Przysucha Synagogue, Poland.

BIM stands for Building Information Modelling, and it is a process that begins with the creation of an intelligent 3D model and enables document management, coordination, and simulation during the entire lifecycle of a project (plan, design, build, operation, and maintenance). [Argasiński, and Kuroczyński, 2023] BIM is a digital representation of both the physical and functional characteristics of a facility. It serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle, from inception to demolition. This shared knowledge includes everything from basic geometric data to complex performance attributes and operational details.

The key components of BIM are:

- Geometry: The 3D shapes and dimensions of the building's components.
- Spatial Relationships: How different components interact within the space.
- Geographic Information: Location data and environmental context.
- Quantities and Properties of Building Components: Materials, dimensions, and other physical properties.
- Cost Information: Budgeting and financial planning data. Performance Criteria: Energy efficiency, sustainability metrics, and other performance-related data.
- Holistic Approach BIM (Figure 53) integrates multiple layers of information into a single, comprehensive model. This model is not just a visual representation; it is enriched with data that provides detailed information on every aspect of the building. This includes geometry, spatial relationships, geographic information, and quantities and properties of building components. By providing a holistic view of the building, BIM facilitates better collaboration and coordination among all stakeholders involved in the design, construction, and maintenance processes.

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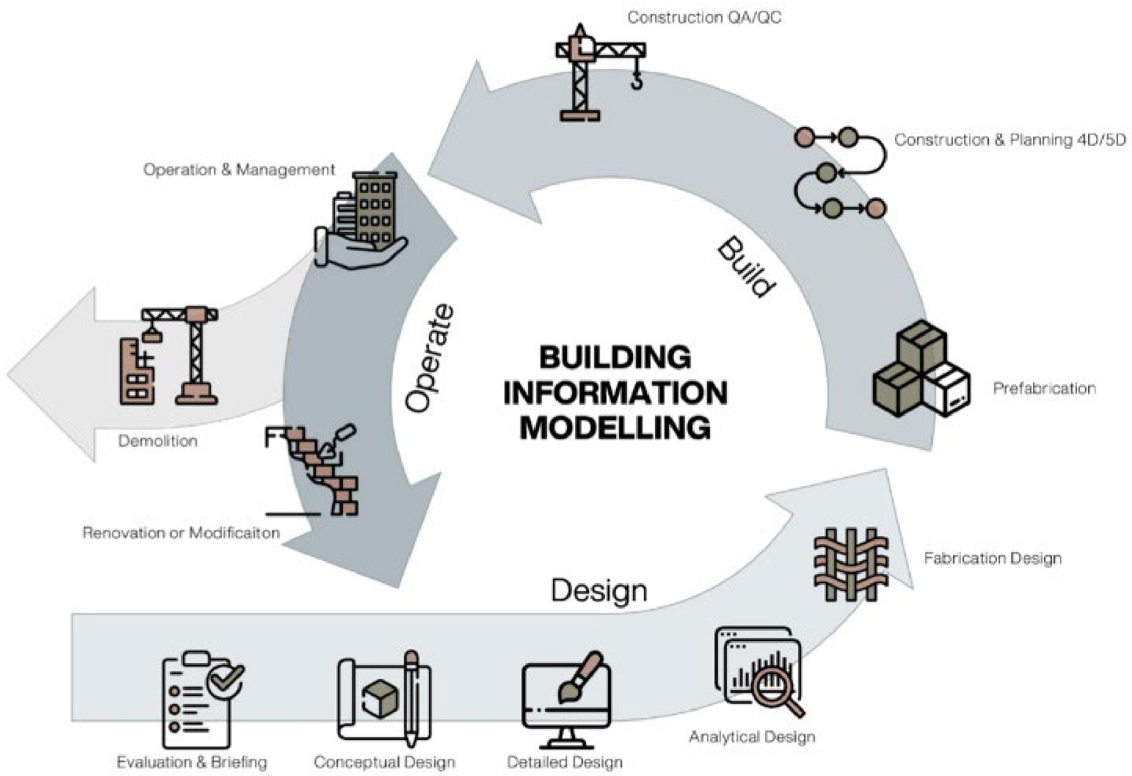

Figure 53: BIM holistic approach – it can be used through every building's lifecycle phase.

BIM as a methodology is crucial for several reasons:

- Improved Efficiency: BIM streamlines the design and construction process by enabling all stakeholders to work from a single, coordinated model. This reduces the time and effort required to make changes and ensures that everyone is working with the most up-to-date information.
- Reduced Errors: By providing a detailed and accurate model of the building, BIM helps to identify and resolve potential issues before construction begins. This reduces the likelihood of errors and rework, saving time and money.
- Enhanced Communication: BIM improves communication among project stakeholders by providing a shared platform where everyone can access and update information. This collaborative environment helps to minimise misunderstandings and ensures that everyone is on the same page.
- Better Decision Making: With BIM, architects, engineers, contractors, and owners have access to a wealth of information that can be used to make informed decisions. This includes data on materials, costs, performance, and more, allowing for more accurate planning and budgeting.

- Lifecycle Management: BIM is not just for design and construction; it is also a valuable tool for managing the building throughout its lifecycle. From maintenance and repairs to renovations and demolitions, BIM provides a comprehensive record of the building's history and condition.
- Sustainability and Energy Efficiency: BIM allows for the simulation and analysis of various performance criteria, including energy efficiency and sustainability metrics. This helps in designing buildings that are more environmentally friendly and cost-effective to operate.

Levels of Geometry (LoG)

Firstly, let's discuss the Level of Geometry, or LoG. LoG refers to the precision and complexity of a 3D model's geometry (Figure 54). Essentially, the higher the LoG, the more detailed and accurate the representation of the physical characteristics of the model. This means that every small detail, from intricate carvings on a historic monument to the exact curvature of an arch, is captured with high precision.

Importance and Application of LoG:

- Precision in Planning and Construction: Higher LoG enables more precise planning and construction, as every aspect of the building is thoroughly detailed. This precision helps in identifying potential issues during the design phase, reducing errors and rework during construction. Detailed models assist in creating accurate construction schedules, cost estimates, and material requirements, leading to more efficient project management.
- Historical Preservation: In historical preservation, maintaining the integrity of original structures is paramount. Advanced LoG can include high-resolution scans and detailed digital reconstructions, providing an in-depth understanding of the building's physical characteristics. Detailed geometric data ensures that restoration efforts are accurate and respectful of the original design, preserving historical authenticity.
- Complex Architectural Features: High LoG is crucial for representing complex architectural features such as ornate facades, detailed mouldings, and intricate structural elements. This level of detail is essential for both new constructions and restorations of historic buildings.
- Visualisation and Simulation: High-detail models enable better visualisation and simulation, allowing stakeholders to see the building as it will appear in reality. This is particularly useful for client presentations, public consultations, and design reviews.

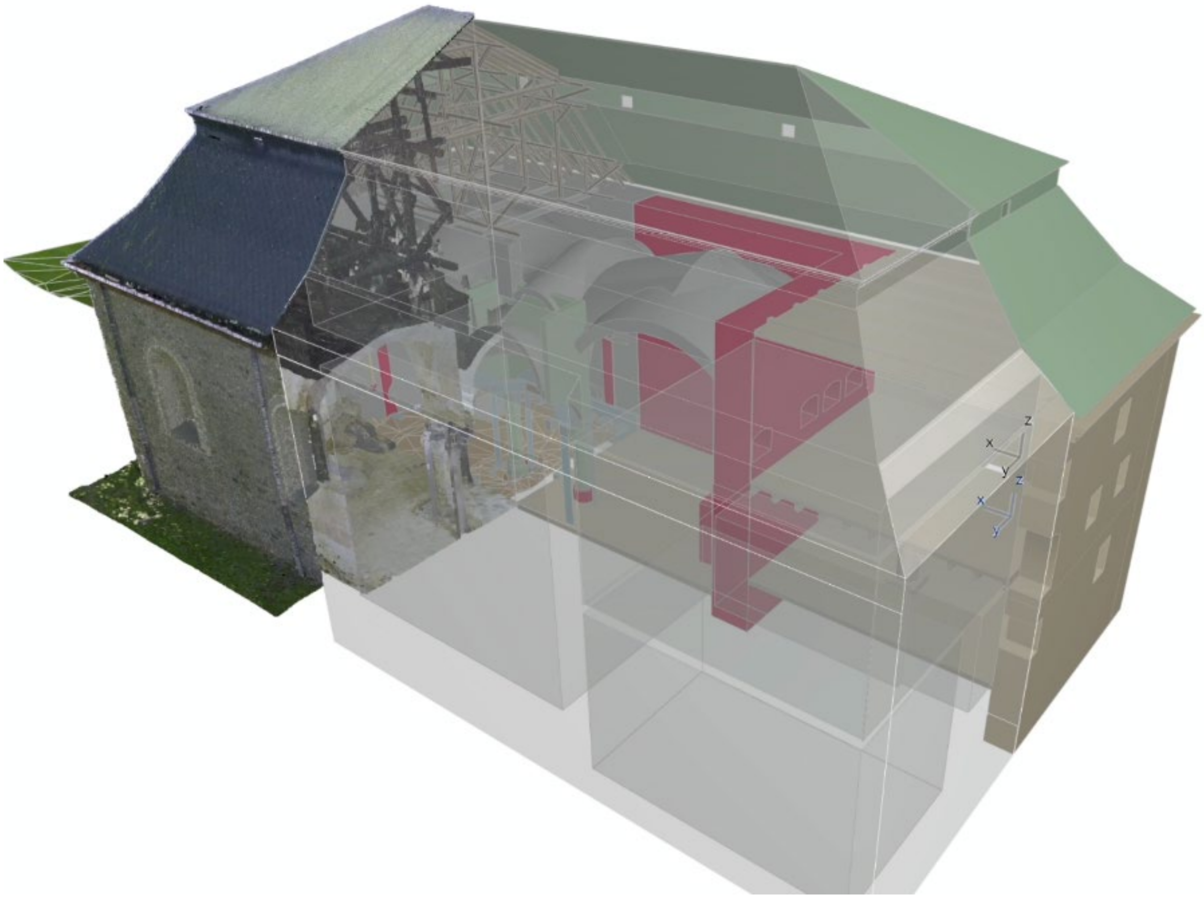

Figure 54: Example of different model Geometry representations.

Examples of LoG in Practice:

- Basic LoG: Simple geometric shapes and basic structures used for initial planning and concept stages.
- Intermediate LoG: More detailed geometric representations including walls, windows, and doors, used for detailed design and construction documentation.
- Advanced LoG: High-detail models capturing every architectural detail, used for complex projects, heritage conservation, and high-fidelity visualisations.

Level of Information (LoI)

On the other hand, the Level of Information, or LoI, pertains to the depth and breadth of information associated with the model's components. This can include a wide range of data, such as materials used, historical data, conservation status, and even previous restoration efforts. The LoI ensures that the model is not just a visual representation but also an information-rich resource.

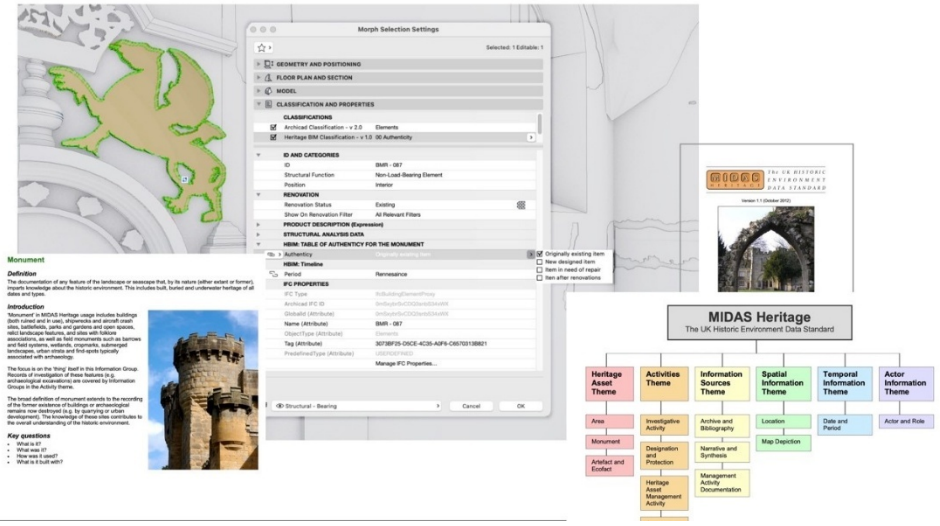

Figure 55: The classification information systems which serve as data containers in HBIM/BIM model.

The application of LoI and classification (Figure 55) is important for the following reasons:

- Comprehensive Decision-Making: Having comprehensive information linked to each element of the model allows for more informed decision-making. For instance, knowing the historical modifications and materials used in a building can guide restoration efforts and ensure that any interventions are sympathetic to the original structure.
- Maintenance and Management: Detailed information about materials, construction methods and historical changes is crucial for ongoing maintenance and management. This data helps facility managers plan maintenance schedules, predict future repairs, and manage the lifecycle of building components.
- Regulatory Compliance and Documentation: Detailed information is essential for ensuring regulatory compliance and preparing documentation for planning permissions, conservation approvals, and heritage listings.
- Enhanced Collaboration: Rich information models facilitate better collaboration among architects, engineers, conservationists, and other stakeholders. Everyone has access to the same data, reducing misunderstandings and improving coordination.

Level of Information Need (LOIN)

LOIN extends the concept of LoG and LoI by specifying the information required for particular use cases or users [ISO 7817-1:2024]. This approach ensures that the model serves the specific needs of various stakeholders, such as conservationists, researchers, or architects. For example, a conservationist might need detailed information about the materials and historical modifications, while a researcher might be more interested in the structural assessments and conservation documentation.

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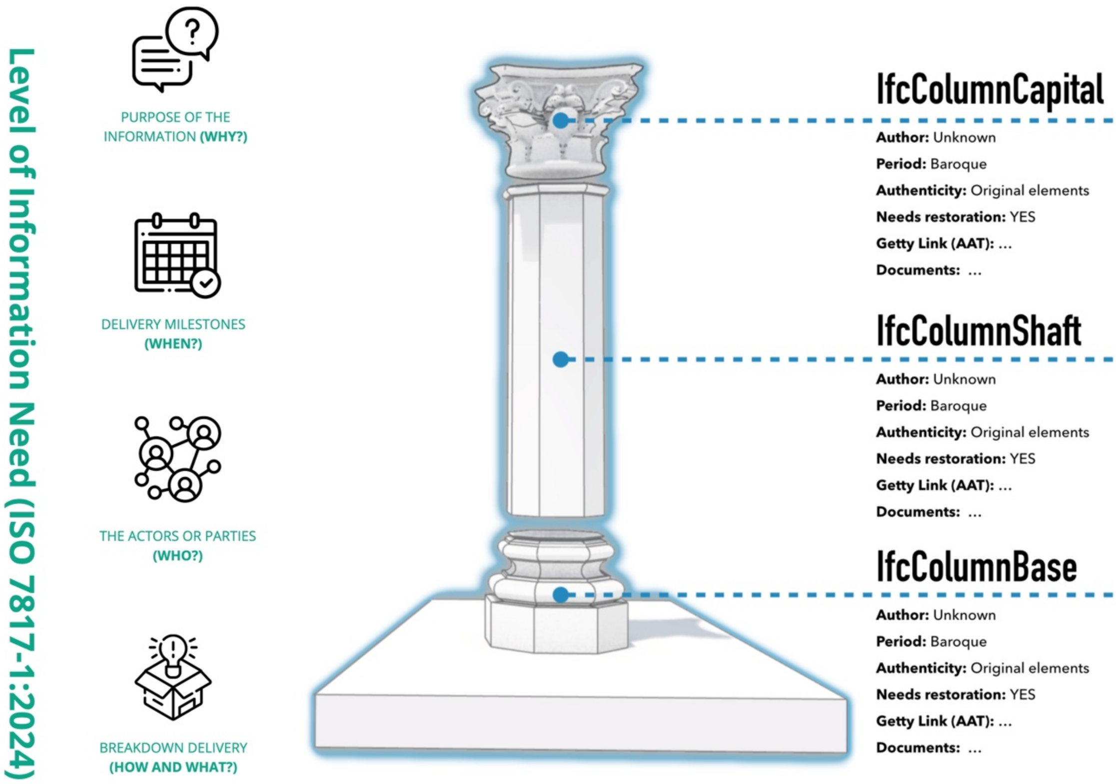

Figure 56: Level of Information Need as an International Standard ISO 7817-1:2024.

The application of LOIN (Figure 56) is important for the following reasons:

- Tailored Information for Stakeholders: By defining the LOIN, we can tailor the model to meet specific project requirements, ensuring that all necessary data is available for stakeholders. This targeted approach enhances the model's usability and ensures that it provides maximum value to all involved parties.
- Focused Data Management: LOIN helps in managing and focusing data collection and integration efforts, ensuring that only relevant information is included in the model. This prevents data overload and makes the model more manageable and efficient.
- Optimization of Resources: Tailoring information needs helps in optimizing resources, ensuring that effort and budget are directed towards gathering and maintaining data that is genuinely useful for the project.
- Enhanced Model Usability:
- Ensuring that the model meets the specific needs of its users makes it more practical and valuable. For instance, architects might need detailed geometric data, while conservationists require in-depth historical information.

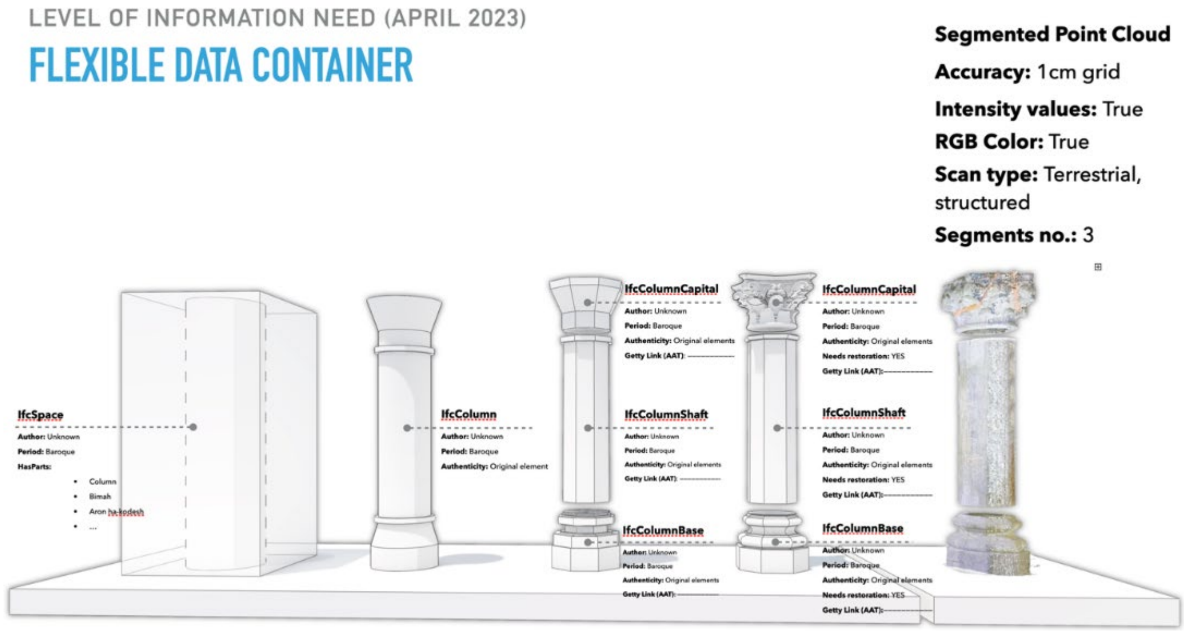

Figure 57: level of Information Need can serve different purposes. [Karol Argasiński, Piotr Kuroczyński, 2023].

Examples of LOIN in Practice:

- Conservation Projects: Detailed material and historical modification data to guide restoration efforts.
- Research Projects: Structural assessments, performance data, and comprehensive historical documentation.
- Construction Projects: Geometric precision and material specifications for accurate building and cost estimation.

Segmentation in BIM/IFC Models

Imagine we have an IFC (Industry Foundation Classes) [ISO 16739-1:2024] model of a historic building. The IFC model is a standardised, open data format that is widely used for sharing building and construction information. This model can be segmented by its structural elements, such as walls, floors, and roofs. Segmentation involves dividing the model into its constituent parts (Figure 57), each of which can be managed and analysed independently. This approach allows for a more granular level of detail and control over the model.

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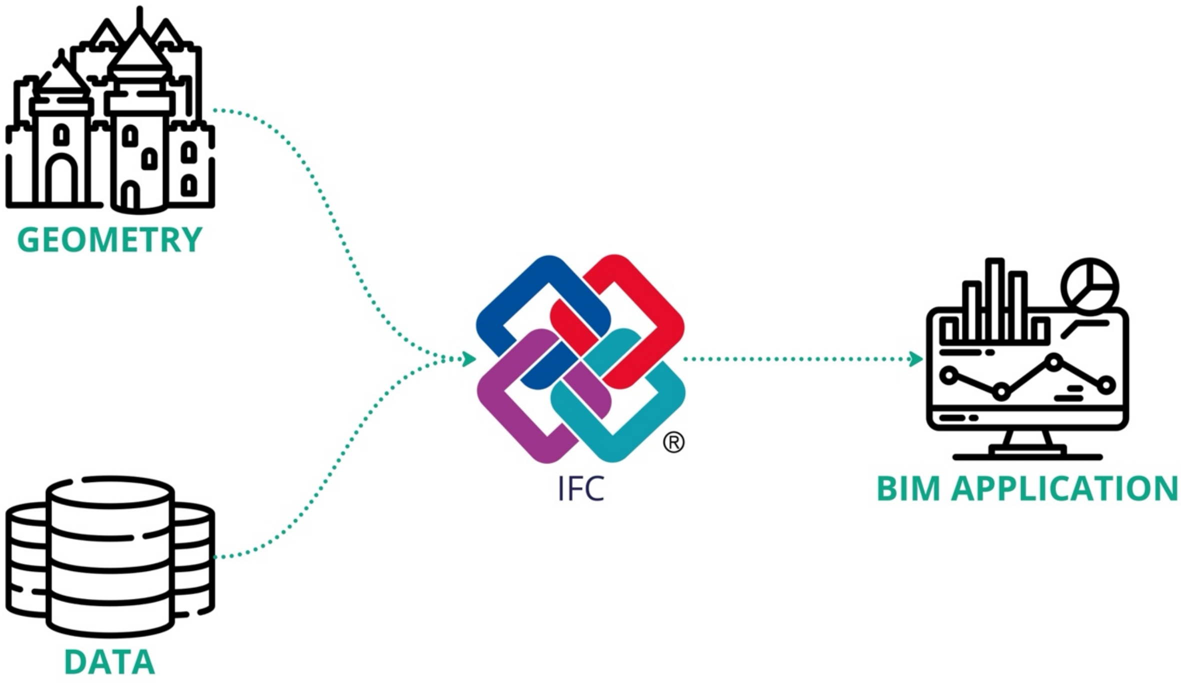

Figure 58: openBIM model can serve as a unified and universal data container for any type of construction model-based project.

Each of these segments can then be enriched with a wealth of data (Figure 58). For instance, the walls can have information on the materials used, historical modifications, structural assessments, and links to conservation documentation. This not only enhances the model's utility but also ensures that all necessary information is available for decision-making processes.

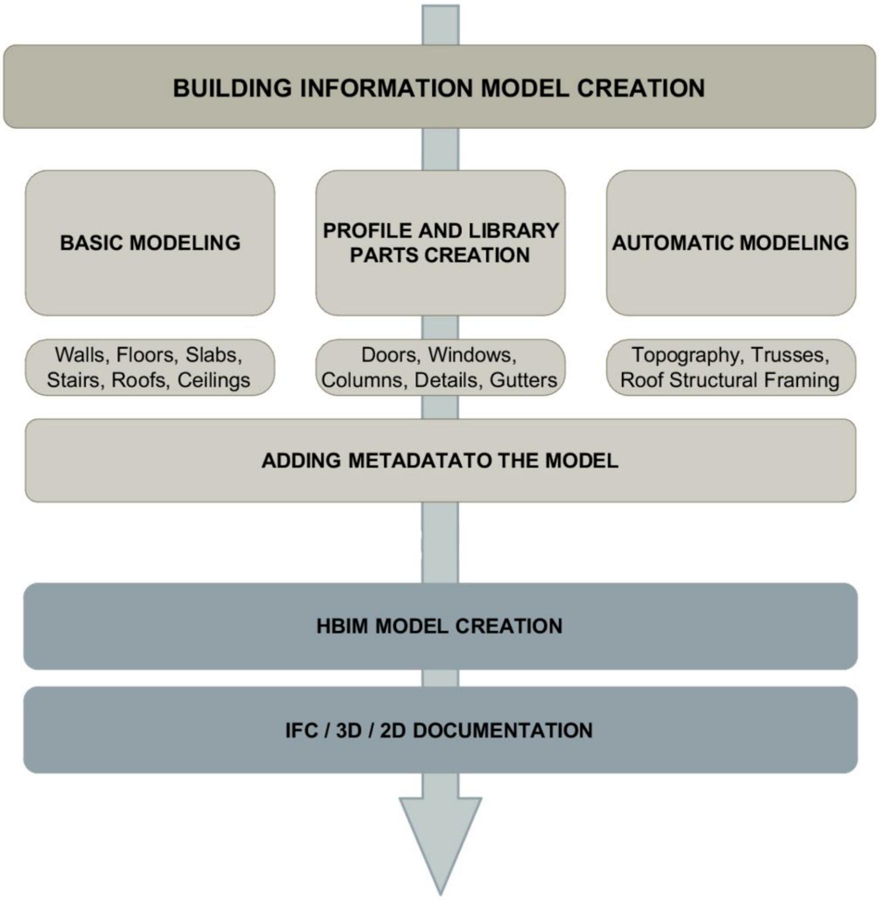

Figure 59: BIM model creation.

Let's analyse the example of BIM model segmentation. Note that the example (Figure 59) provides only a couple of element types:

Walls:

- Materials Used: Information about the types of materials (e.g., brick, stone, wood) used in the construction.
- Historical Modifications: Data on any changes made to the walls over time, including repairs, additions, and restorations.
- Structural Assessments: Reports on the structural integrity and any issues identified in the walls.
- Conservation Documentation: Links to documents detailing conservation efforts, preservation status, and guidelines for future work.

Floors:

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- Construction Materials: Data on the materials used in the flooring (e.g., marble, hardwood, tiles).
- Load-Bearing Capacity: Information on the structural capacity and any assessments performed.
- Historical Repairs: Records of past repairs and modifications.
- Maintenance Logs: Detailed logs of maintenance activities performed on the floors.

Roofs:

- Roofing Materials: Information about the materials used (e.g., shingles, metal, clay tiles).
- Weatherproofing: Data on the effectiveness of weatherproofing measures.
- Historical Interventions: Records of interventions, such as replacing damaged sections or reinforcing the structure.
- Conservation Plans: Documentation of plans and strategies for future conservation work.
- Benefits of BIM/IFC Model Segmentation

The segmentation in BIM/IFC models brings significant benefits. It facilitates efficient management and coordination among different professionals involved in the conservation or restoration of historical buildings. By segmenting the model, each part can be analysed, modified, or conserved separately, making the entire process more streamlined and manageable. For example, while one team works on the restoration of the roof, another can simultaneously focus on the conservation of the walls, ensuring that the project progresses smoothly and efficiently.

Figure 60: Model segmentation as a crucial differentiator of data inside the BIM model.

The segmentation in BIM/IFC models (Figure 60) brings significant possibilities:

- Efficient Management and Coordination: Segmentation facilitates efficient management and coordination among different professionals involved in the conservation or restoration of historical buildings. By segmenting the model, each part can be analysed, modified, or conserved separately, making the entire process more streamlined and manageable. For example, while one team works on the restoration of the roof, another can simultaneously focus on the conservation of the walls, ensuring that the project progresses smoothly and efficiently.
- Focused Conservation Efforts: Segmenting a model allows for a more detailed and focused approach to conservation. Each segment can be studied independently, and specific strategies can be developed for different parts of the building. This method supports parallel workflows, reducing the overall project timeline and improving efficiency. Specialized teams can work on their respective segments without interference, ensuring high-quality work and adherence to conservation standards.
- Improved Decision-Making: With detailed data available for each segment, stakeholders can make informed decisions. For instance, knowing the exact

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condition and historical context of a specific wall segment helps in choosing appropriate restoration techniques and materials. Segment-specific data allows for precise budgeting and resource allocation, optimising the conservation process.

BIM/IFC Model Enrichment

Enrichment in BIM/IFC models provides a comprehensive, multidimensional view of the structure. It incorporates not just the physical and geometric data but also historical, material, and conservation-related information. This holistic approach is crucial for informed decision-making in preservation efforts.

- Comprehensive Data Integration: Enrichment ensures that the model includes detailed information about materials, historical changes, and conservation status. This data is invaluable for planning and executing restoration projects, as it provides a complete picture of the building's history and current condition. For example, knowing the exact materials used in a historical building and their current conservation status can help in choosing the appropriate restoration techniques and materials, ensuring that the integrity and authenticity of the monument are preserved.
- Enhanced Utility: Enriched models serve as a valuable resource for a wide range of applications, from restoration and maintenance to educational purposes and research. By integrating extensive information, these models provide a deeper understanding of the building and support more effective preservation strategies. Educators and researchers can use these enriched models to study architectural history, conservation methods, and the impact of historical modifications.
- Support for Conservation Strategies: Enrichment supports the development of targeted conservation strategies by providing detailed insights into the building's structure and history. Conservationists can use this data to plan interventions that respect the building's historical significance and structural integrity. Detailed enrichment helps in documenting and preserving the building's history, ensuring that future generations have access to comprehensive records of its evolution.

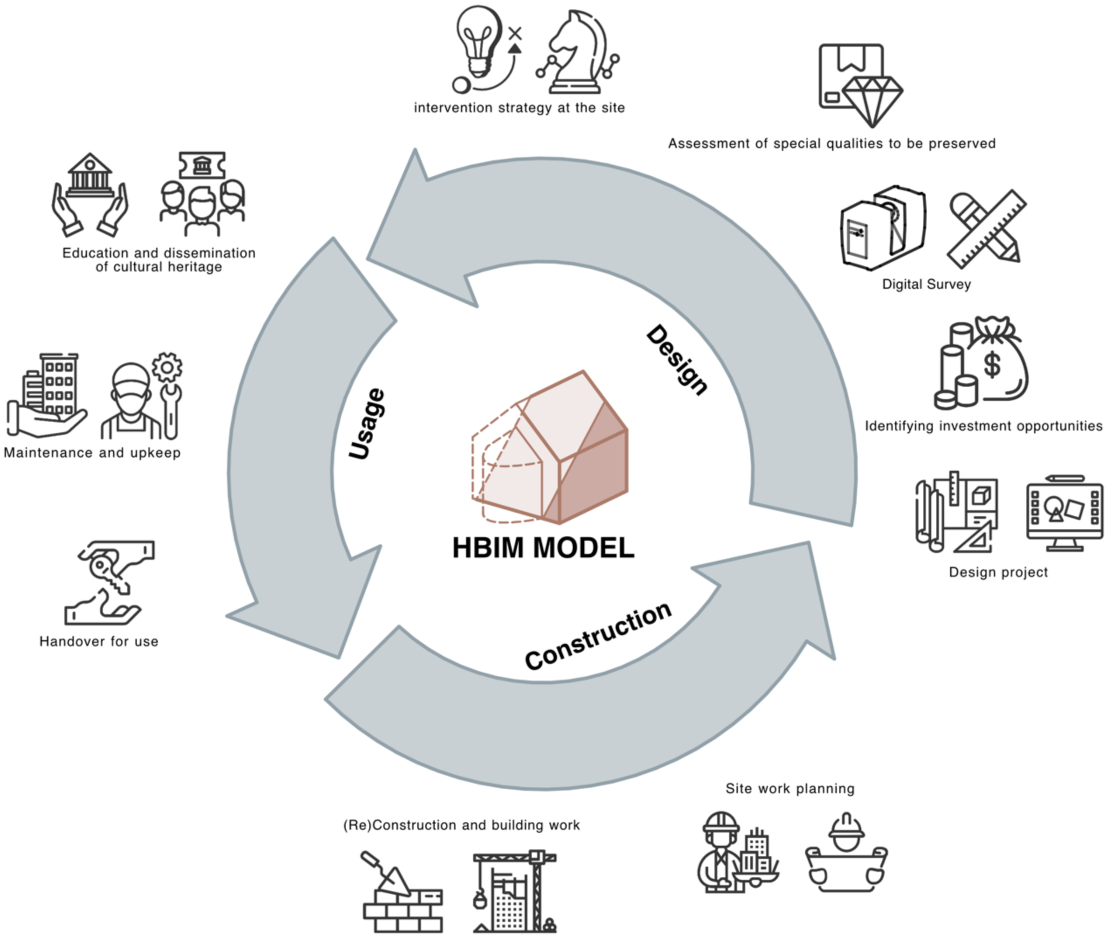

Figure 61: Different possibilities of maintaining and enriching BIM-based models.

Conclusions

The structured approach of BIM, incorporating LoG, LoI, and LOIN, along with segmented and enriched models, ensures that 3D models are not only visually and structurally accurate but also serve as rich information resources. This dual focus on geometry and information enhances the utility of models, making them indispensable tools for planning, construction, preservation, and educational purposes. By integrating these concepts, we are able to create digital models that capture the physical essence and cultural significance of historical monuments, ensuring their preservation for future generations to appreciate and learn from.

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12. Communicating the Uncertainty

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Is Communicating Uncertainty Important?

Figure 62: False-colour view of the uncertainty of the geometry of Piazza delle Erbe (image from [Apollonio et al. 2024])

In the context of hypothetical 3D reconstruction of lost or never-built architectures, documentation and dissemination processes, are of crucial importance because they contribute to increasing reproducibility and thus verifiability of the results by third parties.

Previous works, that set the basis for the CoVHer Erasmus+ project [CoVHer, 2022], such as the London Charter [London Charter, n.d.], the Seville Principles [Principles of Seville, 2017]; and the DFG German network [DFG website, n.d.; Münster et al., 2024], already highlighted the importance of documenting the reconstruction process, and have laid the groundwork for standardizing the scientific exchange of knowledge in this field. In particular, the assessment and communication of uncertainty is a fundamental part of the documentation and dissemination processes. The scale of uncertainty is a synthetic tool that allows evaluating at a glance the quality of the work and the level of reliability of the reconstruction, in a way that is accessible and comprehensible to both specialised scholars and laypersons in formal or informal contexts without necessarily needing to read all the specialistic appended documentation (metadata, paradata).

There are many ways to assess and communicate uncertainty, one of the most popular is through false-colour scales (Figure 62), the way these false-colour scales are designed and the way they are applied to the 3D models influence greatly the effectiveness of the communication and readability of the results. Aiming for an unambiguous, standardised methodology to build, document, and share 3D reconstructive hypothetical models is of crucial importance in order to avoid misconceptions, and prevent historical falsehoods.

What are the Most Common Ways to Quantify and Visualise Uncertainty?

Different approaches have been proposed over the years to measure uncertainty. Some are based on the assessment of the sources used or their characteristics [Ortiz-Cordero et. Al., 2018; Dell'Unto et. al. 2013], others use fuzzy logic [Nicolucci and Hermon, 2010], while others evaluate the quantity, age, or quality of archaeological remains [Pashkova, 2023]. Complex cases use the same scale to assess different features of the same 3D model [Apollonio et al. 2024] or multiple scales to assess various features of the same 3D model in form of multi-dimensional matrices, such as the Extended Matrix [Demetrescu, and Ferdani, 2021; Extended Matrix Glossary, (n.d.)].

To differentiate visually the various uncertainty levels, the most popular approach uses false-colour scales [Ortiz-Cordero et. Al., 2018; Dell'Unto et. al. 2013; Apollonio et al. 2024], others use different levels of transparency/alpha [De Luca et al., 2010], other uses lines or wireframes with different thicknesses and or treatments of the strokes [Kensek et al., 2004; Potter et al. 2007], and others uses patterns, or icons [Cazzaro, 2023].

Any of these methodologies have their criticalities and potentialities, but the most popular in the architectonic field is certainly the evaluation of uncertainty based on the assessment of the sources used and visualised through scales of false colours.

Why is it Important to Develop a Shared User-Independent Standard Method for Quantifying Uncertainty?

Numerous methodologies have been developed over the years for the assessment and communication of the uncertainty in the hypothetical architectural reconstruction field, however, there is still not a shared standard methodology. A shared standard methodology would help improve the readability and comparability of the results, crucial aspects in a shared scientific research environment.

If all scholars follow different methodologies and do not share a common way to disseminate and communicate the results the web repositories would be full of 3D reconstructive models hardly reusable by other scholars.

The academic community is already aware of the importance of communicating uncertainty and most scholars already adopt self-made methodologies and scales. Nevertheless, even if the objectives of different scales of uncertainty are the same, not all proposed solutions are equally effective. For example, sometimes scales are ambiguous, too subjective, inaccurate, difficult to apply, or even misleading.

Therefore, in the context of the CoVHer project, we have defined good practices for creating uncertainty scales that are reusable, exhaustive, unambiguous, and objective, and we proposed a ready-to-use scale, for hypothetical 3D reconstructions of lost or never-built architectures, that follows these principles.

How to Design an Effective Scale?

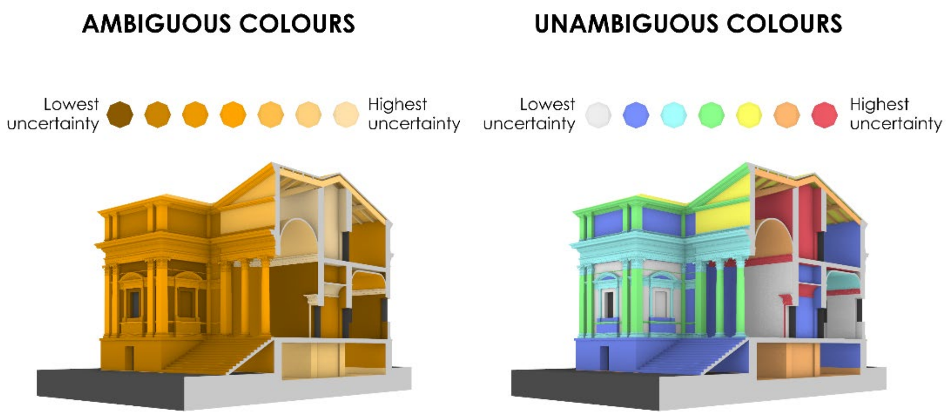

Figure 63: (left) ambiguous scale of colours that are too similar and hard to recognise, (right) a scale of colours that is unambiguous even when applied to a shaded model.

An effective scale must be: Reusable, Exhaustive, Unambiguous, and Objective.

- Reusable: means that it should be applicable not only to the project for which it was developed but also to other projects. This characteristic promotes the comparability of results in different case studies.
- Exhaustive: means that it must be complete for the context in which it was developed. It is important to design a scale with all the necessary levels to cover the widest possible variety of cases, even if not all levels are used in the study project. Adherence to this principle improves the reusability of the scale.
- Unambiguous: means that the scale should be clear, both regarding the recognizability of colours (Figure 63) and the clarity of textual definitions. This characteristic is important for improving readability, as well as its applicability. An ambiguous scale would contribute to producing different interpretations both in the analysis and in the fruition phase, an aspect to be avoided in a scientific context.
- Objective: means that two different operators that are asked to analyse the same hypothetical model should be able to independently produce comparable results. This characteristic is possible only if the definitions of the various levels of uncertainty are designed with attention to avoid overlaps, and if the assignment of these levels is based on a user-independent criterion.

The uncertainty scale developed for the Critical Digital Model [Apollonio et al., 2022], and refined in the context of the CoVHer project, is based on these principles and will be explained in depth in the next unit. It has proven effective for analysing, quantifying, and visualising the uncertainty of reconstructions of never-built or lost architectures, and has been further developed and refined for use in other contexts and up to the urban scale [Apollonio et al., 2022].

This solution is certainly not the only one possible; however, aspiring to develop an approach capable of quantifying uncertainty that becomes systematic even if only for certain categories of reconstructions, is crucial for improving the readability, comparability, and reusability of models published in a shared scientific environment.

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13. An Example of Scale of Uncertainty

Authors: Riccardo Foschi, Fabrizio Ivan Apollonio, Federico Fallavollita

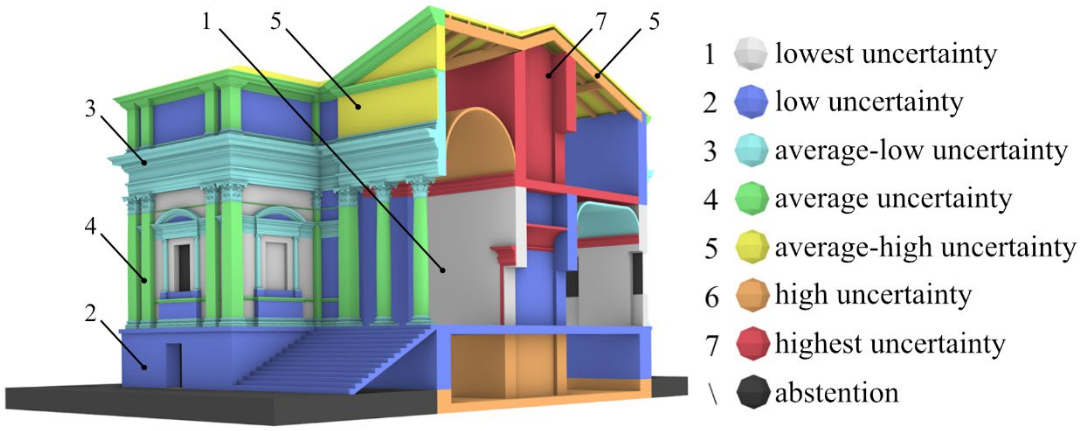

Figure 64: Example of a false-coloured 3D reconstructive hypothetical architectural model (image derived from [Apollonio et al., 2021] and further elaborated).

Among the various possible scales of uncertainty, in this unit, we will present the example of the scale developed over the years by the Department of Architecture of the University of Bologna for never-built or lost architectures, refined for the Critical Digital Model [Apollonio et al., 2021], updated to make it work also for urban-scale reconstructions [Apollonio et al. 2024], and further implemented and tested during the CoVHer project. This example is proposed more for its methodological value rather than its specific definitions or use cases. In fact, in some contexts, the textual definitions of the scale could not be sufficient to describe the complexity of the project. In these cases, the definitions could be changed, but if the structure of the scale and the methodology to quantify the uncertainty are preserved, the results will still be relevant and comparable. What matters is the proposed scheme based on a scale of seven values (that can be reduced to five and three) and an evaluation method based on a mathematical formula linked to the volumes of the architectural elements.

This scale consists of seven levels of increasing uncertainty plus one for abstention. Colours with varying hues have been assigned to the levels, ordered along the visible light spectrum, with white and black placed at the extremes of the scale. The colours were chosen in a way that could be easily named and recognised: white, blue, cyan, green, yellow, orange, red, and black. No rigid RGB values have been assigned to the colours to ensure versatility of use. It is possible to make slight variations to the colours as long as they remain recognisable and nameable, this ensures comparability across different projects. This scale has proven readable and effective for normal colour vision users, nevertheless, a visualisation that is effective also for every type of colourblind user might be a challenging future work. For now, adding the levels as textual callouts in the false-coloured images, as shown in Figure 64 is a provisional but effective solution.

Concerning the textual definitions of the various scale levels, they have been written synthetically and without overlaps to simplify the use of the scale (Figure 65). The assignation of the levels to each element of the 3D reconstructive architecture aims to be as user-independent as possible, which is why the uncertainty evaluation was chosen to be based mainly on the type, authorship, quality, and level of detail of the sources, all these pieces of information are obtainable as objectively as possible from the sources themselves and do not require a completely arbitrary guessing by the operator.

Colour Code	Uncertainty	Description
1	Lowest uncertainty (~0 to 14% uncertain [1])	The analysed feature [2] of the 3D model is derived mainly from good-quality, REALITY-BASED DATA which reaches the target LoD [3]
2	Low uncertainty (~14 to 28% uncertain)	Reliable conjecture based mainly on clear and accurate DIRECT [4]/PRIMARY [5] SOURCES which reach the target LoD. When REALITY-BASED DATA are unavailable, available but unusable, or not reaching the target LoD
3	Average-to-low uncertainty (~28 to 43% uncertain)	Conjecture based mainly on INDIRECT/SECONDARY SOURCES, by the SAME AUTHOR/S, which reach the target LoD, or logic deduction/selection of variants. When DIRECT/PRIMARY SOURCES ARE AVAILABLE, but minimally unclear, damaged, inconsistent, inaccurate, or not reaching the target LoD
4	Average uncertainty (~43 to 57% uncertain)	Conjecture based mainly on INDIRECT/SECONDARY sources by DIFFERENT AUTHOR/S (or unknown authors) which reach the target LoD. When DIRECT/PRIMARY SOURCES ARE AVAILABLE, but minimally unclear, damaged, inconsistent, inaccurate, or not reaching the target LoD
5	Average-to-high uncertainty (~57 to 71% uncertain)	Conjecture based mainly on INDIRECT/SECONDARY SOURCES by the SAME AUTHOR/S which reach the target LoD. When DIRECT/PRIMARY SOURCES ARE NOT AVAILABLE or unusable
6	High uncertainty (~71 to 86% uncertain)	Conjecture based mainly on INDIRECT/SECONDARY sources by DIFFERENT AUTHOR/S (or unknown authors) which reach the target LoD. When DIRECT/PRIMARY SOURCES ARE NOT AVAILABLE or unusable
7	Highest uncertainty (~86 to 100% uncertain)	Conjecture based mainly on personal knowledge due to missing or UNREFERENCED SOURCES
\	Abstention	Not relevant, not considered, left unsolved, missing data, and missing conjecture (does not count for the calculation of the average uncertainty).

[1] The % is calculated by dividing 100 by the number of steps of the scale.
[2] In our case, the features are geometry, constructive system, surface appearance, and position.
[3] The target LoD is the level of detail chosen for the reconstruction. Sometimes, the LoD provided by the sources does not reach the target LoD. In this case, new sources with higher LoD can be gathered.
[4] Direct sources are all the sources where the object is directly represented, reported, or recorded with any level of accuracy and detail (i.e., drawings, sketches, surveys, pictures, paintings, texts, books, coins, medals, reliefs, physical models, sculptures, etc.).
[5] Primary sources are first-hand sources providing information on a specific object.

Figure 65: 7 levels scale of uncertainty published in [Apollonio et al., 2024].

How to Improve Usability of the Scale and Why it is Important

If the uncertainty assessment methodology is too complex it would hardly be adopted by the scientific community, which would make the tool ineffective. For this reason, this scale was made in a way that was as simple as possible to use, without sacrificing the fundamental qualities of an effective scale (reusability, exhaustiveness, unambiguity, objectiveness).

To simplify its use in some contexts, the seven-level scale can be reduced to five or three levels, which can be used in case of reduced budget, time, or complexity of the case study. The more compact scales with five and three levels were designed to preserve the comparability of results with other projects even when they used a scale with different granularity, however, the accuracy of the result would be reduced due to bigger uncertainty steps in the scale. In the five-level scale, authorship is no longer considered, thus levels three and four are combined, as are levels five and six. Similarly, in the three-level scale, levels one and two are merged, along with levels three to six. Thus, the only criterion for quantifying uncertainty in the three-step scale is differentiating between direct and indirect sources.

Another tool to help new users in the application of the scale is the yes/no flowchart shown in Figure 66.

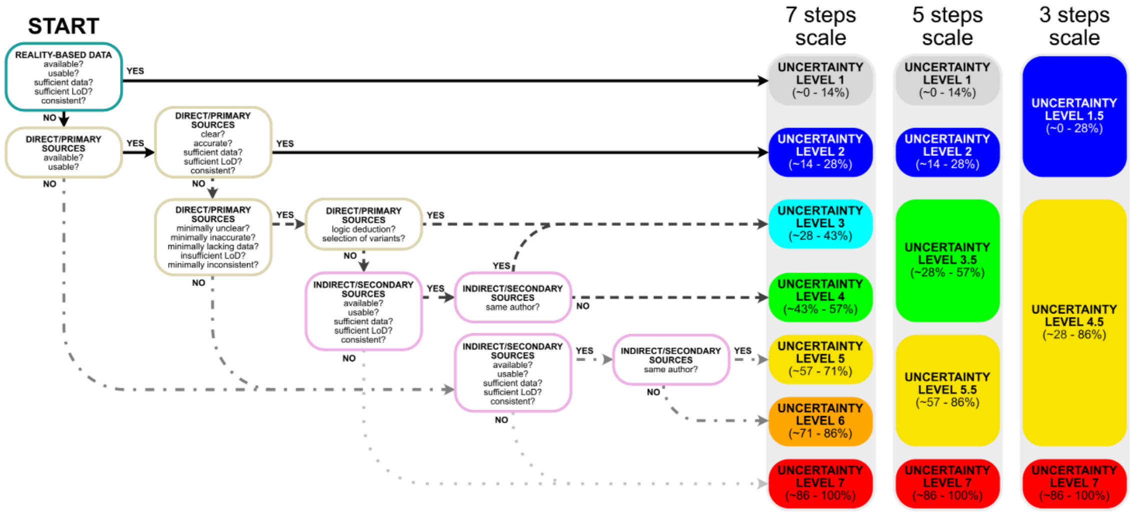

Figure 66: Yes/no flowchart published in [Apollonio et al., 2024]

Why is it Important to Calculate the Global Average Uncertainty?

False-colour visualisations are certainly useful tools for communicating information synthetically and at a glance for laypersons in dissemination contexts such as museums or documentaries. At the same time, for scholars and professionals, this tool can be viewed as an aid to have a preliminary synthetic view of the case study before reading the appended textual documentation.

Nevertheless, false-coloured views, despite being synthetic by definition, still need a certain time to let the viewer observe them and interpret the results, thus a further synthesis can be also useful. The two formulas of the Average Uncertainty Weighted on the Volume (AU_V) and the Average Uncertainty Weighted on the Volume and Relevance (AU_VR) serve this purpose. Each of these formulas produces a value that represent the extreme synthesis of the uncertainty assessment. These numbers could be useful, for example in the context of public online repositories as a preliminary way to filter and compare numerous reconstructive models. In order for these values to be comparable, however, they need to be calculated in the most user-independent way possible.

It is important to highlight that reconstructive models with higher uncertainty are not necessarily less scientifically valid or interesting. In fact, is often the opposite, because the scientificity of the study depends on its reproducibility and plausibility and not on its level of uncertainty, furthermore more uncertain reconstructions foster the scholarly discourse, and add more knowledge to the state of the art, by relating the case study to different sources.

How Does the AU_V and AU_VR Formulas Work?

Once the scale is applied, each element of the 3D model embeds, other than geometric and dimensional information, also information about its uncertainty, which is in the form of texts, colours and numbers. In the exemplificative case, each level of the scale has a numerical value from 1 to 7 which express the level of uncertainty. These numbers can be used as input for the AUV_ and AU_VR formulas to extract the global average uncertainty.

The reason why these formulas are designed like this is extensively explained in [Foschi et al. 2024], in synthesis, the formulas are simply averaging the uncertainty values of each element of the reconstruction and weighing them for the relative volume of each of these architectural elements. These formulas were developed because the probability formulation was not suitable for evaluating reliability in this field as already discovered by Nicolucci et al. [2010], and the arithmetic average without the weighting for the volume was not user-independent because returned different results based on how the model was segmented. The formulas are shown below:

$$\mathrm{AU\_V} = \frac{\sum_{i=1}^{n}(Vol_i \times Uncert_i)}{\sum_{i=1}^{n}(Vol_i)}\%. \quad (1)$$

$$\mathrm{AU\_VR} = \frac{\sum_{i=1}^{n}(Vol_i \times Relev_i \times Uncert_i)}{\sum_{i=1}^{n}(Vol_i \times Relev_i)}\%. \quad (2)$$

Where:

- AU_V: is the total average uncertainty weighted with the volume of the individual elements;
- AU_VR: is the average uncertainty weighted with the volume of the individual elements and a relevance factor assigned by operators based on their critical/subjective judgment of the importance of the individual elements;
- n: is the total number of elements;
- i: is the index of the considered element;
- Vol: is the volume of the considered element;
- Uncert: is the uncertainty value of the considered element.

- Relev: is the relevance factor of the considered element (which can be larger or smaller than 1 but never equal or smaller than 0).

The AU_V formulation is the most user-independent because the uncertainty values are assigned based on a scale that aims to be as objective and unambiguous as possible, and the volume is simply read by querying each element of the model from the CAD software of choice. This formula however prioritises the elements with larger volumes (such as: floors, walls, etc.) which might bias the result.

The AU_VR formulation tries to solve this problem by implementing the relevance factor which is assigned critically but subjectively by the operator performing the analysis. The relevance factor is a multiplicative factor that serve to increase the weight of some of the elements based on their importance. In other words, the volume of the most important elements can now be multiplied by a certain amount proportionally to their importance based on the judgement of the operator. Since the AU_VR formulation is more user-dependent/subjective but gives more knowledge-enriched results it is intended as complementary and not substitutive to the AU_V formula.

Why it is Important to Weight the Elements on Their Volume and the Relevance Factor?

The weighting with the volume is important because this guarantees that the result does not depend on how the model is segmented. Let us think about a simple example where the 3D model is subdivided into two parts, one part has a level of uncertainty equal to 1 and the second part a level of uncertainty equal to 4. The arithmetic average between the parts would be: (4+1)/2=2.5, now let us take the same model and subdivide one of the two parts into 4 individual parts, the formula would update as follows: (4+4+4+4+1)/5=3.4, as you can see the result changes drastically. This of course is not acceptable if the aim is objectiveness and comparability.

The weighting for the volume solves this problem because it makes the formula independent of how the model is segmented. Let us take the same example as before, but this time let us consider that each of the two pieces has a volume equal to 8 m3, the first formula would be updated as follows: [(4*8)+(1*8)]/(8+8)=2.5, and the second as follows: [(4*2)+(4*2)+(4*2)+(4*2)+(1*8)]/(2+2+2+2+8)=2.5, the results stayed unvaried despite the different segmentation, this is the AU_V formulation.

Let us consider the same example with two parts and let us imagine that one of the two parts is more important than the other; the previous formula does not highlight this. To solve this problem we can apply a relevance factor of 3 to one of the parts to change the result subjectively but critically. The example formula would become [(4*8*3)+(1*8)]/(8*3+8)=3.25, before the average uncertainty (AU_V) was equal to 2.5, now it changed to a value that is closer to the uncertainty of the part that was assigned with a greater relevance factor. This is the AU_VR formulation.

Which Tools can be Used to Automate These Calculations?

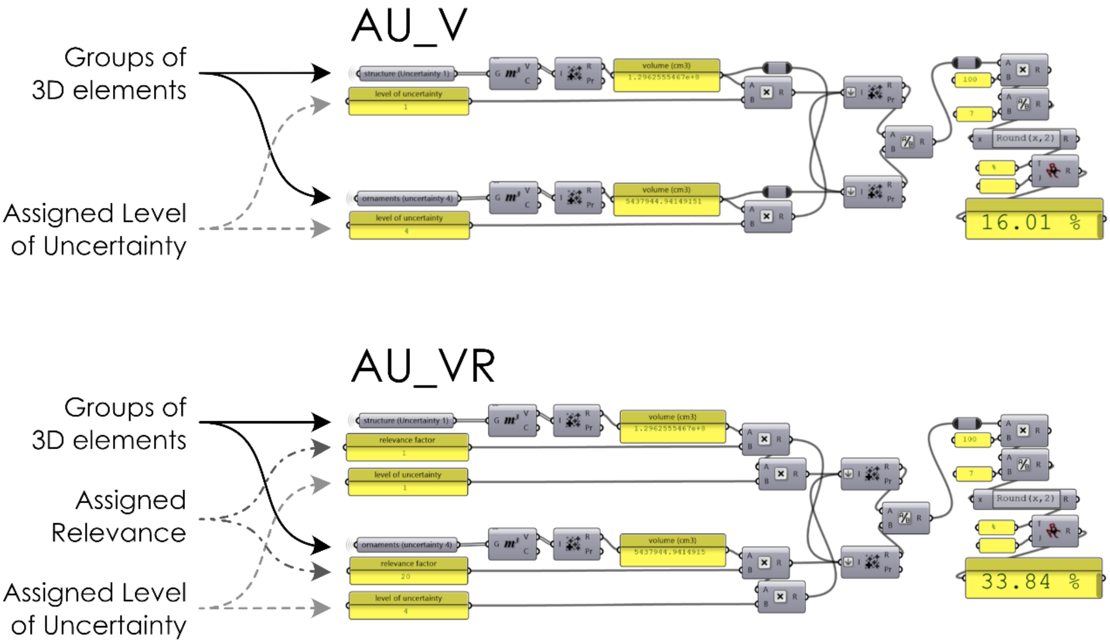

Figure 67: Grasshopper algorithm for the AU_V and AU_VR automatic calculation (for clarity's sake in the algorithm in figure there are only two levels of uncertainty and two relevance factors applied to the entirety of the object belonging to one of the levels).

The calculation of the AU_V and AU_VR could be performed manually as far as the volumes and uncertainties of each element of the model are known. However, since the 3D hypothetical architectural reconstructive models are usually made of hundreds of parts this solution would be too time-consuming. Thus, it is preferable to automatise the application of this formula through computer scripting. Grasshopper for Rhinoceros (or analogous tool) is a great solution since it provides a visual scripting interface integrated into a software package usually used by architects and designers. In Figure 67 two exemplificative algorithms for the application of the AU_V and AU_VR formulations are reported.

In the future, if an online repository adopts this methodology for the quantification of the uncertainty, it could process the model automatically and output the result without needing the users to calculate these values by themselves in advance.

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14. Visualising the 3D Model

Authors: Jakub Franczuk, Riccardo Foschi

Introduction to 3D Visualisation

Visualisation is a core aspect of 3D reconstruction, making complex data more accessible and comprehensible to everyone, from professionals to laypersons. 3D computer-based visualisation refers to all those methodologies adopted to produce, represent, describe, transmit, and present graphically/visually digital 3D models in a way perceivable by the human eye [Münster et al., 2024]. Visualisation involves various techniques to convey digital 3D models visually. [Roussou & Drettakis, 2003] This technology is essential in 3D reconstruction, enabling us to synthesise complex data into a visual format. Graphics help professionals in their fields and make it easier for the public to understand intricate concepts.

Similarly, digital 2D-3D visualisation is the process of creating graphics and renderings by combining 2D and 3D modelling and rendering software. This process has applications in diverse fields such as architecture, film, gaming, engineering, manufacturing, advertising, and fashion [Traviglia, 2015]. Before the widespread use of digital 3D modelling and visualisation systems, knowledge about the 3D world was often conveyed through 2D media (like paper or cloth) or physical 3D mock-ups made from wood, cardboard, or clay. Physical methods were labour-intensive and required significant manual effort for any modifications [Bendicho, 2013].

Digital 2D-3D visualisation allows for versatile use and implementation in the modern context. Static and dynamic visualisations from multiple points of view can be quickly produced and updated. This approach enables automatic checks for inconsistencies, easy extraction of analytical data (such as surface area and volume), and immersive explorations at different scales. [Bryan & Boardman, 2018] Despite these advantages, digital 3D models only approximate real objects and lack the tactile feel of physical models. Moreover, their long-term preservation poses challenges compared to physical counterparts, and adequate software and hardware are required to experience virtual content [Kuroczyński et al., 2019].

Interdependence of 3D Modelling and Visualisation

```
! Cube.gsm

pen gs_cont_pen
hLineID = 1000

if angle_1 > 0 or angle_2 > 0 Then
        HOTSPOT2 0,0
        project2{2} 3, 270, 32+3, gs_back_pen, 0, 0, 90
else
        if drawrubik then
                line2 a/3,0,a/3,b
                line2 2*a/3,0,2*a/3,b
                line2 0,b/3,a,b/3
                line2 0,2*b/3,a,2*b/3
        endif

        ADD2 a/2,b/2

        HOTSPOT2 0,0
        HOTSPOT2 A/2,B/2
        HOTSPOT2 -A/2,B/2
        HOTSPOT2 -A/2,-B/2
        HOTSPOT2 A/2,-B/2

        hotline2 -a/2,-b/2,a/2,-b/2, hLineID : hLineID = hLineID + 1
        hotline2 a/2,-b/2,a/2,b/2, hLineID : hLineID = hLineID + 1
        hotline2 a/2,b/2,-a/2,b/2, hLineID : hLineID = hLineID + 1
        hotline2 -a/2,b/2,-a/2,-b/2, hLineID : hLineID = hLineID + 1

        fill gs_fill_type
        poly2_b 5, 1+2+4+64,gs_fill_pen,gs_back_pen,
                A/2,B/2,1,
                -A/2,B/2,1,
                -A/2,-B/2,1,
                A/2,-B/2,1,
                A/2,B/2,-1

endif

end
```

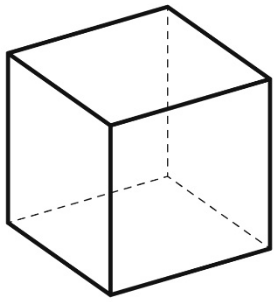

Figure 68: (left) COde in GDL creating a cube. (right) Visualisation of the code effect.

Visualisation is so essential that one might argue that 3D modelling and 3D visualisation are inherently linked. Creating a 3D model without continuous visual feedback would be almost unfeasible. [Bentkowska-Kafel et al., 2016] This visual feedback is indispensable at every stage, guaranteeing the final model's precision and detail. Without such feedback, we would be working with code, lacking an effortless way to verify the results (Figure 68).

This perspective aligns with the understanding that everything in modern computers is stored as sequences of ones and zeroes. Since binary code is impractical for human interpretation, it must be translated into a more comprehensible form and displayed visually. This necessity is particularly pronounced in the realm of digital 3D models. Their binary data must be processed and rendered visually for effective interaction and presentation, typically as RGB values on a display. The interdependence of 3D modelling and visualisation becomes clear, as one cannot feasibly exist without the other. In cultural heritage, generating a 3D model without ongoing visual feedback would be impossible. Visual feedback is not only crucial for verification but also for ensuring the accuracy and completeness of the final model.

Core Aspects of Digital 3D Visualisation

Four primary aspects contribute to the effectiveness of 3D visualisation: formal/geometrical, shading, representation methods, and media/interfaces [Kuroczyński et al., 2021].

- Formal/Geometrical Aspects: Formal and geometrical aspects involve the structural elements of the 3D model, including spatial relationships, levels of detail, and mathematical descriptions of surfaces. These aspects ensure that the 3D model accurately represents the dimensions and relationships of the modelled real-world or conceptual objects (Figure 69).

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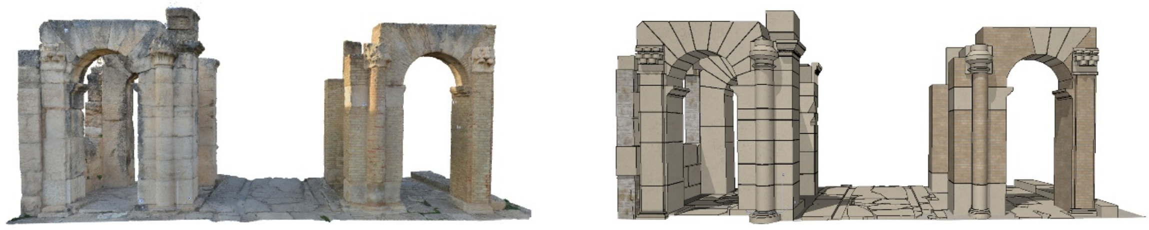

Figure 69: (left) Point cloud based on photogrammetric model.

- Shading Aspects: Shading aspects deal with the surface appearance of the 3D model, including textures, material properties, and the application of light and shadows. Shading can vary from photorealistic to abstract, depending on the desired effect. Photorealistic shading aims to replicate real-world appearances as closely as possible. In contrast, abstract shading might be used to highlight specific features or convey diverse types of information (Figure 70).

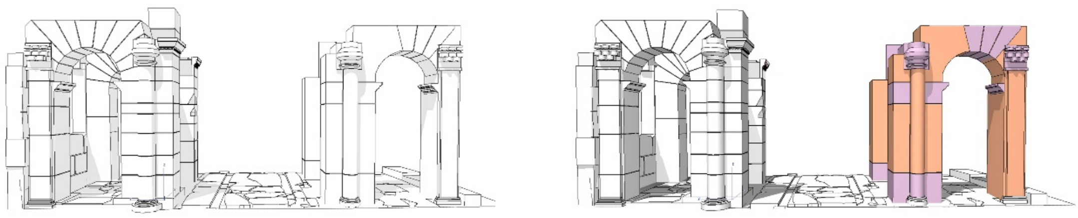

Figure 70: (left) White model. (right) Visually represented classification of elements: white - existing elements, orange recostruction based on archeological evidence, pink-anastylosis. Tripple double arch fate, Musti, Tunisia.

- Representation Methods: Representation methods can be categorised into traditional and digital. Traditional methods like those used in descriptive geometry include various projection techniques like double orthogonal, axonometric, perspective, and topographic terrain projections. These methods have been used for centuries to represent three-dimensional shapes on two-dimensional media. Digital representation methods, on the other hand, leverage the intrinsic mathematical and geometrical nature of 3D models. These methods include polygonal numerical modelling and Non-Uniform Rational B-Splines (NURBS) mathematical modelling. Digital techniques allow greater flexibility and precision in representing complex shapes and structures.
- Media and interfaces: 2D displays, such as computer monitors and projectors, have been the primary means of viewing 3D models. However, recent advancements have introduced more immersive technologies such

as Virtual Reality (VR), Augmented Reality (AR), 3D displays, and holograms. These new interfaces provide more engaging and interactive ways to explore 3D models, enhancing the overall visualisation experience. However, recent advancements have introduced more immersive technologies such as Virtual Reality (VR), Augmented Reality (AR), 3D displays, and holograms. (Figure 71). These new interfaces provide more engaging and interactive ways to explore 3D models, enhancing the overall visualisation experience.

Figure 71: monitors, smartphones, VR, AR, 3D display, hologram.

Viewing Technologies and Interfaces

The most popular media and interfaces for viewing digital content include 2D displays like those on smartphones, TVs, laptops, and desktop PCs. Although older technologies such as cathode-based displays are still available, they have been replaced by newer LCD and LED displays. These displays, primarily 2D, can also support 3D visualisation by reproducing two images simultaneously and synchronising them to give the illusion of depth through stereoscopic views. Techniques such as parallax displays offer depth perception without needing secondary optical devices. Head tracking or eye tracking can enhance visualisation based on the viewer's position, improving depth perception and interactivity while limiting the number of simultaneous users. Technologies like head-mounted displays, including VR headsets and holographic glasses, provide further options for immersive experiences. Additionally, fixed screens can be used for holographic visualisations, including volumetric displays of heritage objects.

Deviceless approaches, such as rapid prototyping of manufactured models or printed images, allow viewers to observe without specific devices. Rapid prototyping offers a more democratic way of presenting 3D objects, enabling direct interaction without prior digital tool knowledge. This approach also aids in understanding the relationship between 3D volumes and light interactions better than on-screen models. Despite these benefits, physical models can wear out, break, and take longer to produce and modify. They are also unsuitable for remote collaborative work or inspection at different scales.

Methods of Presenting 3D Models

Methods for presenting 3D models can be categorised in various ways, for example, they can be categorised based on the level of interactivity: static presentation, precomputed animated presentation, and interactive presentations.

- Static presentation (e.g. images): it is a quick and straightforward way to present 3D models. These images capture the model from a fixed viewpoint, providing a snapshot that is easy to share and view across various platforms. However, this method limits interaction, as the viewer cannot explore different angles or perspectives of the model. The fixed viewpoint offers no dynamic exploration but is helpful for documentation and initial presentations. (Figure 72).

Figure 72: Visualisation of the virtual reconstruction of Forum Transitorium, Musti, Tunisia.

- Precomputed animated presentation (e.g. videos, animations): it involves creating a predetermined sequence or tour of the 3D model, often rendered as a video. This method enhances depth perception through motion, giving viewers a better understanding of the spatial relationships within the model. While animations can effectively communicate complex scenes and transitions, they restrict the viewer's ability to navigate the model freely. These are typically used in educational materials, promotional content, and guided tours.
- Interactive presentation (e.g. computer games): it involves real-time and free exploration of a virtual 3D modelled scene, such as computer games or VR apps.

Other than the level of interactivity, the methods for representing 3D models can also be categorised based on the media/technology adopted, such as: traditional displays, interactive VR and AR headsets, holographic Displays, Rapid prototyping, etc.

- Traditional displays: they are the most popular way to represent 3D digital models. Since the visual output is not stereoscopic, the tridimensionality of the 3D digital object is explored by dynamically changing the point of view.
- Interactive VR and AR headsets: VR creates a fully immersive environment where users can navigate through the 3D model as if physically present. AR

overlays the 3D model onto the real world, allowing users to interact with it in a real-world context. These technologies provide a deeper understanding and engagement with the 3D model but require specialised equipment and software. Extended Reality (XR): encompasses both VR and AR, as well as Mixed Reality (MR), which combines elements of both. XR allows more advanced interactions and a seamless blend of real and virtual environments. Cultural heritage and education benefit from XR, where models can be placed in historical contexts or interactive educational settings. All these solutions can offer stereoscopic vision, and other depth cues such as motion parallax.

- Holographic Displays: present 3D models in a way that they appear to float in mid-air, viewable from multiple angles without the need for glasses or headsets. These displays can be used in museums, exhibitions, and marketing to provide a captivating viewing experience. They offer an impressive visual representation but are currently limited by excessive costs and technical complexity.
- Rapid Prototyping: Rapid prototyping involves creating physical models from digital 3D data through methods like 3D printing. This allows for tangible interaction with the model, offering a unique perspective to digital-only presentations. Physical models are valuable in design, architecture, and education, providing a hands-on understanding of the model's geometry, scale, and proportions [Münster et al., 2024]. However, this method is time-consuming and resource-intensive. By leveraging these various methods, the presentation of 3D models can be tailored to diverse needs and audiences, from quick visualisations and detailed guided tours to immersive and interactive experiences, enhancing both understanding and engagement with the models.

Shading Techniques

Shading is a critical component in visualisation and communication, enhancing the comprehension of 3D models while posing the risk of creating misleading impressions if not accurately applied. There are two primary shading techniques: photorealistic and abstract shading.

- Photorealistic Shading: Photorealistic shading aims to achieve high realism by accurately depicting material properties, textures, and lighting effects. This technique is commonly used in entertainment and visualisations that require a realistic appearance. However, the challenge lies in obtaining precise material information to ensure accuracy. For instance, achieving a scientifically accurate photorealistic rendering necessitates comprehensive documentation and careful management of uncertainties to avoid misinterpretation. Even with advanced rendering engines, achieving perfect accuracy can be difficult due to the limitations in the available data about the materials and lighting conditions (Figure 73).

Figure 73: (left) A photogrammetric model of a capital. (middle) A low-poly mesh model with a texture imitating reality. (right) A virtual 3D reconstruction using BREP geometry with the same texture.

- Abstract Shading: Abstract shading, or non-photorealistic (NPR) shading, simplifies representations to convey additional information effectively. Techniques such as false colouring and projection of graphical sources onto 3D models highlight specific aspects of the data (Figure 74). For example, false colours can indicate different levels of uncertainty, restoration stages, or historical layers, making it easier to communicate complex information at a glance [Münster et al., 2024]. This approach helps avoid the pitfalls of photorealistic shading by focusing on conveying data rather than replicating reality.

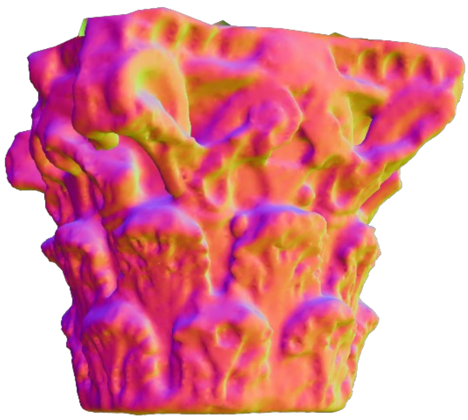

Figure 74: Photogrammetric mesh model of a capital with overlayed normal map to highlight face directions

Enhancing Understanding through Shading Techniques: Both shading techniques have their applications and can complement each other. In some scenarios, combining photorealistic and abstract shading can enhance the visualisation (Figure 75). For instance, photorealistic shading for well-documented areas and abstract shading for uncertain or conjectured model parts can provide a balanced representation. This combination can help users differentiate between verified data and hypothetical reconstructions, improving overall understanding and reducing the risk of misconceptions. In cultural heritage projects, accurately representing historical sites and artifacts is crucial. Misrepresentations, such as depicting Greek temples as plain white, can lead to widespread misconceptions. Using both shading techniques appropriately can ensure that such reconstructions are informative and visually accurate.

Figure 75: Figure 10: Example virtual reconstruction overlayed on the photogrammetric model, Musti, Tunisia.

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15. Introduction to Sharing the 3D Models

Authors: Igor Bajena, Piotr Kuroczyński

Why Should We Share the Data?

Digital technologies are rapidly transforming the world, providing new opportunities for the improvement of our lives. These technologies offer cultural heritage institutions more effective tools to engage broader audiences and the public to access, discover, explore, and enjoy cultural assets in innovative ways. They also open new possibilities for reusing datasets for the creation of innovative and creative services and products in various sectors, such as cultural and creative industries, education and tourism. Data sharing benefits not only the scientific community but the whole society. By making our data publicly available, we contribute to the expansion of knowledge in fields such as architecture and art history. This way allows the data to be used as derivatives to help disseminate an understanding of cultural heritage to a broader audience. Published 3D models can be used in the games and film industry as ready-made assets or in tourism and museums through use in augmented or virtual reality experiences. Furthermore, published 3D data can also contribute to preserving cultural heritage assets and foster the development of new tools for engaging with digital cultural resources.

Given these benefits, we should always consider making our data available online and providing open access to it. Any data created with academic rigor holds significant value. Even misrepresented reconstructions can serve as a foundation for initiating academic discussions and developing new, more accurate hypotheses. For this reason, it is strongly recommended that virtual, hypothetical reconstruction work should always be shared online with open access. Restricting results of such demanding intellectual work for personal use only, holds us back as a community from faster development and access to knowledge.

Importance of Documentation

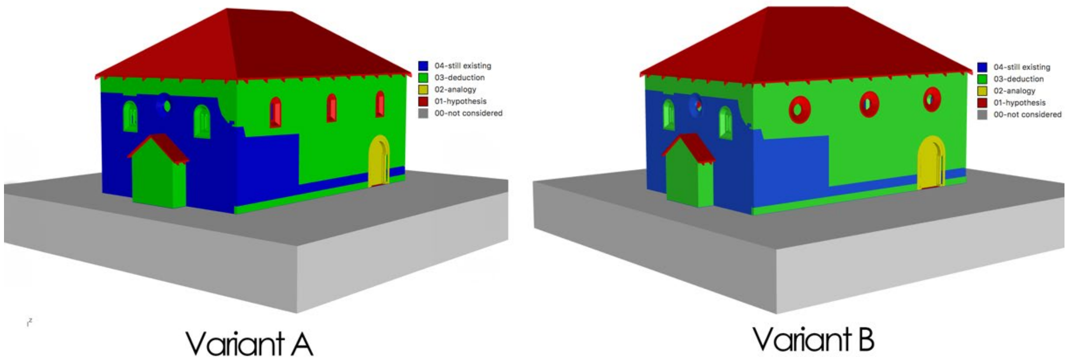

Figure 76: Presentation of two variants of the synagogue in Speyer as it was in 13th century with colour mapping of the levels of uncertainty of the reconstruction according to given scale.

The publication of data on the web involves the preparation of appropriate documentation. It should allow other users to explore, understand and reuse the data for their own purposes without unnecessary issues. Proper data documentation ensures transparency and validation of our work, minimising the risk of incorrect or misleading interpretations. Transparency is a cornerstone of scientific integrity, allowing others to investigate and understand the research process. This facilitates data sharing and reuse, as other researchers can confidently use the documented data for their own studies.

Documentation is particularly important in researching the past of a lost or never realised architectonical heritage, where we often cannot guarantee certainty of the form of reconstructed objects [Kuroczyński, 2017]. Often, the available source materials allow for multiple reconstruction variants and various saturation of levels of hypotheses (referred as levels of uncertainty) for different object's components (Figure 76). Without proper documentation, we cannot communicate our thinking and critical analyses that led us to the this results. This, in turn, can lead to incorrect conclusions from an incomplete presentation of the entire process.

Publication Objectives and Their Implications

Sharing data requires providing access through publication in an online repository or a digital archive. Each platform for publishing data may require specific preparation, influenced by various factors, where the target audience is one of the most significant. Why do we publish data? Who intends to use it, and for what purpose can data be used? Answering these questions can help us structure our document and the files we want to share.

Hypothetical digital reconstructions are a humanistic field of science. One of the main problems is the lack of transparency in research and reuse of 3D data. These issues primarily concern academia and researchers working on architectural heritage reconstructions. Therefore, they are responsible for providing accessibility, reliability and information transparency in their data [Bajena & Kuroczyński, 2025]. There are many groups showing interest in using 3D models in practice, such as students and educators involved in the history of architecture and art, museums and cultural institutions, and finally, professionals from a wide range of expertise, such as artists, architects, game designers, animators and others. However, matching a potential user's needs requires documenting 3D model specifications in certain aspects, e.g. the technological solutions used, the historical context of the building, or possible ways of integrating the model with other data [Albrezzi et al., 2022]. We often cannot clearly define or predict our target audience, but we can publish our data for the general public. In this case, it is a good idea to include complete documentation that should meet the expectations of audiences from different groups of users.

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16. Digital 3D Model Documentation

Authors: Igor Bajena, Piotr Kuroczyński

Definition and Guidelines

In the context of 3D reconstruction, documentation can be understood as a set of digital and non-digital materials in the form of texts and multimedia (3D models, 2D images, videos, presentations, etc.) complementing the 3D reconstruction model with additional information concerning the authenticity, hypotheses, source materials and their analysis, as well as archival, historical, archaeological and architectural research that have been conducted, and other materials supporting a good understanding of the reconstruction process [Bajena & Kuroczyński, 2025].

Every digital reconstruction project is unique and requires a different approach to documentation. While no standards have emerged for the scientific documentation of digital models of architectural monuments of the past, attempts have been made to set some requirements. Over the years, joint efforts have led to the publication of two important documents: the London Charter (LC) [2009] and the Seville Principles (SP) [2017]. They constitute a set of guidelines for computer-based visualisation of cultural heritage, where a significant part is devoted to documentation. The extracted documentation guidelines from both documents are shown in Table 1 and Table 2.

These guidelines cover three groups of documentation problems:

- Documentation Content: What information should the documentation include in addition to visual materials?
- Visual Presentation: What issues should visual materials address, and how should they be prepared?
- Documentation Output: How should all the collected materials be organised and presented as a cohesive, comprehensible document for the reader?

Table 1: A list of guidelines related to the documentation of digital reconstruction extracted from the London Charter (LC). The yellow colour distinguishes the principles for documentation content, the grey colour for documentation output, and the green colour for visual presentation.

London Charter (2009) guidelines on documentation			
Code	**Text of principle**	**Topic**	**Group**
LC 3	*In order to ensure the intellectual integrity of computer-based visualisation methods and outcomes, relevant research sources should be identified and evaluated in a structured and documented way.*	*Sources, Structure*	*Documentation Output*
LC 4.1	*Documentation strategies should be designed and resourced in such a way that they actively enhance the visualisation activity by encouraging, and helping to structure, thoughtful practice.*	*Structure*	*Documentation Output*

LC 4.2	*Documentation strategies should be designed to enable rigorous, comparative analysis and evaluation of computer-based visualisations, and to facilitate the recognition and addressing of issues that visualisation activities reveal.*	*Evaluation*	*Documentation Output*
LC 4.3	*Documentation strategies may assist in the management of Intellectual Property Rights or privileged information.*	*Intellectual Property*	*Documentation Content*
LC 4.4	*It should be made clear to users what a computer-based visualisation seeks to represent, for example, the existing state, an evidence-based restoration or a hypothetical reconstruction of a cultural heritage objector site, and the extent and nature of any factual uncertainty.*	*Knowledge Claims*	*Documentation Content*
LC 4.5	*A complete list of research sources used and their provenance should be disseminated.*	*Sources*	*Documentation Content*
LC 4.6	*Documentation of the evaluative, analytical, deductive, interpretative, and creative decisions made in the course of computer-based visualisation should be disseminated in such a way that the relationship between research sources, implicit knowledge, explicit reasoning, and visualisation-based outcomes can be understood.*	*Paradata*	*Documentation Content*
LC 4.7	*The rationale for choosing a computer-based visualisation method, and for rejecting other methods, should be documented and disseminated to allow the activity's methodology to be evaluated and to inform subsequent activities.*	*Methodology*	*Documentation Content*
LC 4.8	*A description of the visualisation methods should be disseminated if these are not likely to be widely understood within relevant communities of practice.*	*Methods*	*Documentation Content*
LC 4.9	*Where computer-based visualisation methods are used in interdisciplinary contexts that lack a common set of understandings about the nature of research questions, methods and outcomes, project documentation should be undertaken in such a way that it assists in articulating such implicit knowledge and in identifying the different lexica of participating members from diverse subject communities.*	*Terminology*	*Documentation Content*
LC 4.10	*Computer-based visualisation outcomes should be disseminated in such a way that the nature and importance of significant, hypothetical dependency relationships between elements can be clearly identified by users and the reasoning underlying such hypotheses understood.*	*Levels of Hypothesis*	*Visualisation Presentation*
LC 4.11	*Documentation should be disseminated using the most effective available media, including graphical, textual, video, audio, numerical or combinations of the above.*	*Formats*	*Documentation Output*
LC 4.12	*Documentation should be disseminated sustainably with reference to relevant standards and ontologies according to best practice in relevant communities of practice and in such a way that facilitates its inclusion in relevant citation indexes.*	*Standards*	*Documentation Output*

Table 2: A list of guidelines related to the documentation of digital reconstruction extracted from Seville Principles (SP). The yellow colour distinguishes the principles for documentation content, the grey colour for documentation output, and the green colour for visual presentation.

Seville Principles (2017) guidelines on documentation			
Code	***Text of principle***	**Code**	**Group**
SP 4.2	*Prior to the development of any computer-based visualisation, the ultimate purpose or goal of our work must always be completely clear*	*Goals*	*Documentation Content*
SP 4.4	*Computer-based visualisation normally reconstructs or recreates historical buildings and environments as we believe them to have been in the past. For that reason, it should always be possible to distinguish what is real, genuine, or authentic from what is not. In this sense, authenticity must be a permanent operational concept in any virtual archaeology project.*	*Authenticity*	*Visualisation Presentation*
SP 4.4.1	*Since archaeology is complex and not an exact and irrefutable science, it must be openly committed to making alternative virtual interpretations, provided they afford the same scientific validity. When that equality does not exist, only the main hypothesis will be endorsed.*	*Versioning*	*Visualisation Presentation*
SP 4.4.2	*When performing virtual restorations or reconstructions, these must explicitly or through additional interpretations show the different levels of accuracy on which the restoration or reconstruction is based.*	*Levels of Hypothesis*	*Visualisation Presentation*
SP 4.4.3	*In so far as many archaeological remains have been and are being restored or reconstructed, computer- based visualisation should really help both professionals and the public to differentiate clearly between: remains that have been conserved "in situ"; remains that have been returned to their original position (real anastylosis); areas that have been partially or completely rebuilt on original remains; and finally, areas that have been restored or reconstructed virtually.*	*Authenticity*	*Visualisation Presentation*

Co-funded by the Erasmus+ Programme of the European Union

SP 4.5.1	*The historical rigor of any computer-based visualisation of the past will depend on both the rigor with which prior archaeological research has been performed and the rigor with which that information is used to create the virtual model.*	Historical rigor, Paradata	Documentation Content
SP 4.5.2	*All historical phases recorded during archaeological research are extremely valuable. Thus, a rigorous approach would not be one that shows only the time of splendour of reconstructed or recreated archaeological remains but rather one that shows all the phases, including periods of decline. Nor should it display an idyllic image of the past with seemingly newly constructed buildings, people who look like models, etc., but rather a real image, i.e. with buildings in varying states of conservation, people of different sizes and weights, etc.*	Historical rigor, Phases	Visualisation Presentation
SP 4.5.3	*The environment, landscape or context associated with archaeological remains is as important as the ruin itself (Charter of Krakow, 2000). Charcoal, palaeobotanical, palaeozoological and physical paleoanthropological research must serve as a basis for conducting rigorous virtual recreations of landscape and context. They cannot systematically show lifeless cities, lonely buildings, or dead landscapes because this is a historical falsehood.*	Historical rigor, Context	Visualisation Presentation
SP 4.7.1	*It is clear that all computer-based visualisation involves a large amount of scientific research. Consequently, for the virtual archaeology projects to achieve scientific and academic rigor, it is essential to prepare documentary bases in which to gather and present the entire work process in a completely transparent fashion: objectives, methodology, techniques, reasoning, origin, and characteristics of the sources of research, results and conclusions.*	Transparency	Documentation Output

Documentation Content

Documentation Content should include a list of the source materials used [LC Principle 4.5], along with their paradata [LC Principle 4.6, SP Principle 4.5.1]. Paradata are data about the process, in this case, about our research and digital reconstruction. They can present critical analysis and interpretation of collected sources, module analyses, comparative analyses with similar objects and much more. Paradata can also refer to evaluating our source materials in terms of their readability, consistency, or assessment of the level of uncertainty for our reconstruction.

In addition, we should attach to the documentation a description of the research methods [LC Principle 4.7, LC Principle 4.8] and a clear presentation of the assumptions and objectives of the conducted research [LC Principle 4.4, SP Principle 4.2]. A good practice is also to adhere to the intellectual property of the materials used [LC Principle 4.3] and to clarify specialised terminology [LC Principle 4.9]. For digital reconstructions, we may use terminology specific only to our field or even to a research group. In that case, referring to established glossaries in the documentation makes a significant difference to the clarity of the provided information.

The Art & Architecture Thesaurus® Online [The Getty Research Institute, n.d.] may be helpful here for terms related to architecture and art history. Some concepts related to preserving 3D models are presented in the glossary of terms developed by the Community Standards for 3D Data Preservation [CS3DP, 2020]. The terminology associated with hypothetical digital reconstructions, 3D modelling technologies and digital representation of models has not yet been standardised. We addressed this issue in our glossary, which provides clear concept definitions for the documentation of virtual reconstructions.

Visual Presentation

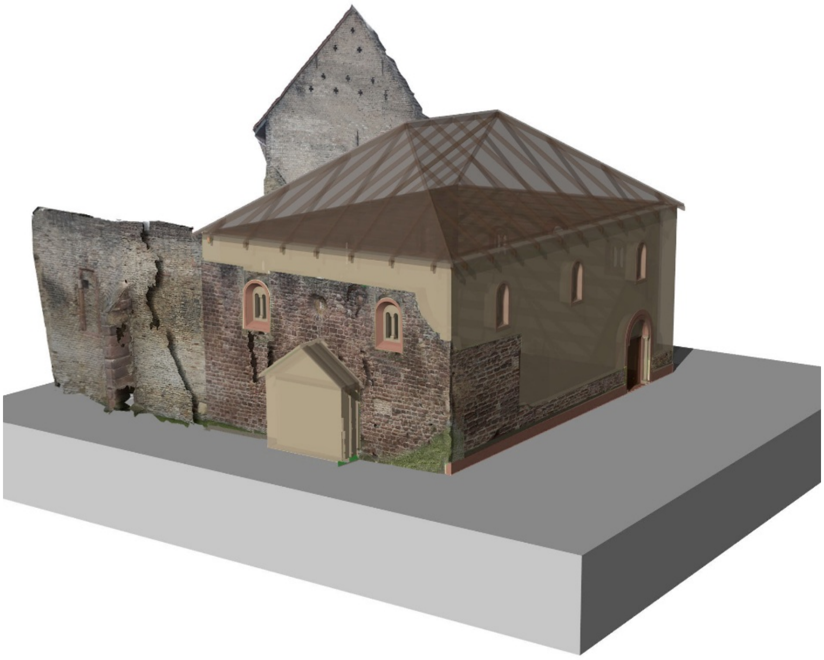

Figure 77: Presentation of the reconstruction project of the Speyer Synagogue (Germany) as it was in the 13th century, showing the elements still preserved today.

Visual presentation of the reconstruction project should allow the identification of authentic elements of the object [LC Principle 4.10, SP Principle 4.4.2] and different levels of reconstruction uncertainty [SP Principle 4.4, SP Principle 4.4.3] (Figure 77). Besides, if alternative reconstruction hypotheses arise, we should document them accordingly [SP Principle 4.4.1] (Figure 78). The presentation of visual materials should also maintain historical rigour (Figure 79). This means documentation of all construction phases and recording changes in their original structure over time. For many buildings, the presentation of only one phase in the lifespan of a building does not allow its history to be captured. It is necessary to present, or at least mention, all other historical phases of the object.

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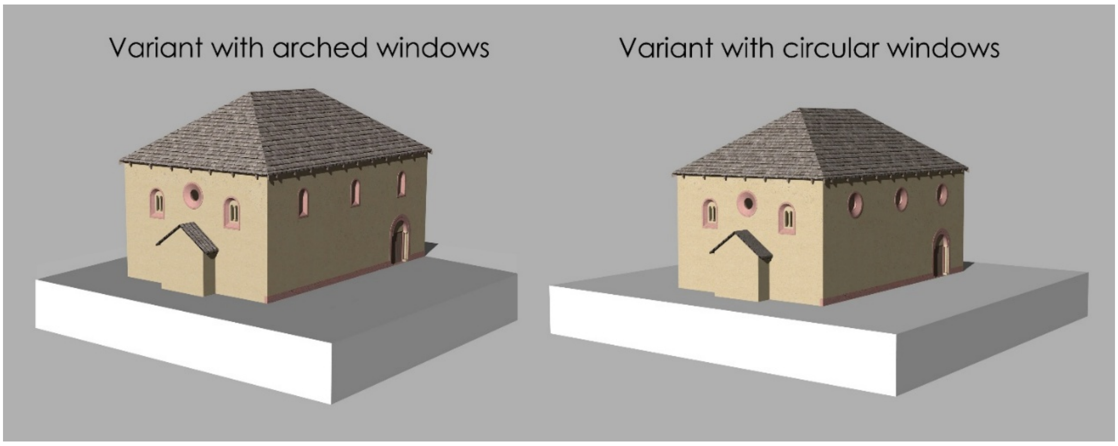

Figure 78: Presentation of the reconstruction project of the Speyer Synagogue (Germany) as it was in the 13th century, a comparison of two possible reconstruction variants.

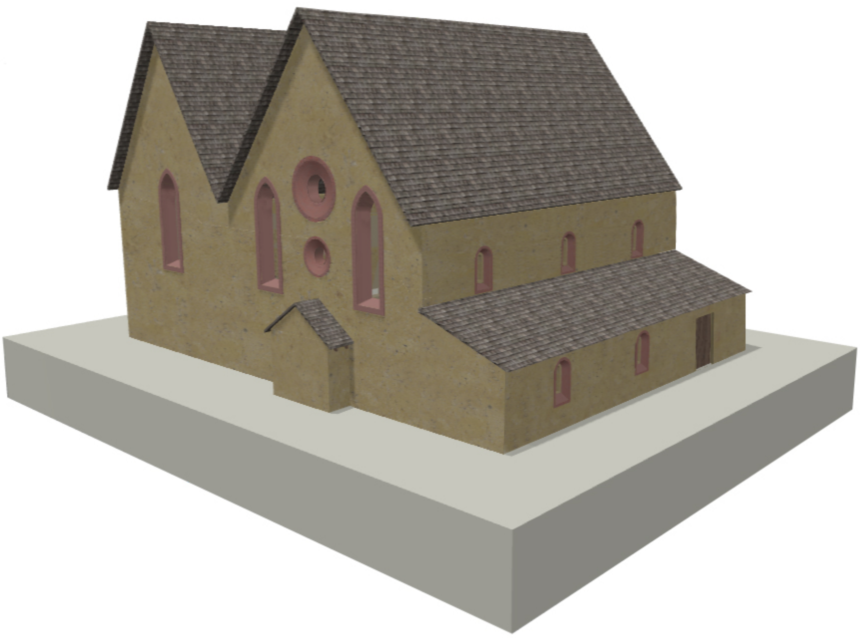

Figure 79: Presentation of the reconstruction of the Gothic phase of the Speyer Synagogue (Germany) as it was in the 15th century

Finally, our object should be presented in the context of its surroundings [SP Principle 4.5.3] (Figure 80). Reconstructing architectural objects without embedding them in their surroundings can result in reconstruction errors that cannot otherwise be caught. It is also a kind of inconsistency, as architecture cannot exist without being embedded in a specific context, the absence of which can alter the perception of space.

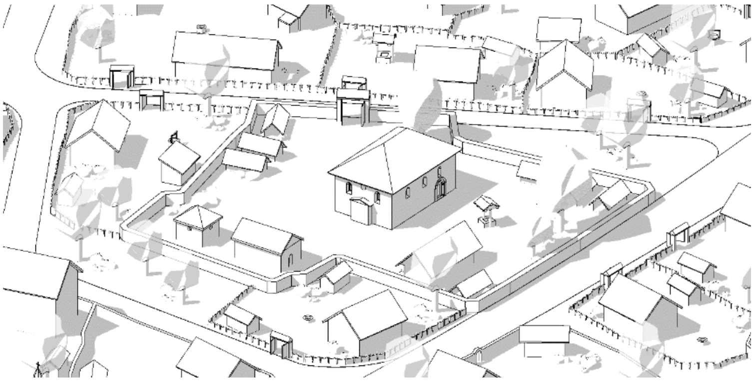

Figure 80: Presentation of the reconstruction project of the Speyer Synagogue (Germany) as it was in the 13th century, setting object in the context of a medieval town

Documentation Output

Documentation output has to be prepared in a structured manner [LC Principle 3, LC Principle 4.1], ensuring complete research transparency [SP Principle 4.7.1] and allowing for evaluation in terms of historical or scholarly rigour [LC Principle 4.2]. This means introducing a hierarchical structure for our documentation, dividing it into sections and subsections and naming the appendices accordingly. Maintaining a fixed naming scheme for files is good practice. It should be understandable not only to the creator but also to others. To set the order in which the files are displayed, an identification number can be entered before the proper name to maintain the desired sorting, even when the file names are not alphabetical. If we want to maintain version control of our documents, using dates in the naming system is a good idea. This can be done by using a prefix with the formatting YYYYMMDD before the actual file name, where YYYY stands for the year, MM for the month and DD for the day. Applying a naming system to our files will also make management of our project much easier.

We should also rely on relevant standards and use the most effective data formats [LC Principle 4.11]. Some of the communities around digital reconstruction have developed their own methods that are worth applying. For example, those trained as architects may prefer to provide documentation similar to architectural design and use 3D file formats tied to HBIM. At the same time, art historians may desire a descriptive text of the entire process with extensive references. On the other hand, computer graphic designers may desire only a brief technological specification and an easily integrable 3D file in a common data exchange format. The documentation preparation should reflect our intentions and clearly communicate the purpose for which the 3D model has been developed.

Methods of Documentation – Graph

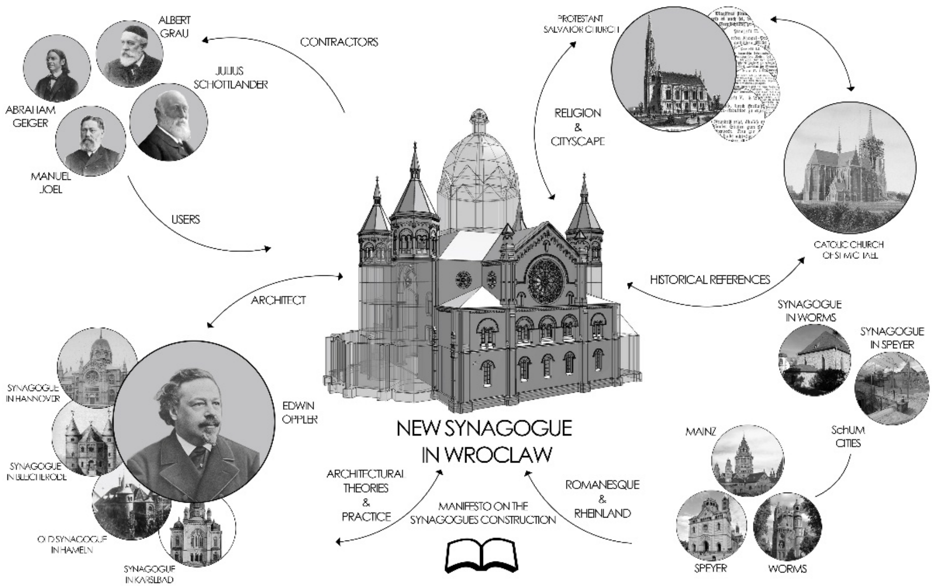

Figure 81: Map of the project of the New Synagogue Reconstruction in Wroclaw (Poland) with the use of a graph.

Documentation can be developed in many ways. No guidelines have emerged to indicate the superiority of one method of virtual 3D reconstruction documentation over another. The most common method is to produce an illustrated text or multimedia presentation of the project. Both of these methods are widely used in academic and scientific communities and are based on generally accepted standards for scientific work.

One of the more unconventional documentation methods is using a graph. Graphs are an effective method of documentation, representing information as a collection of nodes (or bubbles) connected by edges (or lines). These edges indicate the relationships between different entities. Within each node, we can include various types of information, such as source materials, analogies, people, visualisations of reconstructions, and many other elements. This approach allows us to create a comprehensive mind map of our project (Figure 81).

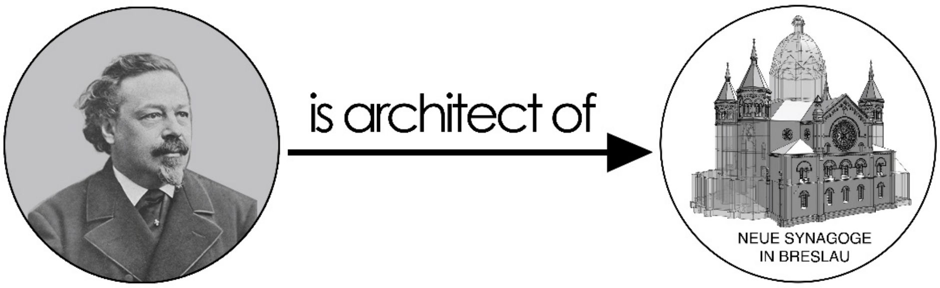

Figure 82: n example of a triple showing the relationship between two entities: a person and an object of New Synagogue in Wroclaw. The label 'is the architect of' is a predicate that defines the relationship type. Arrow below label indicates direction of the relationship.

By specifying the type of relationship that each edge represents, we create a special kind of graph known as a knowledge graph [Gutierrez & Sequeda, 2021]. In a knowledge graph, two nodes connected by a defined relationship form a structure called a "triple" (Figure 82). Using graphs in this way provides a clear, visual method for documenting complex information and the relationships between different data points, facilitating better understanding and accessibility. This structured representation of knowledge is widely used in computer science to store data in relational databases [Kuroczyński et al., 2021].

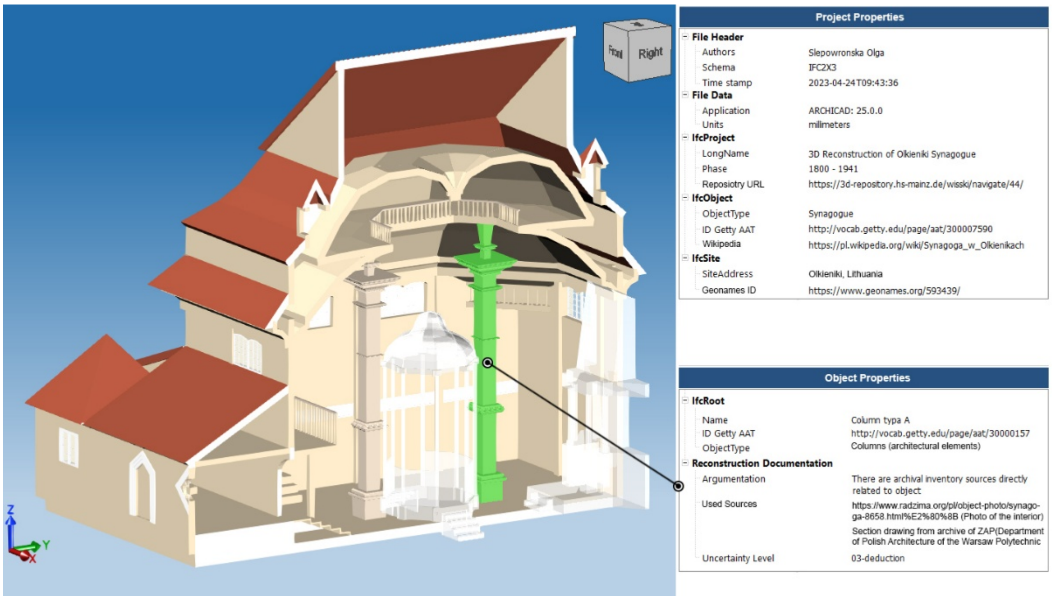

Figure 83: Example of reconstruction documentation directly in a 3D model using IFC format on the example of the Olkieniki Synagogue reconstruction.

Another method involves integrating documentation into the 3D model. We can do this directly in the 3D modelling software or during the creation of data deposit in a repository with a web-based 3D viewer equipped with an annotations feature. Inserting documentation directly into our 3D programme requires using a tool called object properties. It allows each element of the 3D model to be represented as an object with specific properties, such as material, condition, or historical significance (Figure 83). It is one of the basic principles of BIM (Building Information Modelling) and HBIM (Heritage Building Information Modelling) used in the architecture design and construction domain. This approach allows for detailed documentation and analysis, as properties can be customised to include information on hypothesis levels, sources used, and other relevant data. Exchange of data within this method requires the exportation of the file to one of the standardised file formats, such as Industry Foundation Classes (IFC) or Geography Markup Language (GML), which can be opened in free 3D file viewers [Kuroczyński et al., 2023].

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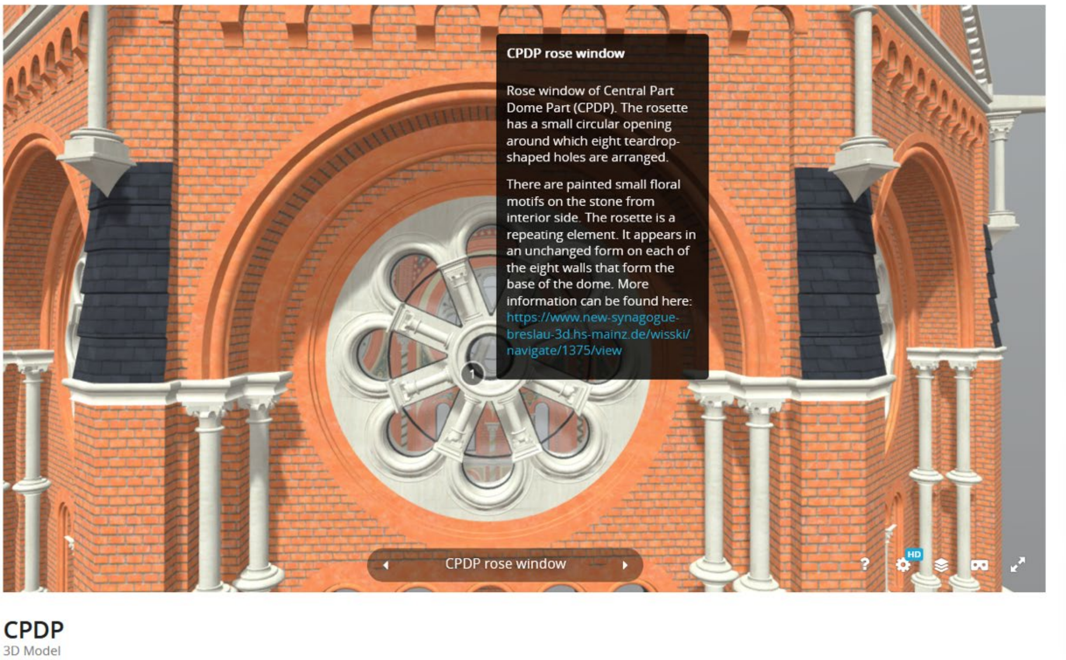

Figure 84: Example of annotations attached to 3D reconstruction of the Dome Part of the New Synagogue in Wroclaw in Sketchfab viewer.

Adding documentation as multimedia annotations to the 3D model requires a web-based 3D viewer. Viewers such as Sketchfab, Smithsonian Voyager, or Kompakkt support this function. Each of these solutions allows you to test their functions for free. The annotations allow the creation of an interactive point on the model's surface, which, when clicked on, can display the desired text or multimedia (Figure 84). However, it should be borne in mind that the preparation of this type of documentation requires additional work after the publication of the 3D model itself. In addition, this work is carried out in the viewer software interface, which differs significantly from the modelling software. The preparation of annotations may also require formatting our documentation material to the requirements of the selected online viewer.

Reconstruction Argumentation Method and IDOVIR

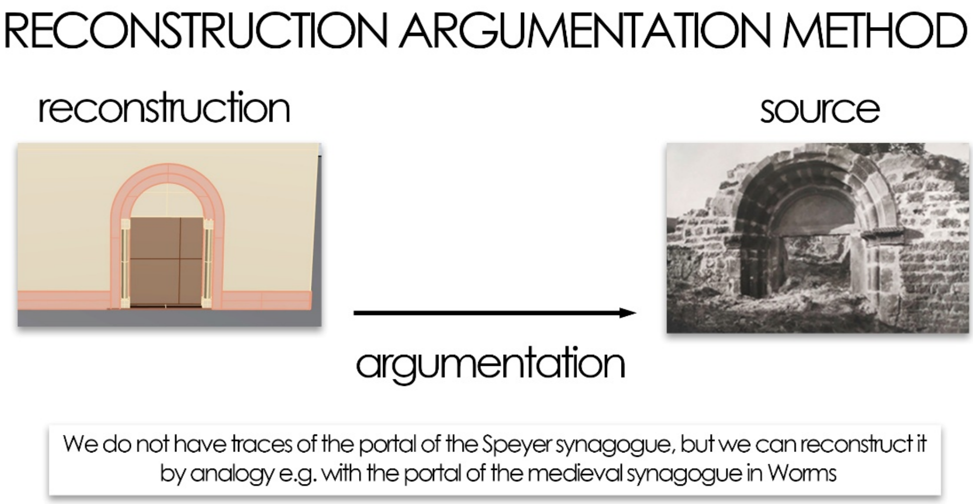

Figure 85: A triple representation of the Reconstruction Argumentation Method (RAM. On the right is a historical source; on the left, a digital reconstruction is presented. Below is the argumentation describing the relationship between source and reconstruction.

Among the diverse documentation methods used for virtual 3D reconstruction, the Reconstruction Argumentation Method (RAM) appears to be the most optimal in terms of effort for the results obtained [Grellert et al., 2018]. This method uses the fundamentals of the graph concept in its principles. It relies on the triple created from the historical source, the visualisation of the reconstruction and the link between them with a predicate containing the argument of the presented reconstruction (Figure 85).

By combining the visualisation of the reconstruction with the source material, we can make quick comparative analyses to assess the compatibility of the reconstruction with the source. I and spot any inconsistencies or errors. Additionally, textual argumentation can clarify spotted inaccuracies or uncertainties. This combination of visual and textual documentation helps preserve the historical rigour of the reconstruction and provides a comprehensive understanding of the decision-making process.

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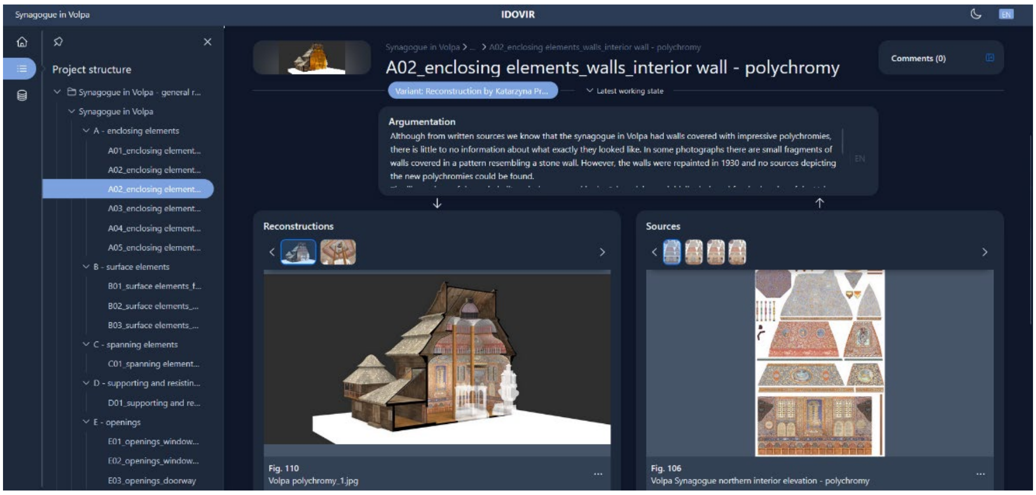

Figure 86: Use of the RAM method in the documentation of the polychrome reconstruction of the Volpa Synagogue in the IDOVIR system

An infrastructure for the documentation of virtual reconstructions (IDOVIR) has been created based on this method as the principle(Figure 86). Thanks to its intuitive interface and ease of use, we can relatively quickly obtain appropriately structured and formatted documentation, which can be exported from the system in PDF [Grellert et al., 2023]. As the platform's developers write: "The research project IDOVIR strives for making results in the field of digital architectural reconstruction available in a comprehensible, permanent, and open-access form and to facilitate scientific discussion of the research results. The project outcome is to be seen as documentation of decisions, i.e., presentation of:

- the reasons for a specific reconstruction,
- further possible variants,
- comprehensible documentation of negative results.
- Central here is the textual argumentation, i.e., a qualitative analysis that connects a digital reconstruction with sources and which only makes it possible to trace the connection between the sources used and the reconstruction. At the same time, the project infrastructure should support and meaningfully structure the communication of those involved in the genesis of a reconstruction.
- The goal is a freely accessible, web-based, collaborative online platform based on the latest server and web technologies, so easy to understand within a 15-minute briefing time. Based on the preliminary work of the TU Darmstadt and the HTW Dresden, the advantages and synergies of both systems are to be consolidated in a common platform. Many analysed projects have shown that instead of a uniform documentation structure, the researchers involved wish for different scenarios of documentation."
- Our practical tests of the platform have given positive results, so we recommend trying it to document your own reconstruction and test systems functionality. To make the process easier, we have prepared a short guidebook to help you navigate throughout the platform, which is

available at the following link (https://seafile.rlp.net/f/c97de58da2714acba510/).

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17. Publication Process and Requirements for Web-Based Repositories

Authors: Igor Bajena, Piotr Kuroczyński

Publication Methods

A well-documented 3D reconstruction model can be a valuable knowledge resource, but only when one condition is met. It requires making our reconstruction data public to others through the publication process. The publication differs from the documentation. It focuses not on the whole process but on presenting the final results. It is the public release of a digital resource consisting of a 3D reconstruction alongside available documentation that allows a specific target group to explore, validate, and use the 3D model [Bajena & Kuroczyński, 2025]. Also, although the publication does not focus on the process, the documentation should supply it with additional information to better understand our reconstruction.

We can divide publications into digital and non-digital. Non-digital publications refer to all books, journal articles, and printed advertising material, such as tourist leaflets. Digital publication is based on making a certain data set available in a digital repository or archive. Unlike a non-digital publication, the data itself can be made available as a valuable scientific package. As with documentation, the choice of publication method depends mainly on the target audience. When choosing a digital publication, it is worth focusing on platforms that offer open access to published resources. It makes it easier for potential audiences to find and use our project results.

A further subdivision of digital publications may include direct and indirect methods. The direct method involves publishing the model as a 3D file. The release of 3D data allows for the direct analysis of our model. Unfortunately, the use of the data will only be limited to practitioners of 3D modelling in the programme in which the model has been created. There are some methods that can increase the interoperability of the published model, such as the use of web-based 3D viewers or the publication of data exchange file formats. You can find an example of direct publication as a record in a virtual research environment of the project of virtual reconstruction of the New Synagogue in Breslau: https://www.new-synagogue-breslau-3d.hs-mainz.de/wisski/navigate/1480/view.

In the indirect digital publishing method, we do not share the 3D file but its derivatives. These may include 2D visualisations, animations, graphics, plans, and many other materials prepared based on our model, but the 3D model itself has not been made public. By using derivatives, such as images or videos, which are easier

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to access than 3D files, the chances of reusing the results of our work may increase. However, we take away the opportunity for users to analyse our model. This method of publication may also be more advisable when our 3D model is restricted for legal reasons.

An example of an indirect publication as a video derivative can be found under the following link: https://vimeo.com/417172262.

FAIR Principles

Data for publication should be properly prepared and structured i so that they can be used by others. The usability of the data is influenced by several factors, which are known as the FAIR Principles [Wilkinson et al., 2016]. They are guidelines that aim to improve the Findability, Accessibility, Interoperability, and Reusability of data. These principles ensure that data is properly managed and shared to maximise its utility and impact in the scientific community and beyond.

The findability and accessibility of published data depend to a large extent on where one chooses to deposit the data. More common repositories can increase a file's findability but may not provide sufficient fields for data description. The input fields in repositories, known as metadata, serve as a package of basic information about our resources, which can enhance the findability of our data. The other important factor is ensuring that the repository of our choice guarantees a unique identifier for our deposit, which allows indexing our data and, as a result, also fosters the visibility and findability of our deposit.

While FAIR Principles attribute most of the responsibility for published data to metadata and the way it is stored and preserved, it is also worth keeping an eye on other factors. The accessibility of a file is largely determined by the license we grant when uploading the model to the web. To allow access to the data, it is advisable to use open licenses that do not restrict the use of the data. Alternatively, we can choose one of the Creative Commons licenses, designed to share creative work in a way that fosters collaboration between creators [Creative Commons, 2019].

Interoperability and reusability, in turn, depend largely on our working habits on the file and our decision on the data format. 3D files based on popular formats such as OBJ, STL or IFC can significantly affect the level of interoperability of a resource. Preparing a file for reuse, on the other hand, requires stripping it of all redundant information. We need to remove unnecessary geometry and take care of the appropriate structure and naming of layers and elements in the model. We must ensure that our file is as clear and understandable as possible.

3D Viewers for Web Browsers

3D models can weigh up to several GB without proper processing. Forcing the user to download such large data packages without the possibility of prior data verification will make our data package unusable. Including appropriate documentation can, of course, partially reduce this problem, but the best solution is to provide a preview of the 3D data. This can be achieved by using 3D viewers that have been designed to run in our web browser.

The 3D viewer is a feature that allows us to view 3D data. It differs from 3D modelling software, where we can change the model's geometry. The 3D viewer is limited in functionality to manipulate how geometry is displayed. It is also important to distinguish between the concept of a repository and a 3D viewer. A repository is a database which function is to store files. It does not need to be equipped with a viewer. Some repositories have their own viewers with the same name (e.g. Sketchfab or Kompakkt), which can be confusing. There are also many open viewers, which require you to set up your own server in order to use them (e.g. Model Viewer, 3D HOP, Smithsonian Voyager, or Portree).

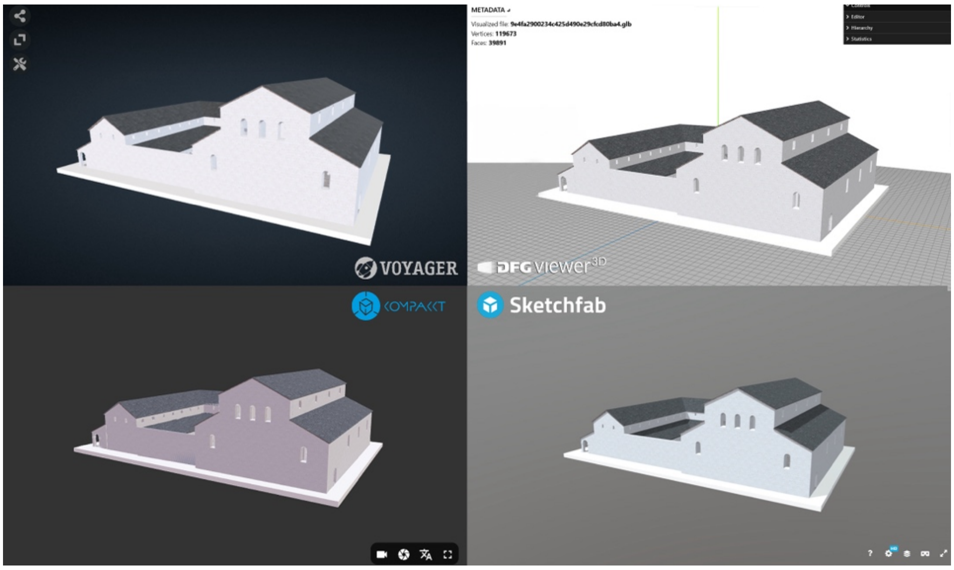

Figure 87: Overview of the visualisation of the reconstruction of the church of St Johannis in Mainz as it was in 9th century in four selected 3D viewers, starting from the top left corner: Smithsonian Voyager, DFG 3D-Viewer, Kompakkt, Sketchfab.

The 3D model's visualisation in the web viewer serves as a preview of our data and does not require a data download. This allows an initial verification and inspection of the model before further work. It can also serve as an attractor to encourage the user to explore our work further. Therefore, it is worth checking whether the repository of our choice is equipped with a 3D viewer tool. It should also be taken into account that different viewers may have different capabilities in terms of the appearance and quality of the visualisation (Figure 87), as well as available additional features such as annotations, 3D sections or manipulation of the 3D environment [Champion et al., 2020].

Preparation of 3D File for Web Browsing

Web-based 3D viewers have some limitations on the 3D files we can use. They are not equipped with the computing power to match our local computers, so it is important to check whether our 3D model is suitable before uploading the file. The

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general requirements are very similar to those for preparing augmented or virtual reality application models and are as follows:

- Reduced number of vertices: The most important factor is the number of vertices. If our model has approached 2 million vertices, it will probably strain the viewer.
- Triangulated mesh: It is a good idea to convert the model mesh into triangles, which are more optimised for web browsing. The maximum number of triangles should not exceed 230,000.
- Optimisation of textures: The smaller the texture size is, the better the model's performance in the viewer. The recommended texture resolution is 1024 x 1024 px.
- Pivot in the object centre: The pivot point is the point in space that defines the mathematical centre of the object for rotation and scaling (Figure 88). If it is not in the centre of mass of your model, its rotation and movement can be difficult.
- Machine-readable file naming: Some viewers may have problems reading files with spaces or native linguistic characters and accents, such as ‘ą’, ‘ć’, ‘ä’, ‘ß’, etc. Use only letters from the English alphabet in file names, and use ‘-’ or ‘_’ instead of spaces. This rule also applies to the naming of texture files!

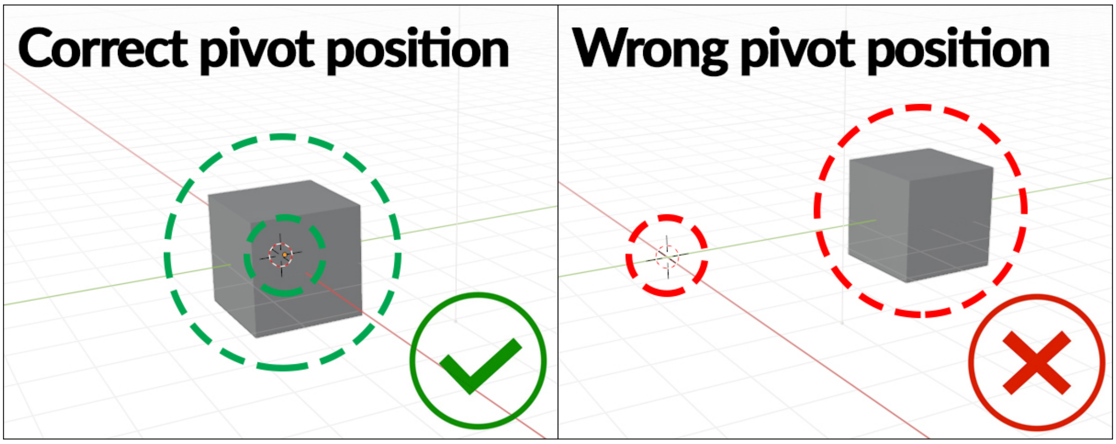

Figure 88: Overview of correct and incorrect placement of the pivot relative to the 3D object.

Once these points have been verified, the model should be exported. Unfortunately, online viewers only support a small number of file formats. The list of supported formats often differs from viewer to viewer, so it is worth checking directly with the repository of your choice. One of the safest options is the OBJ format, which most viewers include. Export is the process of automatically translating our model into a completely different format, changing how texture and geometry information is stored. As a result, after exports, our model may look differently from what we see in our modelling software. For this reason, we should verify the appearance of the 3D model after export before blaming the web viewer. This can be done with the free 3D software Blender.

Several elements can go wrong:

- flipping the Y and Z axis system, which causes a 90-degree rotation of the model;
- no textures or wrong mapping of textures;
- wrong normal of surfaces;
- position of the model far from the viewport centre;
- degradation of the mesh caused by export.

If you encounter any of these problems, it is best to try to correct them directly in Blender using publicly available tutorials [Xoio, 2022; Josh Gambrell, 2020]. By ignoring these errors, we can expect exactly the same display results in the web viewer. Some problems, such as the flipping of the model axis or its wrong position, can usually also be corrected in the viewer itself, but this requires additional work in the viewer interface.

Data, Metadata and Paradata

Publication of a 3D model is not just about publishing the file and attaching a preview in the 3D viewer. It is also about contextual information regarding content, creation process or copyright. Most often, this information is required by the input form during data upload in the repository. The expected content information can be divided into three groups:

- Data - the main subject of our deposit is our 3D files, which will also be the case in the case of digital restorations.
- Metadata - this is the data about the data [Kranz, 2021]. Most often, this is information in textual form, which can provide administrative data (name of the deposit, time of creation, creator, license, etc.) or descriptive data (object depicted on the model, time phase of the reconstitution, 3D modelling software used, etc.). There is still no uniform schema for the documentation of metadata for 3D models of cultural heritage, although steps are being taken to standardise one approach [Bajena & Kuroczyński, 2023].
- Paradata - they are data about the process of creating a resource [Apollonio & Giovannini, 2015]. In the case of digital restoration, these can be additional documentation files showing the arguments behind the restoration decision, a list of sources used, or an assessment of uncertainty.

Scientific publication of 3D models requires the provision of them all: data, metadata, and paradata. Without any of these elements, verification and referencing to our reconstruction project may not be possible.

Deposit in the Repository

While there are many repositories for 3D models and digital data archives, it is difficult to find an open platform tailored to the needs associated with publishing hypothetical virtual reconstructions. That is why, as part of the CoVHer project, we have developed our own platform, which has been designed in a way that offers the possibility of creating a full deposit of virtual reconstruction projects (https://repository.covher.eu/).

Our platform is based on the WissKI system, a virtual research environment that allows data to be stored in a semantic knowledge graph based on ontological solutions such as CIDOC CRM, which is the standard for documenting cultural heritage.

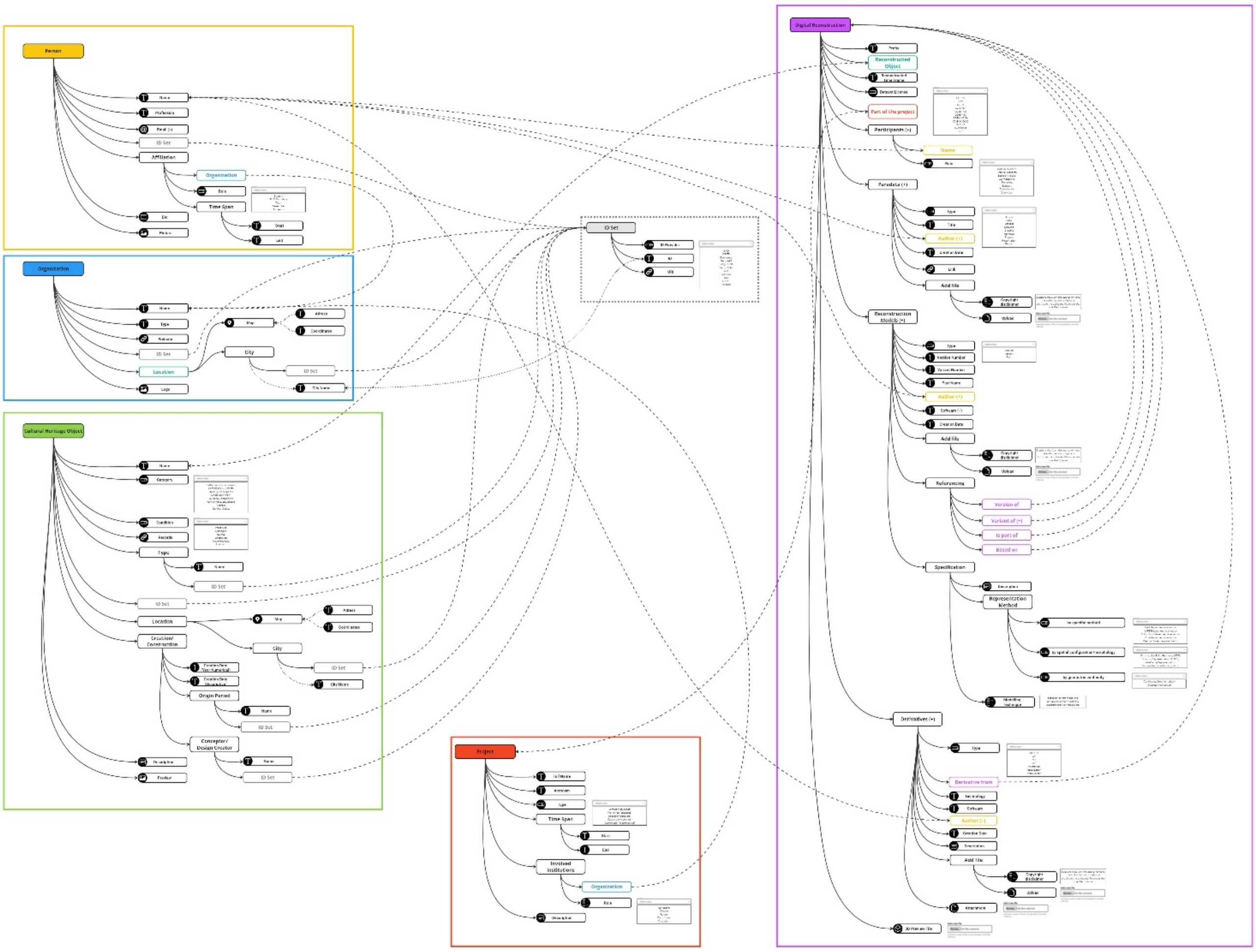

Figure 89: Data documentation scheme in the CoVHer repository.

The documentation process has been divided into several input forms regarding different types of information (Figure 89):

- Organisations
- Projects
- Persons
- Cultural heritage sites
- Digital reconstructions

When completing forms, we can reference and create semantic relationships between entries that have previously been made. Creating these relationships allows advanced filtering of the repository's content and greatly enhances the information retrieval process.

One of the repository's main principles is using identifiers to describe things. Identifiers allow machine readability of contextual data and avoid ambiguities. The distribution of identifiers is handled by databases specialised for this purpose, and they are often grouped thematically. When looking for identifiers for scientists, one can check the Open Researcher and Contributor ID (ORCID) database; for organisations, the Virtual International Authority File (VIAF); and for concepts related to architectural and artistic concepts, the Getty Art & Architecture Thesaurus (Getty AAT). A full list of the identifier providers used can be found at the following link: https://repository.covher.eu/wisski_views/identifier_providers.

The repository uses different types of field formatting and innovative methods of reconstitution documentation, so navigation in the repository and some parts of the form can be difficult to understand at first. Therefore, we therefore encourage you to watch the introductory tutorial before getting started, which can be found under the following link: https://seafile.rlp.net/f/52c1f876196740ab8211/.

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18. Image- and Copyrights in Digital 3D Reconstructions

Authors: Jan Lutteroth

Introduction

A digital 3D reconstruction, digital 3D models, and the set of sources on which they are based are subject to certain legal aspects [Münster, S. et al., 2024]. These aspects differ not only in the handling, display, and publication of said sources but also due to differences in national legislation. Furthermore, since most digital 3D reconstructions are performed by several individuals throughout the reconstruction process, the produced 3D models are subject to different levels of property rights [Borissova, V., 2018].

Historical Imagery

The discussion on image- and copyrights on historic imagery is highly debated and concerns a broader field of scientific publications [Michl. F, 2018; Fischer, V. et al., 2022]. Similar awareness regarding these legal aspects also needs to be considered within the field of digital 3D reconstructions. In our case, these issues can be separated into three questions that need to be answered per case and nationality.

Should I Use any Historic 2D Source for my Digital 3D Reconstruction?

First of all, the quality of the medium that a historic 2D source (Figure 90) is displayed on is a direct indicator of the quality of the digital 3D reconstruction. Therefore, the research and acquisition of the necessary historic 2D sources should be of vital interest for the project. This means that the historic 2D source should not be acquired from untrustworthy online resources with limited citation possibilities, nor as a scan from analogue publications. These mediums can, at best, serve as an overview for information and metadata gathering. If a historic 2D source is considered to be of crucial importance for the digital 3D reconstruction, the institution holding the original source should be contacted in order to receive a high-resolution scan as well as the rights to use the digital 2D source in the project and its publication. Depending on the amount and quality of the sources, this, so called, "official way" goes hand in hand with a significant amount of research time and reproduction fees, all at the expense of the research project. If the use for the project is granted without the possibility of publishing the source itself, the minimum agreed-upon documentation would be to

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provide the necessary reference to the source and, if possible, a DOI of a digital representation of said source.

Why is There Still Copyright on Historic Imagery?

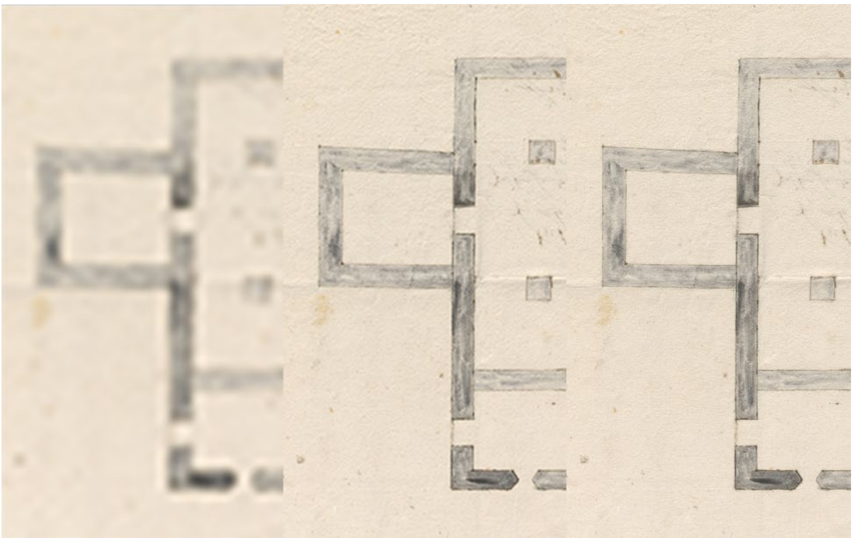

Figure 90: Hand-drawn ground floor plan in three resolutions, Original by Lorenzo Sciasca, Basilica in Vachendorf, 1678, Archive of the archdiocese Munich and Freising, CC BY 4.0

A hand-drawn historic ground floor plan (Figure 90) by an author who died over 70 years ago is no longer entirely protected by copyright and is considered to be public domain (at least according to German legislation). Since digital-born imagery (e.g., a CAD ground floor plan) from an author who died in the 1950s is scarce, and most digital 3D reconstructions deal with imagery produced long before this breaking point in image processing, the concept of public domain should apply to most of the historic 2D sources used for digital 3D reconstructions in the context of historical architecture. An exception to that issue is photographs of existing and lost architecture [Margoni, T., 2014].

The actual problem begins with the transformation of historic 2D sources into a digital format, which is unavoidable for its use in a digital 3D reconstruction. Once a hand-drawn historic ground floor plan is digitised, the digital image is considered a duplication of the original, and the "new" author, in this case, the institution that digitised the original, holds the copyright for the duplication. However, this practice is highly criticised within scientific communities [Truyen, F., & Waelde, C., 2016; Wallace. A, et al., 2020].

What Can I do to Avoid These Issues?

A "workaround" for this issue lies within citation rights. Citation rights grant the publication of imagery within a scientific publication if the publication significantly deals with the image and its display serves the scientific discussion. The citation (e.g., the display of the image) must serve as evidence or a basis for your own explanations. In the case of a digital 3D reconstruction based on a historic ground floor plan, it seems obvious that the display of the image should be considered crucial for the scientific discussion. To avoid disputes, one might consider explaining the importance of displaying the source in the documentation process.

Modern Imagery and Other Media

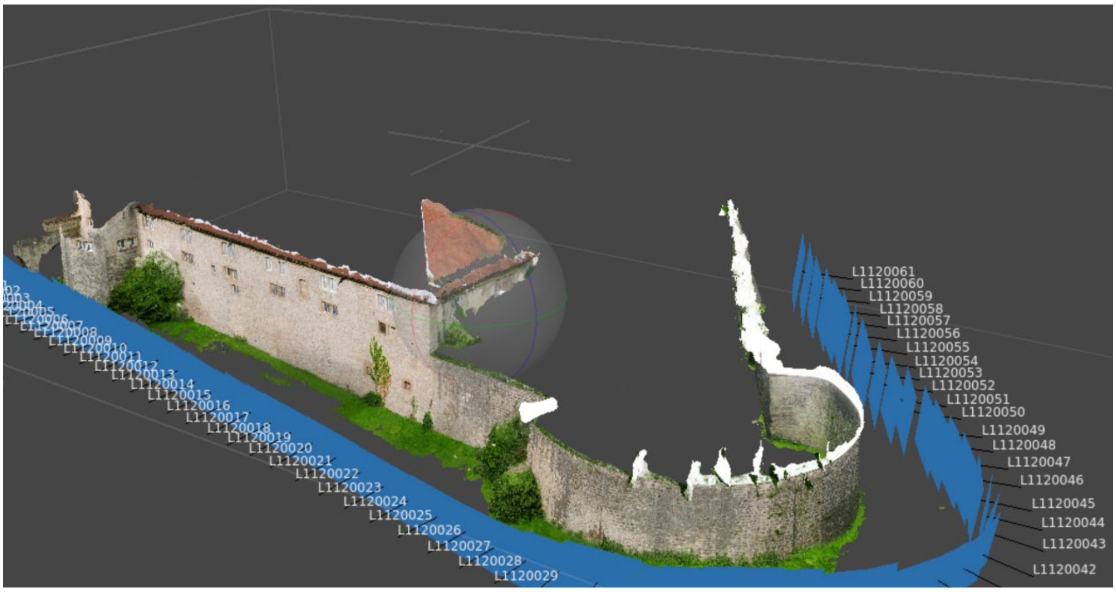

Figure 91: Southwestern Moat of the Castle in Weikersheim, Screen capture of the SFM-Process, 2019, CC-BY 4.0.

A slightly different subject of legal aspects arises from modern survey and measurement campaigns (e.g., Structure from Motion Picture (SFM) or terrestrial laser scanning (TLS)) and their derivatives used for digital 3D reconstruction (Figure 91). If a digital 3D reconstruction is based on point clouds or mesh models that were not produced by oneself but whose use was granted by a third party, such as an institution or company, a mutual contract of use should be drawn up in advance to avoid legal issues.

If the institution in charge of the architectural site or cultural heritage object grants permission to perform a scan campaign, the same process should be considered. The rights to the scan derivatives and their after-use should be regulated to avoid legal issues and to maintain the possibility of reprocessing and/or republishing the outcomes separately or at a later period of time.

However, there is debate on whether such 3D digitisation fulfils all the requirements of producing an original, in the sense of intellectual work, with all associated copyright and property rights, or if it is merely a simple copy (duplication) like a scan of a document, thereby creating only a non-original work without intellectual property rights [Oruç, P., 2020].

If the involved parties agree on mutual after-use terms or the scan derivatives are produced with personal scan equipment (e.g., camera, laser scanner, and software), the issue of property rights arises, especially in the scientific world, where the commercial use of such derivatives finds itself in a sort of grey area.

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Property Rights of 3D Derivatives

	PUBLIC DOMAIN	PUBLIC DOMAIN	BY	BY SA	BY NC	BY ND	BY NC SA	BY NC ND
PUBLIC DOMAIN	✓	✓	✓	✓	✓	✗	✓	✗
PUBLIC DOMAIN	✓	✓	✓	✓	✓	✗	✓	✗
BY	✓	✓	✓	✓	✓	✗	✓	✗
BY SA	✓	✓	✓	✓	✗	✗	✗	✗
BY NC	✓	✓	✓	✗	✓	✗	✓	✗
BY ND	✗	✗	✗	✗	✗	✗	✗	✗
BY NC SA	✓	✓	✓	✗	✓	✗	✓	✗
BY NC ND	✗	✗	✗	✗	✗	✗	✗	✗

Figure 92: Possible combinations of CC Content, Design: Markus Büsges, 2014, CC-BY SA 4.0.

Since the emergence of the open science idea, best practices in the field of digital 3D reconstruction should always involve a regulated and comprehensible strategy for the reuse of project outcomes for further scientific investigations. This should be considered apart from the publication of scientific reports and papers on the project itself. Ideally, this should be done under the FAIR principles (Findability, Accessibility, Interoperability, and Reusability) [Wilkinson, M.D. et al., 2016; Forschungsdaten.org, 2022].

These strategies are connected to the already raised issues concerning image rights, data rights, and property rights. For the publication of scientific data, which in the case of a digital 3D reconstruction should involve the fully transparent publication of the scientific 3D reconstruction process, this also involves the 3d model and its derivates. The already mentioned publication of scientific reports and papers does not sufficiently serve the necessary requirements. The minimal agreed-upon requirements for the publication of a scientific 3D model, without the 3D reconstruction process and its documentation, can be summarized as the following:

- What: Name of the object that has been reconstructed.
- State: Timespan of the object depicted by the 3D model.
- Copyright: License under which the 3D model is published. Ideally in an open licensing system.
- Author(s): Involved persons in the creation of the 3D model.
- Rights Holder: Institution or person that holds the rights to the 3D model.
- Data: The 3D model itself. Ideally in a standardised exchange format.

Currently available 3D repositories, such as the commercial Sketchfab as well as non-commercial scientific repositories like the DFG 3D Repository (https://3d-repository.hs-mainz.de/) as well as Kompakkt (https://kompakkt.de/) and Semantic Kompakkt (https://semantic-kompakkt.de/), fulfil these requirements in more or less elaborate ways. Aside from the possibilities of direct access to the 3D data via download or through visualisation of the 3D model itself, the most crucial attribute of such data sets is the copyright license.

Aside from closed licensing that restricts the reuse of the 3D model without reimbursement (paywall) and should not play a role in publicly funded research projects, especially when the used software runs under educational licensing, the ideal way would be through assigning open licensing. The currently most influential system is the Creative Commons (CC) license system (Figure 92).

Science thrives on the reusability and accessibility of data. Therefore, a fully comprehensible and openly accessible digital 3D reconstruction should, aside from the 3D model, also involve the 3D reconstruction process and its documentation. Ways of semantically handling such processes have already been established; however, the time expenditure increases significantly the more elaborate and detailed it gets. Nevertheless, a minimum of documentation concerning the 3D reconstruction process cannot be omitted, most importantly the display of the used sources and their references.

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19. Reusing 3D Models: File Formats and Derivatives

Authors: Igor Bajena, Piotr Kuroczyński

File Formats Classification

3D models can be stored in various data formats, and the choice of format to share during our publication can significantly affect the usability of our data. Each format fulfils a slightly different function and is used for different purposes. This principle is not only valid for 3D files. For photos, we can distinguish between a dozen different formats (Table 3). Some allow us to save the raw information from the camera (RAW), others store the changes made to the image during processing (PSD), and other formats are used for data exchange (JPEG, PNG) or archiving (TIFF).

Table 3: Overview of the different formats for image files in terms of their specifications and use

Format	Colours	Compression	File Size	Recommendations
RAW	> 68 billion	variable	very large ~10MB	Unprocessed data, editing
PSD	variable	variable	large ~ 8MB	Design and editing
JPG/JPEG	>16 million	lossy	small 0,5-8MB	Websites and storage
GIF	max 256	lossless	small ~1MB	Animation and web
TIFF	variable	lossless	large ~ 8MB	Editing, printing, archiving
PNG	>16 million	lossless	large ~ 8MB	Web, storage, graphic design, editing

The number of possible file formats for 3D models is much larger. Their systematisation is even more complex due to the multiplicity of possibilities for their application, the large number of different software, and the many modelling techniques [McHenry et al., 2008]. In order to attempt to classify them, we must first distinguish between two main types of file formats: closed (proprietary) and open (non-proprietary) (Figure 93). Closed formats are typically owned by specific companies or organisations. They are patented and legally protected. This often restricts their use to the original program that created the file (e.g., PLN, MAX, RVT, BLEND, SKP). In contrast, open formats are system-independent and freely available, facilitating easy file reuse and promoting wider accessibility (e.g., GLB/GLTF, DAE, OBJ, STL, IFC, GML).

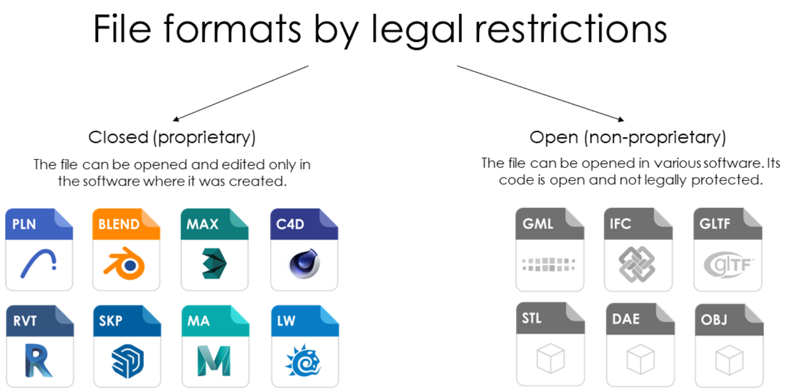

Figure 93: Classification of 3D file formats according to legal restrictions.

Another classification considers the origin of our file, distinguishing between native and export formats. The native format is the file format of the program in which we created our model, while the export format is any file format different from the native format, which was converted by our software. Most often, the process of creating exports is linked to the need to exchange data between different programs. For this reason, export formats are often called data exchange formats. 3D open file formats that can be easily integrated into different 3D modelling software are also known as neutral formats (e.g., IFC, 3DM, OBJ).

Derivatives of 3D Models

Each export of our model to a different format involves changes in how we store information about geometry, materials, or scene attributes. It also entails the risk of some changes in the model's appearance and the way it is visualised on screen. We then say that the export created is a derivative of our reconstruction. The essence of a digital reconstruction derivative is that it should show the same object in the same time frame, based on precisely the same source material. In other words, the state of knowledge represented in the reconstruction should be the same. However, there may be changes in how the geometry, materials and 3D scene information are presented and recorded.

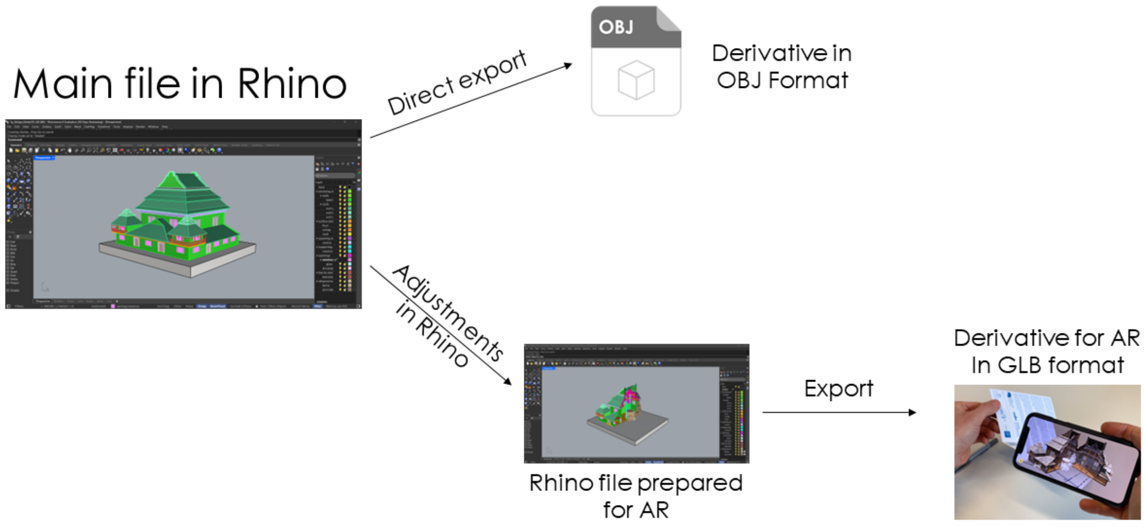

Figure 94: Scheme for creating a 3D model's derivative through direct export and adaptation to AR application requirements.

We create derivatives not only when exporting a file directly but also when we need to adapt our model to the requirements of a specific application (Figure 94). Models for publication in a web viewer or AR or VR application will require significant simplifications to the model's geometry. Models for 3D printing, on the other hand, may retain a very complex model mesh but need to be waterproof solids.

5-star Deployment Scheme for 3D Models

When we publish our 3D files on the web, we should do so in a way that allows for easy data integration, new derivations creation, and further reconstruction development. Therefore, we must consider formats that can easily be used, modified, and integrated with other data. Classifications of data formats in terms of interoperability and the criteria needed for reuse have been developed in the 5-star deployment scheme for Linked Open Data [Berners-Lee, 2006]. The creator of the schema promoted the idea that the data we publish on the web should be open and interconnected to create a machine-readable semantic web [Berners-Lee, 2001].

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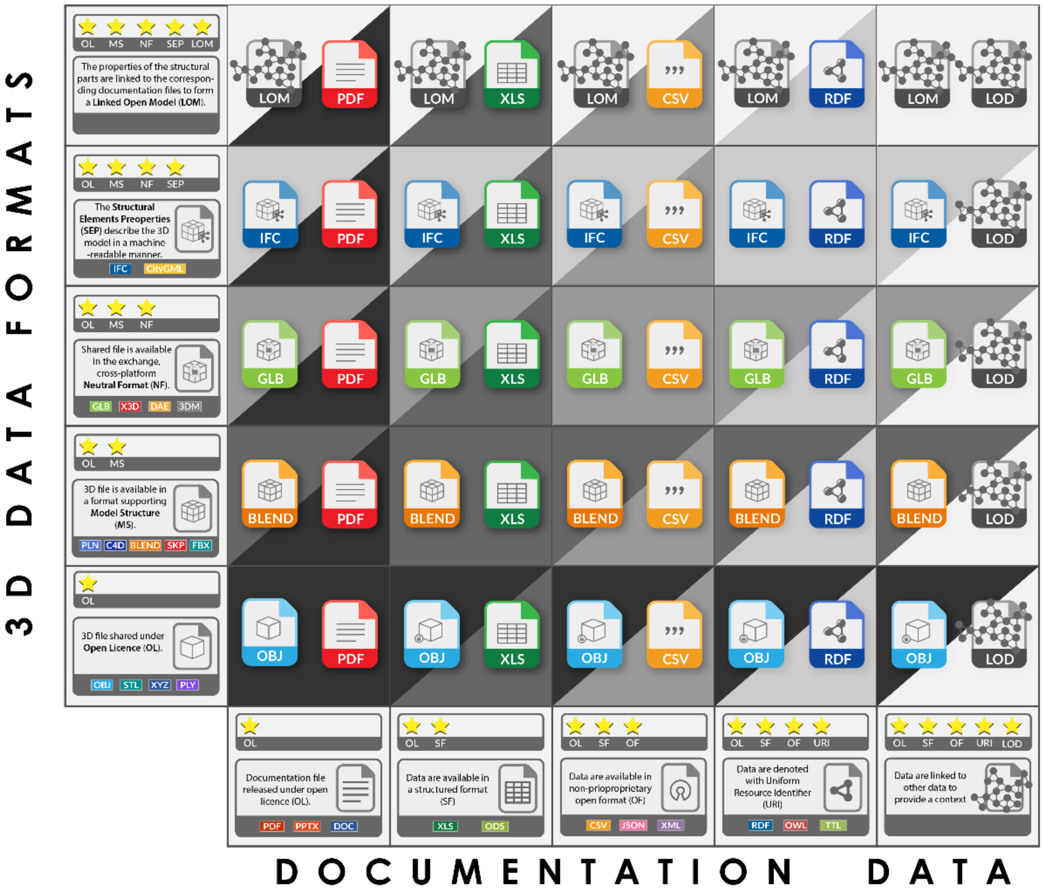

Figure 95: Summary of criteria for the 5-star data sharing scheme (horizontal axis) and 3D models (vertical axis) in the network.

Although the assumptions of the scheme are presented for general data, we can translate these assumptions towards 3D data (Figure 95), as follow:

- ★ Provide your 3D model and the associated metadata on the web under an Open License (OL).
- ★★ Provide your 3D model in a format supporting Model Structure (MS) and the associated metadata on the web in a structured format (SF)
- ★★★ Provide your 3D model in Neutral Format (NF) and use open, non-proprietary formats for metadata (OF)
- ★★★★ Provide your 3D model with Structural Elements Properties (SEP) and use URIs to label things (URI)
- ★★★★★ Provide your 3D model as Linked Open Model (LOM) and link your data with other data to create contexts (Linked Open Data-LOD).

Scientific Reference Model as a Publication Foundation

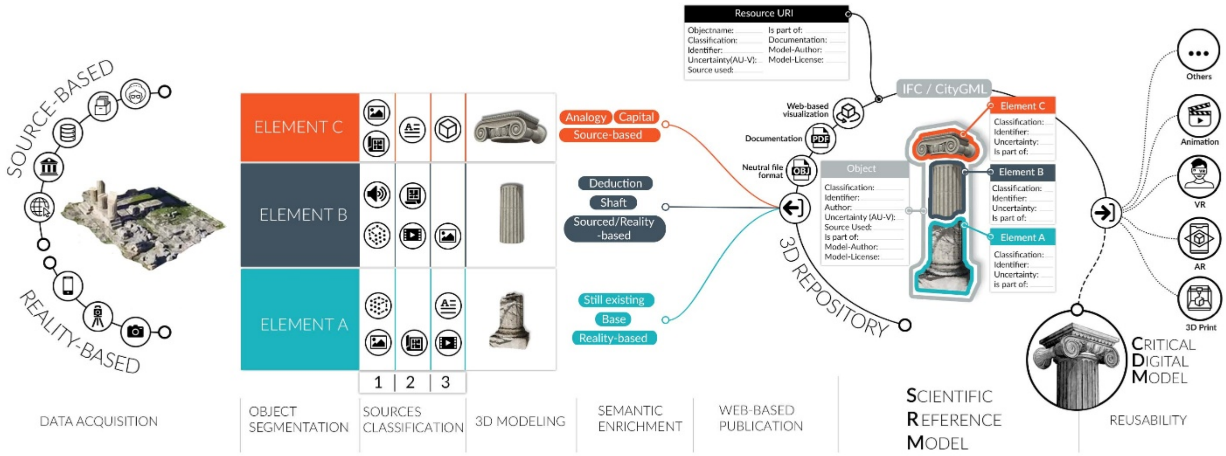

Figure 96: Diagram showing the workflow of the Scientific Reference Model (SRM) methodology

A five-star methodology for sharing 3D data was developed within the concept of the Scientific Reference Model (SRM) (Figure 96). The SRM advocates for sharing results of virtual reconstruction projects under an open license and using non-proprietary file formats to foster referencing, further development, or scientific evaluation by third parties [Kuroczyński et al., 2023].

There are two important points in this methodology. The first is the use of standardised formats storing geometry data and file structure, allowing the assignment of the metadata directly to the dedicated parts of the 3D file. Formats that meet these requirements include Industry Foundation Classes (IFC), used in the architectural, building, and construction industries, and City Geography Markup Language (CityGML), used for integrating urban geodata for various Smart City and Urban Digital Twin applications.

The second point is to make the 3D model available with the corresponding documentation under an open licence in a repository based on linked open data. The CoVHer repository was created for this purpose. The repository uses references to external databases via unique reference identifiers (URIs) to create semantic links between data.

Recommendations for the use of Different Types of 3D File Formats

The SRM methodology promotes the use of formats that are great for storing documentation within a file (IFC, CityGML) but, unfortunately, are unable to store complete reconstruction information, e.g. due to lack of support for textures. There is also a problem with file integration in some 3D modelling software.

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Table 4: Summary of selected 3D modelling software and its ability to import 3D file formats

Format	Archicad	Rhino	Blender	Cinema4D	Revit	Sketchup	Maya	3DS Max
OBJ	✓	✓	✓	✓	✗	✓	✓	✓
DAE	✓	✗	✓	✓	✗	✓	✓	✓
STL	✓	✓	✓	✓	✗	✓	✓	✓
FBX	✓	✓	✓	✓	✗	✓	✓	✓
GLB	✗	✓	✓	✓	✗	✓	✗	✗
PLY	✗	✓	✗	✗	✗	✗	✗	✗
3DM	✓	✓	✗	✗	✓	✗	✗	✗
IFC	✓	✗	✗	✗	✓	✓	✗	✗
BLEND	✗	✗	✓	✗	✗	✗	✗	✗
SKP	✓	✓	✗	✓	✓	✓	✗	✓
RVT	✗	✗	✗	✗	✓	✗	✗	✓
MA	✗	✗	✗	✗	✗	✗	✓	✗
PLN	✓	✗	✗	✗	✗	✗	✗	✗
X3D	✗	✗	✓	✗	✗	✗	✗	✗
C4D	✓	✗	✗	✓	✗	✗	✗	✗
3DS	✓	✓	✗	✓	✗	✓	✗	✓
MAX	✗	✗	✗	✗	✗	✗	✗	✓
IGES	✗	✓	✗	✓	✗	✗	✓	✓

For this reason, it is also useful to include other 3D file formats in publications. especially as different data formats can work with other programs (Table 4). Some of the problems of format integration can be solved by additional plug-ins, e.g. for IFC, there are already dedicated plug-ins for Blender [BlenderBim, n.d.], Rhino [VisualARQ, n.d.] and for CityGML, there is a plug-in for Sketchup [3DIS, n.d.]. However, not everyone is aware of these solutions, as they are not included in the default setup of software packages. It is, therefore, worth supporting the publication with additional neutral formats.

Table 5: List of specifications of selected 3D file formats

Format	Type	Textures	NURBS	Hierarchy	Grouping	Metadata Properties	Recommendations
OBJ	*Neutral, Export*	✓	✗	✗	✓	✗	*3D printing, graphics, 3D scanning, data exchange, web, AR and VR*
DAE	*Neutral, Export*	✓	✗	✓	✓	✗	*Graphics, animation, data exchange*
STL	*Neutral, Export*	✗	✗	✗	✗	✗	*3D printing, data exchange*
FBX	*Closed, Export*	✓	✗	✓	✓	✗	*data exchange, graphics, animation, games development*
GLB	*Neutral, Export*	✓	✗	✓	✓	✗	*3D printing, graphics, data exchange, games development, web, AR and VR*
PLY	*Open, Export*	✗	✗	✗	✗	✗	*3D scanning, point clouds*
3DM	*Open, Native*	✓	✓	✗	✓	✗	*NURBS modelling, graphics, analysis of geometry*

IFC	*Neutral, Export*	✗	✓	✓	✓	✓	*BIM, data exchange, SRM*
GML	*Neutral, Export*	✗	✗	✓	✓	✓	*Geodata, smart cities, data exchange, SRM*
BLEND	*Closed, Native*	✓	✗	✓	✓	✓	*Graphics, animation, polygonal modelling, sculpturing*
SKP	*Closed, Native*	✓	✗	✓	✓	✗	*Graphics, polygonal modelling*
RVT	*Closed, Native*	✓	✗	✓	✓	✓	*BIM, CAD, object-oriented modelling*
PLN	*Closed, Native*	✓	✗	✓	✓	✓	*BM, CAD, object-oriented modelling*
X3D	*Neutral, Export*	✓	✓	✗	✓	✗	*Interactive 3D, coloured 3D printing, CAD, data exchange format, animation*
XYZ	*Open, Export*	✗	✗	✗	✗	✗	*Data exchange, point clouds*
C4D	*Closed, Native*	✓	✓	✓	✓	✗	*Graphics, animation, polygonal modelling*
3DS	*Closed, Export*	✓	✓	✓	✓	✗	*Graphics, animation, polygonal modelling, exchange format*
MAX	*Closed, Native*	✓	✓	✓	✓	✗	*Graphics, animation, polygonal modelling*
IGES	Neutral, Export	✗	✓	✓	✓	✗	*CAD, analysis of geometry, exchange format*

Open formats such as OBJ or DAE can be easily imported into 3D programmes and store both geometry and texture information. However, the only medium for full information about our reconstruction model remains the native file. Any export or conversion of a file involves the risk of losing some data. Selecting suitable formats for publication can be a challenging task, so specifications for the most popular in use are shown in Table 5. Different 3D data formats have different uses and purposes of use, but we cannot always predict for what purpose our data may be used by other users. Therefore, we recommend that the package prepared for publication should contain a set consisting of:

- native format;
- format supported by SRM;
- selected data exchange formats.

Such a package of different file formats can provide a solid basis for others to use our reconstruction, create further derivations, and spread knowledge about lost cultural heritage.

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20. Derivates of the Scientific Reference Model: Augmented Reality

Authors: Igor Bajena, Daniel Dworak

AR in the Context of the Hypothetical 3D Reconstruction of Architecture

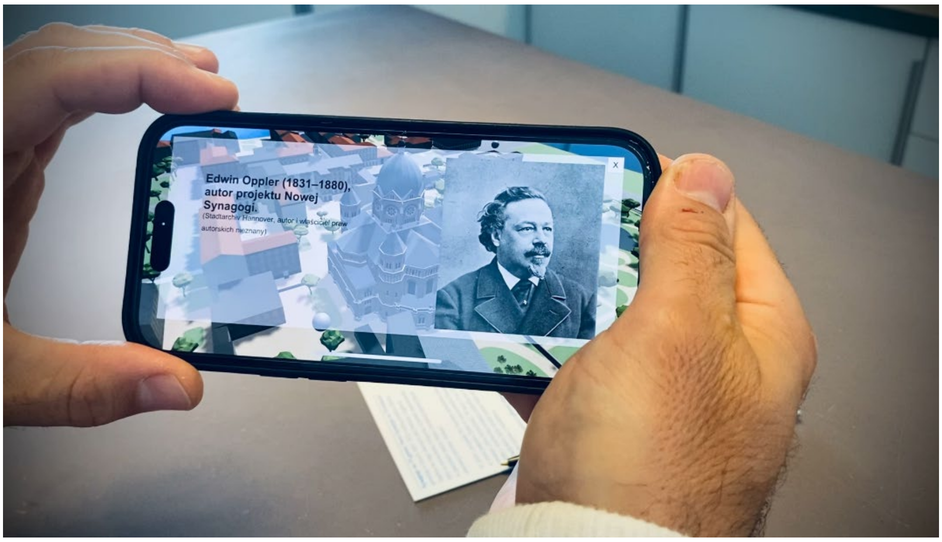

Figure 97: An example of an AR application with interactive dots containing historical information. The photo shows a reconstruction of the New Synagogue of Wroclaw and its architect, Edwin Oppler, in the app 'kARtka z synagogą'.

Mobile devices have become our devices of daily use. By using augmented reality (AR) applications, we can benefit from their potential for disseminating information about lost cultural heritage in an interactive way, without the need for expensive technological solutions. Unlike virtual reality (VR), which fully immerses users in a computer-generated environment, AR overlays digital content (such as 3D models, images, and metadata) onto the real world through devices like smartphones and tablets. It can serve as a powerful tool to visualise historical structures that no longer exist. We also gain the opportunity to display the digital reconstruction in the context of the current world. By providing the appropriate interactions, we can also design an entire tour with a mass of contextual information to better understand the historical context of our object (Figure 97).

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Principle of Operation in AR Applications

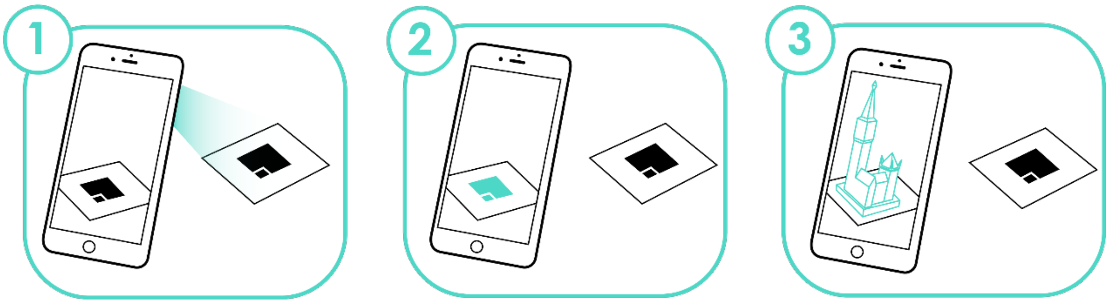

Figure 98: The principle of operation of AR applications in three steps: 1) sensing; 2) recognition; 3) display.

AR technology combines real-world sensory input with computer-generated real-time content using Simultaneous Localisation and Mapping (SLAM) [Peddie, 2017, p.53-58]. The whole process is based on three steps (Figure 98).

- Sensing: it is necessary to use a device equipped with a camera and various sensors. Such as smartphones, tablets, or AR glasses. The camera captures the real-world environment, while sensors like GPS, accelerometers, and gyroscopes provide information about the device's position and orientation.
- Recognition: the AR software uses computer vision technology to process and interpret the live video feed from the camera. It identifies features in the environment, such as surfaces, objects, or markers, to determine where to place digital content. To maintain the correct placement of digital objects, the AR application continuously tracks the position and movement of the device. It often uses SLAM algorithms to build a real-time map of the environment and understand the spatial relationship between the device and the real-world features.
- Display: the AR application renders digital content, such as 3D models, images, or text, in real time. This content is overlaid onto the live camera feed in a way that appears to be part of the real world. The application adjusts the rendering based on the device's position and orientation to ensure the digital content stays correctly aligned with the real-world environment.

In more sophisticated AR applications, there is an additional step that allows interaction with the displayed content. Interaction can happen through touchscreens, gestures, or voice commands, depending on the capabilities of the device and the application. For example, a user might tap on a 3D model to get more information or use hand gestures to manipulate virtual objects.

Types of AR Technologies

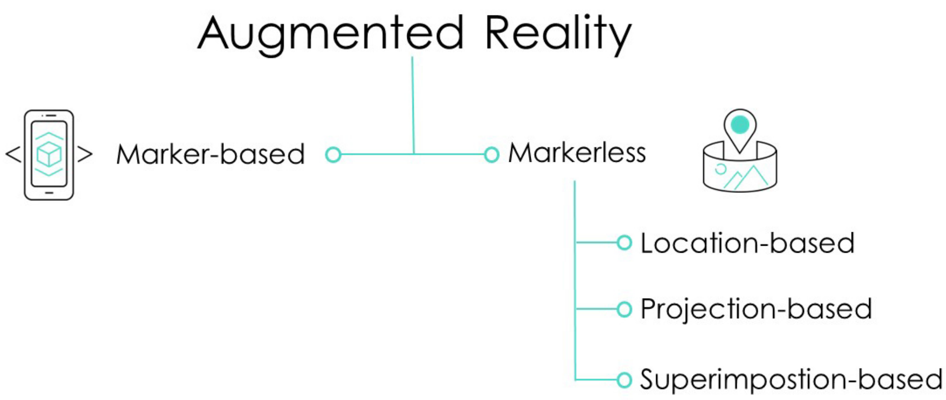

Figure 99: Classification of AR technologies in terms of how objects and spaces are recognised

Step two in the operation of an AR application, recognition, can work, influenced by the AR technology chosen. The basic division of AR technology includes marker-based AR and markerless AR (Figure 99).

Marker-based AR uses specific visual markers (like QR codes or images) to trigger the display of AR content. The device's camera detects the marker and superimposes digital information onto it. Its popular applications are in educational tools, product demonstrations, and marketing campaigns.

Markerless AR technology can be further divided into a few technologies. The first is known as location-based or position-based AR, and it uses GPS, compass, accelerometer, and gyroscope data to place AR content in the real world without needing specific markers. They are used in navigation apps, location-based games like Pokémon GO, and travel guides.

The next markerless AR technology is superimposition-based AR. It replaces the original view of an object with an augmented view, either fully or partially. This often requires sophisticated object recognition technology. This technology is used in medical imaging, where AR can overlay scans onto a patient's body, and repair guides that overlay instructions onto machinery.

Another markerless AR technology is the projection-based AR, which projects digital light onto physical surfaces, allowing users to interact with the projected content. This type of AR often uses sensors to detect user interaction with the projection. It is used in Virtual reality meetings, interactive workspaces, interactive exhibits, and educational tools. There are also many types of wearable AR, which require additional hardware such as a helmet, glasses or lenses. However, these technologies are still in the testing phase and may be very hard to find on the market [Peddie, 2017, p.29-46].

AR technology can also be linked to the programme in which the 3D model is prepared. The most popular and widely used solutions for augmented reality (AR) development include 3D modelling software Blender, ARKit (developed by Apple for iOS), ARCore (developed by Google for Android), and finally accessible for free game development engines: Unity, and Unreal Engine.

Requirements of the Model for AR

Although AR has immense potential, it does face certain limitations. Displaying complex 3D scenes in real-time requires significant data transfer, bandwidth, and computational power, which are often lacking in mobile devices. Therefore, optimizing 3D models is essential to ensure smooth performance and usability. This can be achieved by following several key guidelines [W3rlds Wiki, 2023].

Firstly, it is important to simplify model geometry without compromising visual fidelity. For example, a chair model with an initial vertex count of 6,500 can be reduced to 500 vertices while maintaining its recognizable form. Additionally, models should be divided into smaller parts to prevent overloading the device, with a recommended limit of 65,000 vertices per segment to ensure compatibility with existing hardware.

Using squared textures with dimensions that are powers of two, such as 1024x1024 pixels, is standard practice. Consistency in measurement units, such as meters or centimetres, helps avoid discrepancies. Placing the pivot at the centre of the object allows for accurate rotation and movement of the model.

Model \ File Format [KB]	3DS (BIN)	COLLADA (ASCII)	FBX (BIN)	FBX (ASCII)	OBJ (ASCII)	RIB (BIN)
Cube (8 vertices)	2	7	14	13	1	2
900 Cubes (7200 vertices)	161	2237	197	2313	912	56
Sphere (8066 vertices)	356	2468	341	4023	1131	311
Stairs (44695 vertices)	2668	12652	1667	13486	6696	2230
Building (68472 vertices)	5847	21870	10655	24923	12691	2643

Figure 100: Summary of file weight in KB for various 3D objects after export to selected data exchange formats

The model's mesh should be triangulated, as quads or parametric surfaces can cause issues. When exporting, include normals and texture coordinates to ensure accurate rendering. The OBJ file format is recommended due to its efficiency, established standard, and wide support. While formats like FBX and DAE are also used, they tend to be bulkier (Figure 100). Advanced techniques can further enhance model efficiency. Applying textures and lighting improves visual quality while reducing computational load. Baking light and texture details onto simpler geometry creates visually detailed models with lower vertex counts, resulting in better performance and user experience in AR applications. As not every program has the capabilities to perform this operation, it is recommended to use the free program Blender to carry out the final adjustments [Micun, 2024].

Visual Example of AR: "kARtka z synagogą" App

Figure 101: Postcard of the reconstruction of the Volpa Synagogue cooperate with the AR application 'kARtka z synagogą'

An example of an AR application developed by the Institute of Architecture of Mainz University of Applied Sciences (AI MAINZ) is "kARtka z synagogą", which is a virtual journey to the destroyed synagogues [AI MAINZ, n.d.]. The app works with a series of postcards published by the Hochschule Mainz – University of Applied Sciences, which have a tracker in the form of a plan of the destroyed synagogue (Figure 101). Anyone with a smartphone can view a 3D model of the reconstructed synagogues by pointing the phone's camera at the projection printed on the postcard (the postcard can also be downloaded from the app's website and printed). The Unity engine and Wikitude technology were used to design the application.

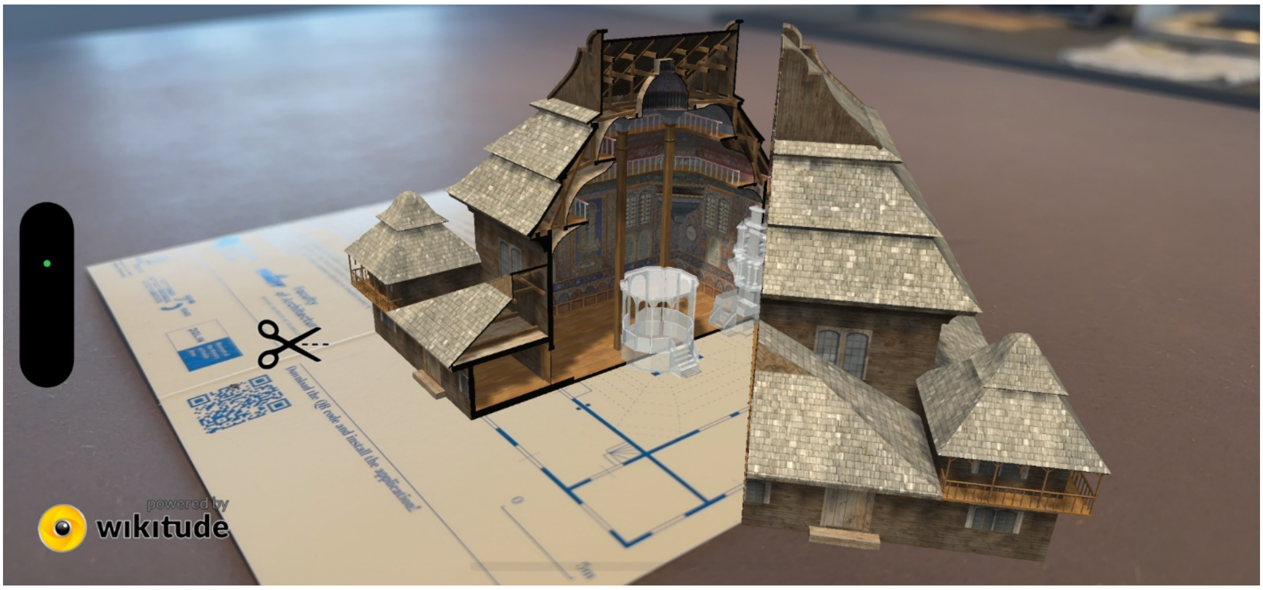

Figure 102: Application visualising the reconstruction of the Volpa Synagogue in place of the building plan from the postcard

Three postcards have been published until 2023. The first shows a reconstruction of the New Synagogue in Breslau/Wrocław (Poland) designed by Edwin Oppler, created in the framework of a scientific project carried out by AI MAINZ in cooperation with Arthur Sarnitz–Königsberg. The second postcard depicts a reconstruction of the Mainz Synagogue (Germany) designed by Ignaz Opfermann, carried out by MONOKL – Explore the invisible. Both 3D models were prepared in Sketchup. The last one shows a reconstruction of the wooden synagogue in Wolpa (today's Belarus), which was created as part of a student course at the Faculty of Architecture at the Warsaw University of Technology in collaboration with AI MAINZ (Figure 102). The author of the Wolpa Synagogue 3D reconstruction is Katarzyna Prokopiuk, who created her model in Rhino.

The combination of an AR app and a postcard encourages the promotion of the rarified heritage of Jewish architecture through the distribution of postcards by post. It is also a great educational resource, giving students working with AI MAINZ the chance to test their skills and promote the results of their work.

Three more postcards are currently in the publication process, which were created in collaboration with students from the Technical University of Łódź, Miłosz Kazuła and Majchrzak (reconstruction of the synagogue in Pilca), Julia Wiśniewska (reconstruction of the synagogue in Mogielnica) and a student from the Warsaw University of Technology, Milena Micun (reconstruction of the synagogue in Olkieniki).

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21. Derivates of the Scientific Reference Model: Virtual Reality

Authors: Riccardo Foschi

VR in the Context of Hypothetical 3D Reconstruction of Architecture

Virtual Reality, commonly known as VR, is one way to visualise and interact with 3D digital models of reconstructed architectures. The term VR refers to the real-time simulation of a digital scene that can be viewed through specific wearable electronic devices called headsets and interacted with particular controllers, gloves, or other advanced equipment.

This type of experience allows users to virtually immerse in the scene, providing greater engagement and better perception of spaces or objects. Although the first experiments with this technology date back several decades, it is only recently that it has started gaining traction in the field of architecture, thanks to the reduction in costs and the increase in quality and computational capabilities of electronic devices.

The initial commercial VR devices required sensors for motion tracking to be installed around the play area (Figure 103) and needed the headset to be constantly connected via cable to a high-performance computer. The significant cost and limited practicality restricted their widespread adoption. Today, there are much more convenient all-in-one devices capable of operating in standalone or wireless modes.

Figure 103: VR setup with environmental sensors.

Available Software and Apps for VR

The rapid advancement in the development of headset devices has led to the emergence of software solutions aimed at professionals in the field of architecture.

Some of the most popular applications come from the gaming industry, they are versatile but hard to learn. Some other solutions are specifically developed for architectural visualisation, and despite being less versatile, they are much easier to use.

Some applications or render engines that allow us to visit architectural models in VR are:

- Unity by Unity Technologies (stand-alone game engine)
- Unreal Engine by Epic Games (stand-alone game engine)
- Twin Motion by Epic Games (standalone real-time rendering app for architecture)
- Enscape by Chaos Group (real-time render engine, integrated as a plug in various third-party CAD software)
- Blender by Blender Foundation (3D modeller with minor VR functionalities for scene inspection)
- Shapespark (web-based real-time-rendering service with VR functionalities)
- 3D vista (web-based virtual tour service with VR functionalities)
- …

Despite the significant progress in recent years, these technologies still have limitations. Indeed, when visiting reconstructed architectural spaces, special precautions must be taken in terms of space design and motion control to avoid misleading the viewers or making them feel uncomfortable.

Available Headset Technologies

Figure 104: standalone VR headset with integrated tracking sensors and 6 degrees of freedom (DoF).

VR headsets can be of two main types: tethered and standalone. The former are devices that simply act as a display for an external device which takes care of the heavy calculation, these devices usually need a direct connection to a computer via cable. The latter are devices that integrate the necessary hardware to run the

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simulation (e.g., sensors, graphic card, processor, ram, hard disk, etc.) directly into the headset and can work without connecting them to any external device (Figure 104). These last types are the most popular nowadays because they can work both in tethered and standalone modes at need.

VR devices can have 3 degrees of freedom or 6 degrees of freedom (DoF). The former can only track head rotations, usually via a simple accelerometer, in fact, a smartphone can be converted into a 3 DoF headset by installing it into a special wearable case provided with special lenses. The latter can track rotations and translations, these devices need special sensors installed in the environment around the user or directly on the headset. For the best experience in visiting hypothetical architectural reconstructions, 6 DoF standalone devices are preferable.

Difference Between Spherical Panoramas and Interactive 3D Explorable Experiences

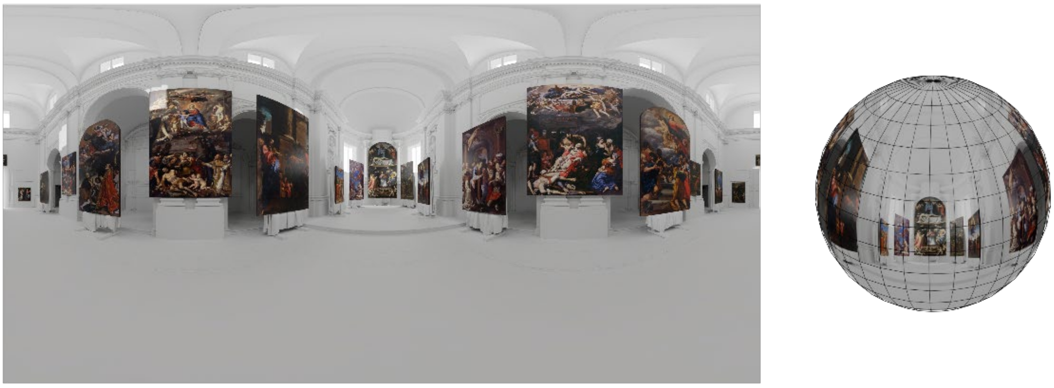

Figure 105: (left) 360° panoramic monocular image, (right) image projected on a sphere.

3D scenes of hypothetical reconstructive architecture can be visualised through 360° panoramic spherical images, or via explorable real-time interactive rendered scenes. 360° panoramic architectural images are as easy to produce as producing a standard 2D render since almost all popular render engines allow the extraction of panoramic images via special virtual panoramic cameras. On the contrary interactive real-time rendered scenes are harder to set up and simulate because the geometry, shaders and lighting of the scene must be optimised in order to achieve a smooth experience, especially if the aim is to run them on a standalone headset which has a much less efficient hardware.

360° panoramic images can be of two types: monocular or stereoscopic. When viewed through a headset the first type projects the same image for both the left and right eye (Figure 105), while the second type projects two different images on the eyes, this gives an improved illusion of depth (Figure 106).

Figure 106: (left) 360° panoramic stereoscopic image, (right) view of the stereoscopic spherical panorama seen from the inside (the anaglyphic effect is used here to give the idea of the different images perceived by the eyes, in the headset the perceived images does not have any anaglyphic effect).

For producing stereoscopic 360° panoramic images a special virtual panoramic camera that supports the omnidirectional stereoscopic projection must be used [Google, n.d.; Marrinan et al., 2021]. The most popular render engines support this type of camera (Figure 107).

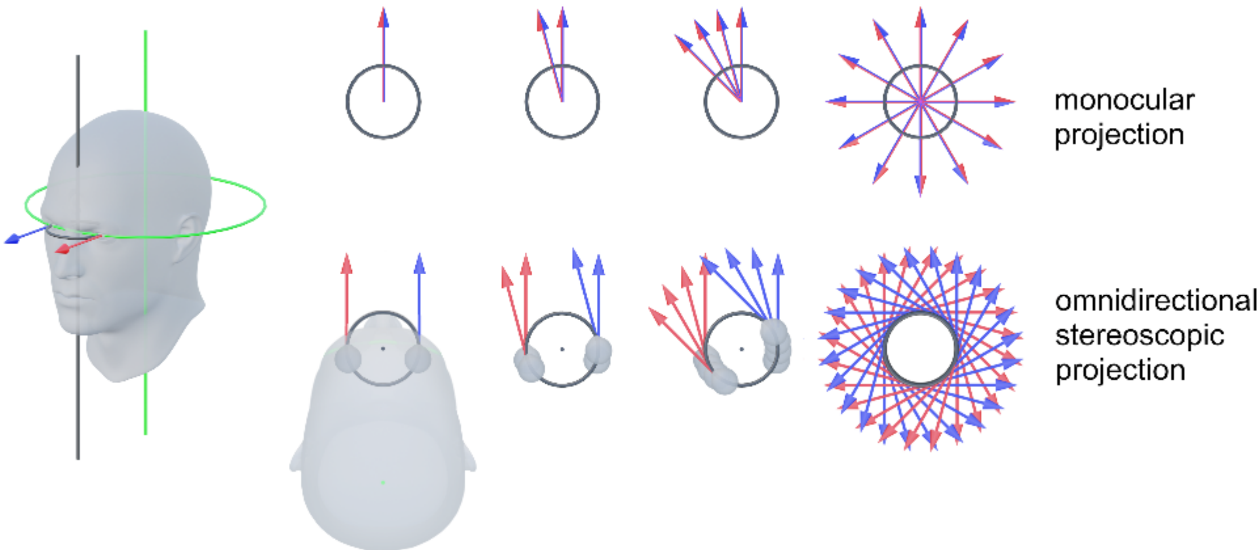

Figure 107: scheme of the projection rays distribution for monocular projection and omnidirectional stereoscopic projection.

Viewing a monocular panoramic image with a head-tracking headset enhances the sense of immersion in a virtual environment, but it can make spaces seem disproportionately large due to the absence of stereoscopy and motion parallax (a phenomenon where closer objects appear to move faster across the visual field than distant ones). In contrast, stereoscopic panoramic images offer a better sense of depth, but they still fail to show motion parallax since the user's viewpoint is fixed. To avoid enlarged space illusions caused by the lack of motion parallax, it is important to limit head movements when viewing 360 stereoscopic panoramic images through 3 DoF headsets.

Full immersion and a much more accurate depth perception are best achieved with interactive fully-explorable real-time rendered scenes through a 6 DoF headset. These systems offer the best available sense of immersion but still face challenges like the fixed distance between the screens and eyes, which disrupts natural eye focusing, known as ocular accommodation. This conflict between eye convergence and accommodation can lead to eye strain [Vergence accommodation conflict, n.d.], an issue not yet resolved in current VR headsets.

Additionally, VR can cause motion sickness in some users or fatigue, which can be mitigated through practice or technical adjustments. For example, VR applications should be designed following well-known good practices [Meta Quest resources, n.d.], and headsets with better resolution, field of view, and frame rate proved to reduce motion sickness for the average user [Wang et al., 2023].

Pre-rendered 360° panoramic images are easier to create and more suitable for producing photorealistic views as the computation is done offline and the reconstructive model does not require specific optimisations, but the trade-off is that only the rotation is tracked, and the perception of distances and spaces is less accurate. On the other hand, an interactive experience explorable in real-time with six degrees of freedom provides better immersion and perception of distances and spaces; however, the trade-off is a reduced level of photorealism, a more complex optimisation of the models, and greater storage space required for archiving and sharing the VR experience.

Aspects of Human Perception in VR

The perception of depth for humans is influenced by stereoscopic and monocular depth cues. The former requires two eyes to be viewed, while the latter are all those cues that can be viewed also with one eye. The main monocular and stereoscopic depth cues are listed in Table 6 [LaValle, 2023, pp. 155–158].

Table 6: Main monocular and stereoscopic depth cues.

Monocular depth cues	***Stereoscopic depth cues***
retinal image size *proximity to the horizon line* *accommodation* *motion parallax* *shadows* *interposition* *atmospheric haze* *image blur (...)*	*ocular vergence* *binocular disparity*

Concerning monocular depth cues, larger images on the retina suggest proximity, while smaller images imply greater distance. Elements closer to the horizon line are perceived as being farther away. Accommodation is the eye's ability to change its focal length, with accommodation our brain assesses depth by monitoring adjustments in the eye's curvature. Motion parallax is another important cue, involving the viewer's movement relative to objects (or vice versa), it allows the brain to infer depth by comparing the speed of retinal images: nearer objects move faster across the visual field than those farther away. Depth can also be assessed by interpreting shadows cast by objects, object overlapping (interposition), atmospheric haze, and image blur.

Stereoscopic depth cues involve both eyes working together. Ocular vergence is the process where the eyes move inward (convergence) or outward (divergence) to focus on a target, proper ocular vergence prevents double vision. The brain interprets changes in muscle tension associated with this eye movement to gauge depth. Binocular disparity relies on the slight differences between the images received by each eye to perceive depth.

Requirements of the Model for VR

For 360° Panoramic images, the 3D model can be unoptimised, the only drawback is that the image might take longer to render but this will not impact the smoothness of the navigation of the panorama with a headset. On the contrary, interactive real-time rendered VR experiences require optimisation in terms of polygon count, texture resolution, shaders complexity, and lighting and shadow calculations. This is essential because rendering a scene in real-time demands the hardware to produce numerous images each second (possibly more than 60 frames per second to minimise motion sickness), and the two displays embedded in the headset have a significantly higher resolution compared to a standard monitor.

It must be said that the optimisation process is nowadays performed partially or entirely automatically by the software of choice. Nevertheless, as of now, it is still useful to know optimisation rules in order to apply them manually in case the automatic result does not provide the expected results.

The most important optimisation steps to perform manually or automatically on a 3D scene are the following:

- reduce the number of polygons of each model as much as possible, and produce various versions of each model with various levels of detail (that will be automatically switched with the high-poly version based on its distance from the viewer)
- reduce the resolution of each texture as much as possible and produce various versions of the texture (that will be switched with the full-resolution one based on its distance from the viewer)
- use minimum amount of dynamic lights (movable lights)
- bake lights and shadows of static lights on the textures
- create low poly hidden collision volumes

- use simple shaders (avoid heavy-to-render effects such as displacement, sub-surface scattering, etc.) to reduce as much as possible the amount of calculations
- limit the use of atmospheric effects and real-time postproduction of the image

Each software has a different level of automatisation and its own guidelines for setting up a VR scene, so it is highly suggested to consult the documentation and comply with it.

Visual Examples of VR Canova's Exhibition

An example of a VR experience developed by the Department of Architecture of the University of Bologna is Canova's exhibition in Spirito Santo Church in Bologna [Apollonio et al. 2024]. In this project, the exhibition organised by Antonio Canova in 1816 was reconstructed virtually and presented at *the Notte Europea dei Ricercatori* – Society in 2023 for scientific dissemination.

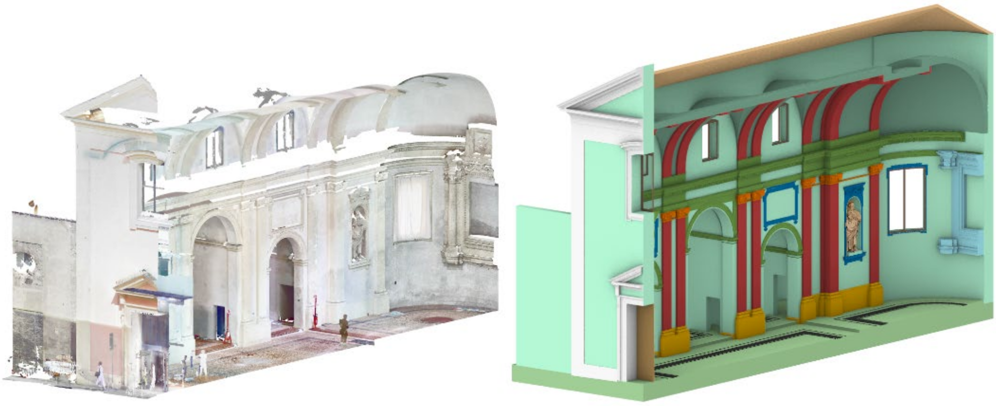

Figure 108: (left) point cloud of the actual Santo Spirito Church in Bologna, (right) NURBS reconstruction as it was in 1816

First of all, the still-existing church was acquired with a laser scanning campaign, then the 3D model of the church was reconstructed with Rhinoceros, as a NURBS solid model, using the point cloud cross-referenced with additional historical sources (Figure 108). The model was then converted into a polygonal mesh and imported into Blender, here the various elements were decimated, cleaned up, UV unwrapped and the lights were baked into the textures (Figure 109).

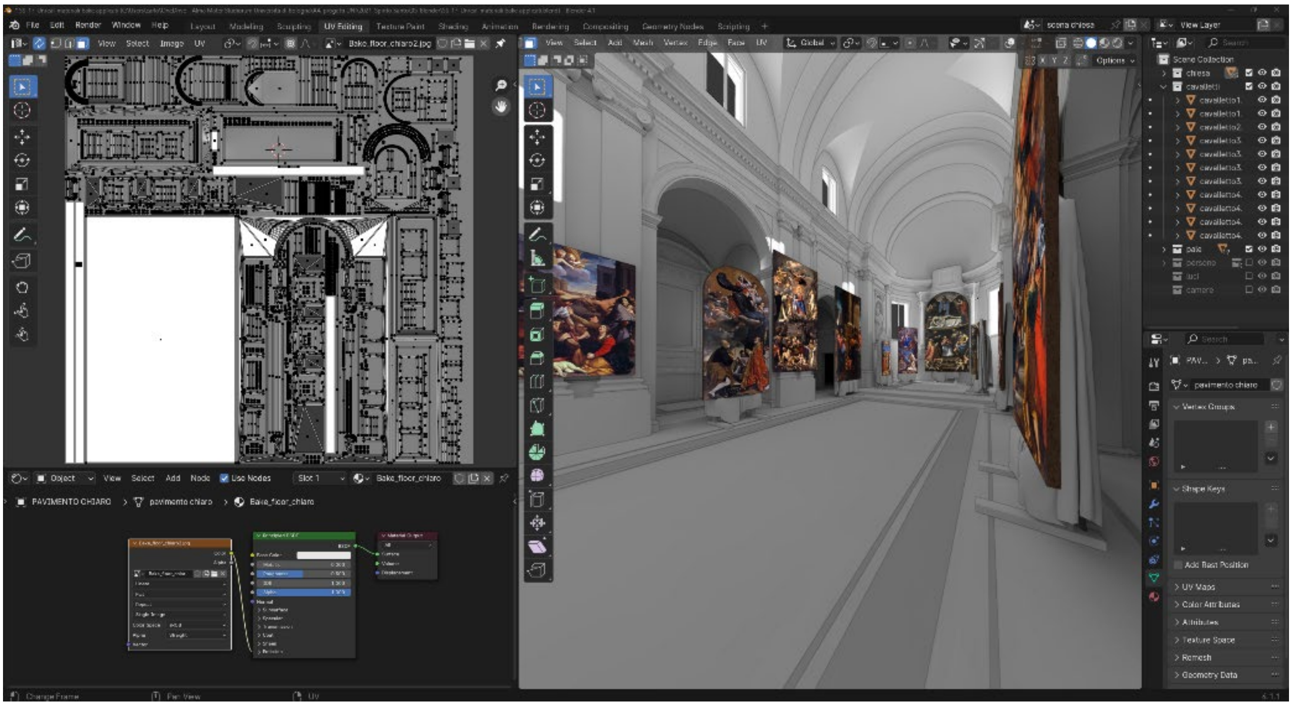

Figure 109: optimisation of the model, UV unwrapping, and light baking in Blender

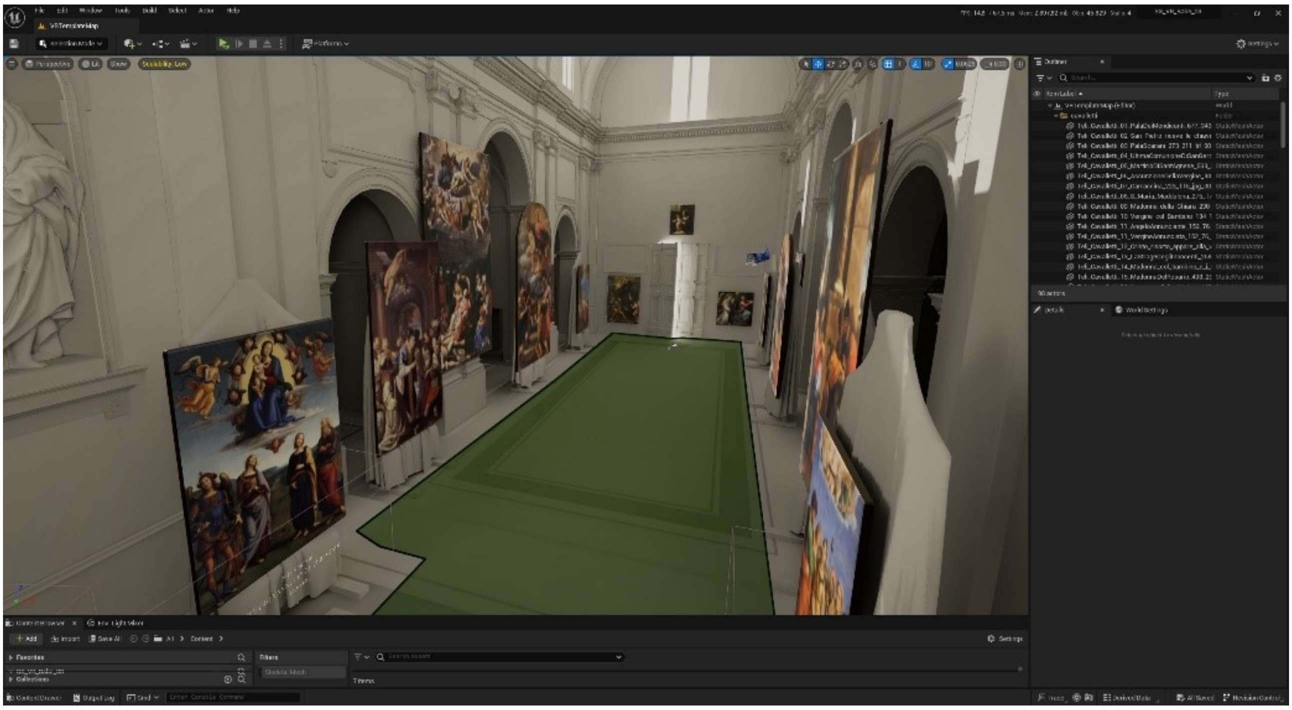

Figure 110: scene setup in Unreal Engine (the green area is where the navigation is allowed)

The model was then imported into the VR template scene in Unreal Engine. The scene was modified at need and set up to make an interactive immersive experience. In particular, the shaders of the model were rebuilt from scratch, collision objects were added and the navigation system was set up in order to limit the explorable area only to the main nave of the church (Figure 110). Responsive texts were added to the scene to add a layer of gamification and interactivity, with the objective of scientific dissemination.

Figure 111: VR scene tested with users at the Notte dei Ricercatori - Society 2023

The experience was presented to the public and tested with visitors who had the chance to navigate the space through the use of controllers and headsets with 6 DoF (Figure 111). The navigation system was teleportation-based because it is convenient for people not used to analogistic navigation and minimises motion sicknesses. The hardware used and some statistics of the scene are reported in Table 7.

Table 7: hardware and scene statistics for Canova's exhibition in Santo Spirito Church in Bologna, 1816.

Laptop configuration	***VR headset***	***Scene statistics***
CPU: i7-10750H 2.60GHz GPU: NVIDIA GeForce RTX 2060 (6GB) RAM: 32 GB Operating system: Windows 64-bit	*Model: Meta Quest 2 All-in-One DoF: 6 IPD: Adjustable with 3 Settings External sensors: no Controllers: Two Touch Controllers Resolution Per Eye: 1832 x 1920 Refresh rate: 60Hz to 90Hz*	*Objects: 66 Vertices: 3.519.493 Edges: 8.202.818 Faces: 4.684.859 Triangles 7.029.887 Texture resolution max: 8192x8192*

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22. Interrogating the Model: Computer Simulation

Authors: Joan Anton Barceló, Evdoxia Tzerpou

Introduction

To "interrogate" a digital model means to interact with, analyse, and extract meaningful information from the digital visualisation. This process involves querying the digital model to understand its various aspects, such as structural details, spatial relationships, and historical context. When dealing with a digital model that depicts the original state of a building recreated from its preserved remains, virtually interacting with it, we can obtain the model and valuable insights into the building's architecture, historical significance, and cultural context. For instance:

- We can examine the structural elements of the building, such as walls, columns, arches, and roofs. This can involve measuring dimensions, identifying materials, and understanding the construction techniques used.
- We can analyse the spatial relationships within the building, including room layouts, corridors, and the overall floor plan. This can help in understanding the functional use of different spaces.
- We can integrate historical data to provide context for the building's design and use. This might include information on the building's original purpose, cultural significance, and any modifications made over time.

In that sense, we will query the model in real time. By rotating, zooming, and slicing the representation to view different perspectives and cross-sections. In so doing, we will extract specific features or elements of interest from the model. For example, you might want to isolate and study a particular architectural detail or ornamentation.

By running simulations, we will understand how the building might have functioned in its original state. This could include lighting simulations to see how natural light would have entered the building or animations to show how people might have moved through space.

Why? Questions

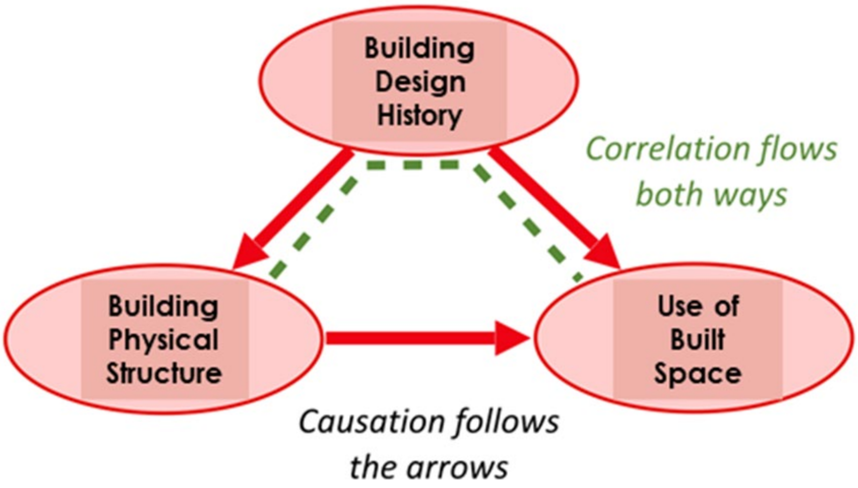

Figure 112: The explanatory content of a 3D model

In philosophy, a why-question typically seeks to understand the reason, cause, or justification for a particular phenomenon, belief, action, or situation. In our case, such questions aim to uncover the underlying principles, motivations, or explanations behind ancient buildings and constructions. We need an interrogative model of inquiry where asking questions is seen as a fundamental method of acquiring and formalizing knowledge. In this context, a "why" question can be seen as an inquiry into the epistemic justification of a statement or belief; that is, they are inherently explanation-seeking. They are not merely asking for descriptions or definitions but are aimed at uncovering causal relationships or reasons that account for the occurrence or nature of the subject in question.

Why is a building or any form of built space the way it is? A possible answer will be “because of its proper functioning”. It has been argued that to ascribe a function to something is always related to its “intended” use. Therefore, the meaning of functioning seems to be intrinsically related to the term using. Obviously, there are many ways of using a building, not just “living” in it! We should distinguish between function, structure, and behaviour as three classes of properties of a design element: function properties would dictate the entity’s intended purpose and requirements; structure properties would represent the description of the whole and its constituents; while the behaviour properties would spell out how the structure of the entity achieves its intended use.

To solve this kind of why? questions, in our case, we should determine causal relationships between the building design history, its actual and deduced physical structure, and the different ways we have documented it was used along its history.

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Computer Simulation

The algorithmic implementation of causal relationships inside a machine to explain why a digital model has the characteristics it has is usually called a computer "simulation" of a causal process. History only runs once. However, on the computer, it can run over and over again. We can explore (by altering the variables) the entire possible range of outcomes for different behaviours. We can compare what did happen with the parameters of its closest silicon analogue and discover what was constructed, when, why and how.

Computers offer the possibility of reversing a hypothetical causal process or mechanism to test whether it is the proper cause we were looking for. If the causal mechanism is computable, then we can reproduce it virtually inside the computer. Computable means here that we can build a logical input-output function, in which the output represents the observed effect –for instance, in terms of the values of some of its physical distinctive properties, and through a series of logical operations (propositional and/or algebraic and/or geometric and/or set theoretic, etc.) we can obtain similar values using the appropriate input.

Computer simulation is a great tool that may allow us to test, validate, and modify digital models. Specialised software allows studying the dynamics of moving parts and how loads and forces are distributed throughout mechanical systems. In that sense, the functional role of the different components of a mechanical system can be measured and evaluated. In our case, the aim would be then to use the geometry of the digital model and find a way to include the original mechanical properties of the materials and components of the ancient building referred to in the geometric model.

Structural Analysis

Structural analysis reproduces how a physical structure is supported, taking into account the interaction between the building structure and the ground or adjacent structures and the interaction between different structural components, such as the contact between stone blocks or the interface between walls and floors. Structural analysis is the determination of the effects of loads on physical structures and their components. In this domain, it refers to the process of assessing the stability, strength, and rigidity of historical structures. For carrying out any form of structural, fatigue, vibration or heat transfer analysis, partial difference equations should be solved to compute relevant quantitative parameters of material transformation, like stress or strain, in order to estimate a certain behaviour of the investigated component under a given load. Stress, for instance, can be defined as force load per unit area and describes the internal forces the structure has experienced. The deformation resulting from applied load is known as strain and is defined as the change in length divided by original length. By convention, tensile stresses and strains are defined as positive, whereas compressive stresses and strains bear a negative prefix.

We can distinguish:

- Linear structural analysis for small deformations and elastic behaviour, which is suitable for initial assessments.
- Non-linear structural analysis to account for large deformations, material non-linearity, and contact problems. This is crucial for understanding the behaviour of cracked or damaged structures.
- Analysis of the natural frequencies and mode shapes of the structure to assess its response to dynamic loads, such as earthquakes.

By considering the structural dynamics of built spaces, the reasons behind an ancient construction collapse can be inferred. Some buildings were intentionally dismantled so they could be mined for construction materials to make new dwellings or other buildings. Those left untouched in all probability collapsed due to lack of maintenance, as points of connection (lashings) loosened, and areas of the frame requiring shoring up were left unattended. On occasion, structures may have collapsed while still occupied. Therefore, the study of structural stability of a historical construction allows, not only the reconstruction of the original building from its preserved remains but also the way it was built and some aspects of its probable use. The results of such analysis allow for comparing different reconstructive hypotheses on the elevation of prehistoric and ancient buildings when the archaeological remains are too fragmentary and incomplete. Given that prehistoric and ancient building technology is not like modern one, such models are aimed at identifying the mechanisms of deformation and potential collapse of a virtual reconstruction of the building and its inferred support system under simulated static or dynamic loads, by identifying the parts of the structure subject to high tensile and compressive stress, and then at risk of damage. Together with the geometry, an accurate knowledge of ancient technology and the properties of materials used in their construction is the first step towards the determination of the stress and deformation states of the building. An accurate analysis of the structural parameters of the different materials –masonry, stone- and backfill –mortar, concrete, dry stone construction, etc.) is needed, even if these materials are no longer in use in modern architecture. In such cases, experimental studies with replicated material will be necessary.

Finite Element Method

Finite Element Analysis (FEA) is a computational technique used to predict how entities respond to physical forces. The surfaces and volumes in the digital model of the ancient built space are modelled as being hypothetically subdivided into an assembly of small parts called elements. In this methodology, an "element" is a fundamental building block of the geometric mesh that decomposes the shape and form of the model into the smallest computational units. The word ‘finite’ is used to indicate that the behaviour of each element should be represented with a minimum of degrees of freedom. Those discrete and finite elements are assumed to be connected to one another, but only at interconnected joints, known as nodes. Therefore, an element in FEA is a small, simple geometric primitive (such as a triangle, quadrilateral, tetrahedron, or hexahedron) that collectively forms the mesh covering the entire geometry of the model.

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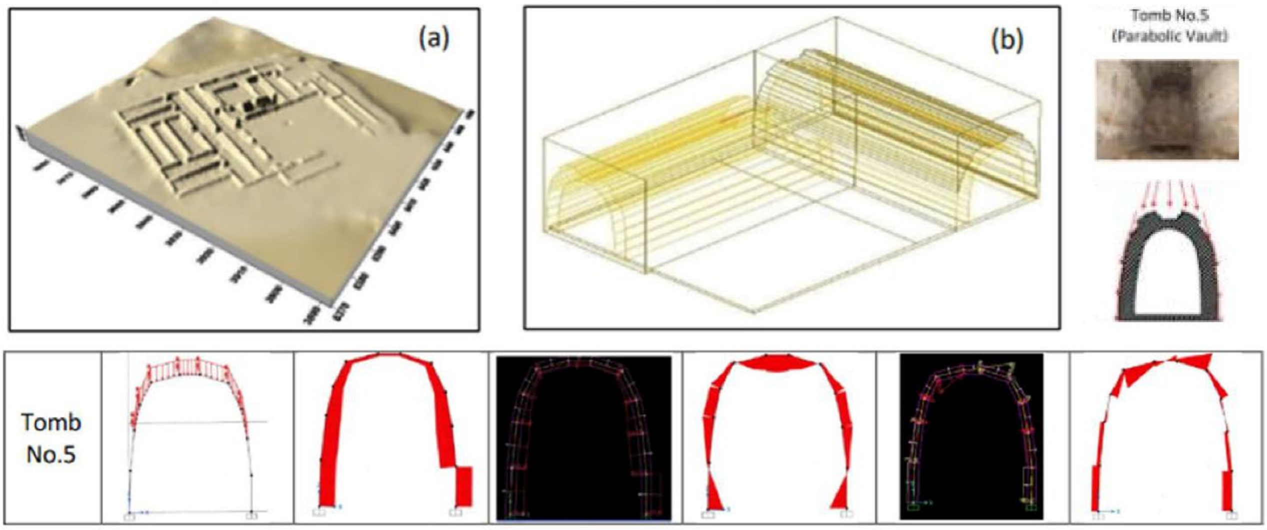

Figure 113: Finite Element Analysis of the underground tombs of Chogha Zanbil (Hosseini et al. (2020). Published with permission of the authors.

Each element represents a discrete portion of the structure and shares nodes with adjacent elements, and they are characterised by:

- The geometry of the element (e.g., triangular, quadrilateral, tetrahedral, hexahedral).
- The degree of the polynomial used in the element's shape functions (e.g., linear, quadratic).
- Key points defining the element's corners and sometimes mid-sides, which connect elements together (nodes).

Once the minimum geometrical units are defined, we should introduce material properties to each element. FEA software incorporates a material library listing all properties for all materials used originally in the studied ancient construction (Young's modulus, Poisson's ratio, density, yield strength, stress-strain data, etc.). The user selects the geometry or part of the model where the material properties need to be applied and assigns the defined material to this geometry. The software will automatically apply the material properties to all elements within this part.

Advanced Forms of Computer-Based Simulation of Building Use

Computer simulations are not only relevant for understanding how ancient constructions were excavated or erected. They also allow for understanding how built space was used by people, reconstructing the way people moved around the building, how the house was illuminated from the outside or inside, and what activities were allowed in the illuminated areas, the acoustic properties of temples and ancient theatres, etc. In general, what we intend to do is to analyse functionally built space to find the way the structural mechanics of the building constrained or determined what people could do inside.

- Understanding orientation. To orientate a building means to position it in a specific direction or alignment, typically with respect to the points of the compass or to the path of the sun.
- Understanding Lighting and Illumination. The study of artificial lighting of architectural heritage is one of the best examples of interrogating a digital model using simulated processes. Its goal is not just to increase the apparent realism of the model representation but to understand what people could do at different parts of the building, depending on the quantity of light arriving at the place of work. Such analysis depends on physically-accurate simulation of light source –natural and/or artificial-, transport and of all components of the visual scene. Such lighting analyses should make use of a simulation of the light energy within the scene, taking into account the luminaires, environmental effects and the materials with which the light energy interacts. Two sets of statistics are commonly produced by such lighting analyses. Firstly, the illuminance or light arriving at a surface is commonly divided into the direct illuminance (i.e. the light that travels from the luminaire to the surface without any intervening reflections) and the indirect illuminance (which summarises the light reflected from surfaces but not received directly from the light source). Secondly, the luminance is the light that reflects from an illuminated surface.
- Understanding Sightseeing. Sightseeing, in technical terms, can be defined as the process of visually perceiving and cognitively interpreting the physical and spatial attributes of an environment, often with the aim of understanding, appreciating, or evaluating its aesthetic, cultural, or functional qualities. This process involves a complex interplay of sensory, perceptual, cognitive, and affective mechanisms, which enable individuals to construct mental representations of the environment and make sense of its various elements and their interrelationships. Simulating sightseeing using computers involves the creation of virtual or digital representations of built spaces and their design features, which can be explored and experienced by users in ways that replicate or approximate the processes and outcomes of real-world sightseeing. We can interrogate the digital model, reproducing the shape and form of the built space to replicate or approximate the sightseeing process. This may involve the use of 3D visibility analysis, which calculates the areas of the built environment that are visible or obscured from different viewpoints or perspectives. The model may also incorporate factors such as distance, angle, or orientation of the view, as well as the cognitive and affective responses of the viewer, such as attention, interest, or preference. The results can be visualised on the digital model using isovists. An isovist is a two-dimensional representation of the three-dimensional visual field of an observer at a specific location in a built environment. It can be created by drawing a line from the observer's location to every visible point

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in the environment and then connecting the resulting endpoints to form a polygon.

- Understanding sound propagation and acoustics. The way sound propagates and reverbs may affect what people would have done inside a built environment, especially related to particular ceremonial or political activities. For more than two decades now, computer simulations of sound fields in built space have been widely adopted in research. Auralisation is the process of creating a sound simulation, often in a 3D environment, to recreate or predict the acoustic properties of a space. In the context of ancient buildings and built spaces, auralisation can be a valuable tool for understanding how these spaces were used in the past. By simulating the acoustic properties of an ancient theatre, for example, researchers can gain insights into how sound was projected and how the audience would have experienced the performances.
- Understanding pedestrian Movement. A very relevant way to interrogate our digital model of heritage architecture is by asking how people could have moved inside a building - or around it - and how the built elements limited or even determined the possibilities of movement in different directions. It is technically easy to simulate in a computer how a virtual avatar representing people moved from point A to point B. If the virtual room or landscape traversed by the virtual avatar has been correctly represented, it is a metrically correct model of some real physical space, then the speed and direction of movement of many people as constrained by architectural structures can be calculated.
- Understanding Spatial Syntax. Space syntax methods are a series of graphical and quantitative procedures allowing the recording and description of the social interaction pattern emerging from the spatial structure of the architectural environment. The degree of presence or accessibility for a social encounter of a spatial unit will, therefore, depend on the number and nature of permeability relations with respect to other spatial units. This implies that the constructed space has a social meaning according to its relational order. This order creates and reproduces a particular model of permeability characterised by the juxtaposition of spaces with different levels of presence or accessibility. In a spatial syntax study, convergence maps allow the establishment of a series of axial lines, arising from the analysis of each building, whose straight-line extension is extended to the next building. The areas of convergence, arising from the intersection of these axial lines, serve to illustrate the main nodes of social gathering within an urban complex or settlement. Accessibility graphics (gamma analysis) have been defined as a topographic method that allows us to represent and interpret the spatial configurations in buildings and settlements. They are, in fact, the adaptation of axiality graphics for the understanding of the presence/permeability of spatial basic cells. These accessibility maps are fundamentally oriented to the interior analysis of buildings.

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23. Enriching the Model with Environmental Elements

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Recreating the Past: the Environment as Context

When virtually recreating a building or site from the past, it is essential not to leave it as an isolated and uncontextualised model. A comprehensive understanding of such structures and places depends on several factors, including material culture (both movable and immovable heritage), landscape, customs, and overall cultural significance, which will be referred to as the environment from now on. Therefore, recreating a building from a past era also requires recreating its context, surroundings, and interaction with the environment.

The use case of the hypothetical virtual recreation of the Catalan village of Guimerà, a medieval town located in the province of Lleida, Catalonia, Spain, at the beginning of the 15th century serves us as an example for the topic concerning this module of the course.

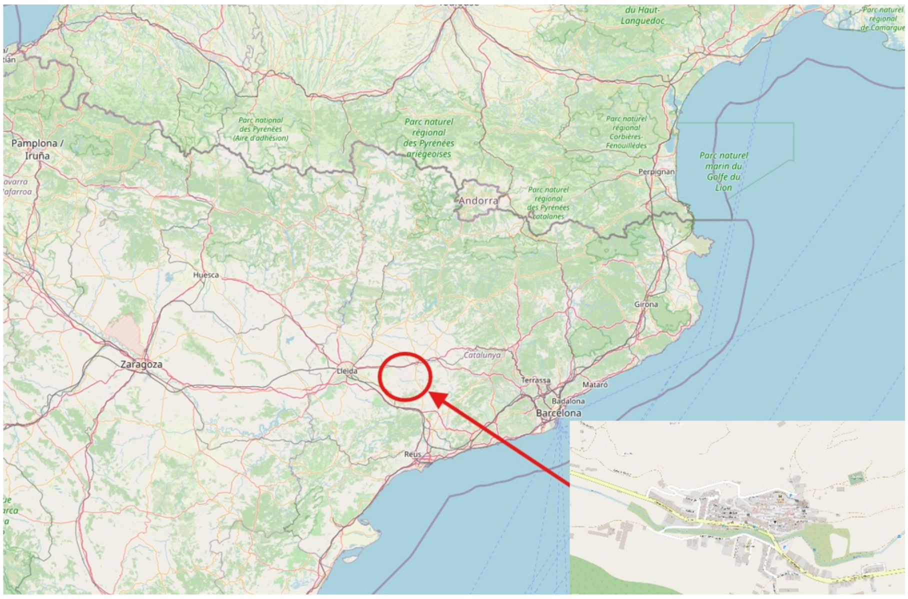

Figure 114: the location of the Guimerà site, in Open Street Maps.

Figure 115: Guimerà site, in Open Street Maps.

Figure 116: A photograph depicting the current state of the Guimerà village

The remains of the watchtower can be seen on the top of the hill. Source: Wikimedia Commons, Public Domain. His 3D reconstruction was specifically developed to support the MOOC units, with the aim of not only reconstructing the castle or the village but recreating the entire surrounding environment with the highest level of historical rigour. The next question is: what are the main guidelines and workflows to follow when recreating a virtual scenario of the past?

The Seville Principles as Guidelines

Any recreation process must follow a scientific methodology, as its goal is not only to aid in the dissemination of cultural heritage but, more importantly, to contribute to the enhancement of humanity's knowledge about the past. The Principles of Seville,

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formally known as the International Principles for Virtual Archaeology and ratified by the 19th ICOMOS General Assembly in New Delhi in December 2017, serve as fundamental guidelines established by the scientific community. In particular, Principles 4 and 5 should be followed when producing accurate virtual recreations of the past. Let's take a closer look at what these two principles represent.

Seville Principle 4, labelled Authenticity, states that computer-based visualisations in archaeology should aim to reconstruct historical buildings, artifacts, and environments while clearly distinguishing between what is authentic and what is not.

This is the reason why, when a virtual recreation is made, a version of it should also be done, showing its scale of uncertainty. According to the scale established in the CoVHer project, the same virtual recreation can be viewed using the 7-step uncertainty colour scale. However, since virtual recreations of archaeological sites include environmental elements often not considered when reconstructing buildings, such as crop fields (areas of land that are cultivated for growing crops such as grains, vegetables, fruits, or other agricultural products), vegetation or tends, the uncertainty scale had to be adapted to encompass these additional elements. This use case proves the versatility of the CoVHer scale to meet the requirements of different types of virtual recreation projects.

Figure 117: Render of a general view of the virtual recreation.

Figure 118 The site is coloured under the 7-step CoVHer uncertainty scale.

The Seville Principle number 5, labelled as Historical rigour, emphasises that any virtual reconstruction or recreation of the past must be supported by solid research and historical and archaeological documentation. This principle also emphasises the importance of depicting the landscape not as an idyllic image of the past but as a realistic representation.

Figure 119: Orthophoto of Guimerà village. Source: National Plan of Aerial Orthophotography (PNOA), Ministry of Transports and Sustainable Mobility, Government of Spain.

Workflow and Main Sources

To ensure scientific and historical accuracy in the virtual recreation, a variety of sources were consulted, including geographical data such as topographic maps, LiDAR coverages and orthophotos, as well as astronomical, archaeological, and historical records. Additionally, extensive bibliographic references were consulted to enhance the understanding of the historical period to be represented as the environmental context.

Figure 120: Render of the site, viewed from the top of the hill.

GIS (Geographic Information Systems)

GIS (Geographic Information Systems) are crucial at establishing an accurate positioning of reconstructed or recreated buildings when combined with archaeological planimetries. GIS integrates and analyses spatial data, allowing precise mapping and recreation of historical landscapes. Digitised elevation models and orthophotos can be added to create detailed and accurate environmental terrain, enhancing the authenticity of the virtual reconstruction. To recreate the terrain and the landscape, a 3D model based on real and official data from the Spanish National Centre of Geographical Information was produced. The digital elevation model was made in QGIS software using the Qgisthreejs plugin, which allows the user to convert geospatial data (geoTIFF file format) into a 3D model (glTF file format), also mapping the orthophoto as its base colour texture.

Archaeological Sources

Archaeological planimetries provide detailed site layouts, ensuring faithful reproduction of dimensions and spatial arrangements.

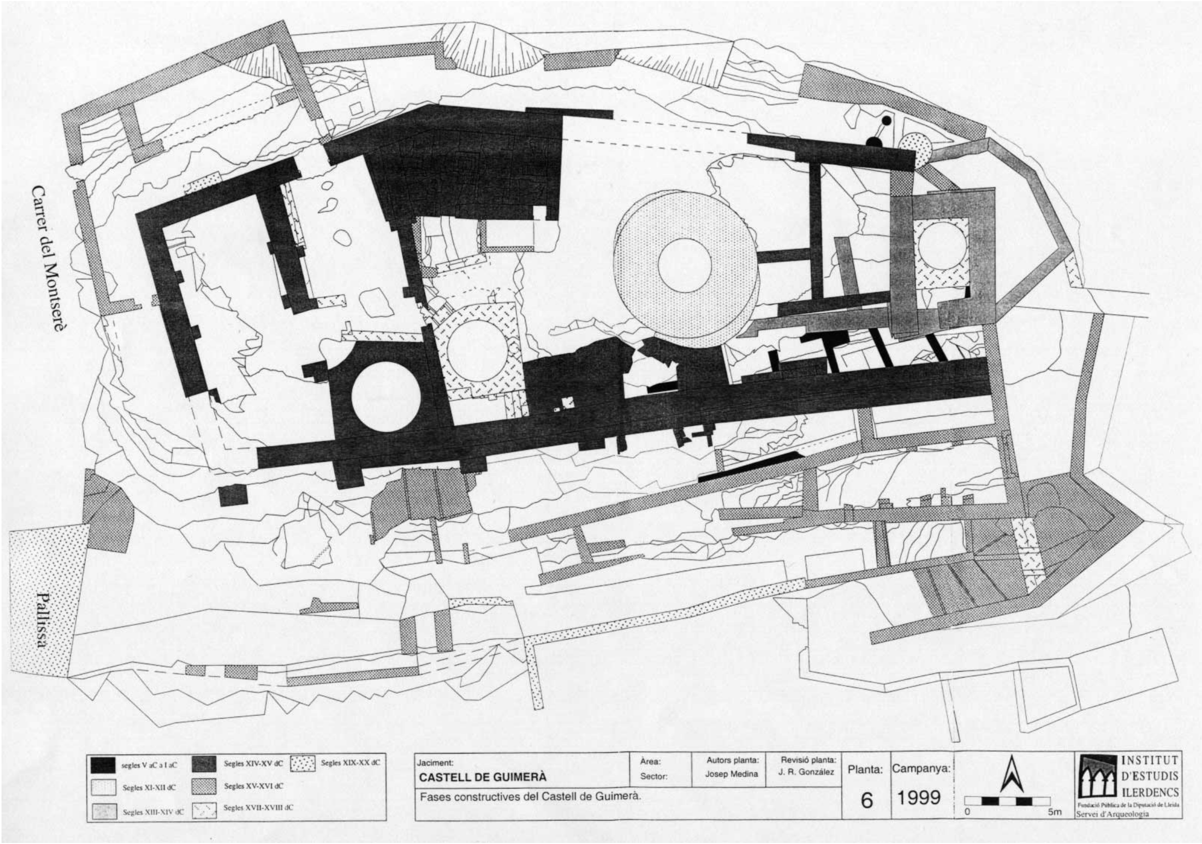

Figure 121: archaeological planimetry of the castle, the different constructive phases are depicted in different colours and patterns. Source: Institut d'Estudis Ilerdencs.

In this case, archaeological sources could only provide us information about the castle and a small section of the wall. The key is to combine the previous GIS documentation process with the archaeological planimetry, providing an added value to both sources. As represented in Figure 122, the accurate placement of the castle was achieved by overlaying the planimetry onto the orthophoto.

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Figure 122: overlaying the planimetry over the 3D model of the terrain.

Historical Sources and Bibliography:

The rest of the village and the natural and cultural environment were recreated from distinct historical sources, some more reliable than others. Primary and secondary historical sources complement and add new information that can help us gain a deeper understanding of the site, its environment, and its material culture, thereby providing a more realistic and rigorous approach to the virtual recreation. For instance, the representation of the main entrance to the watchtower through a rope ladder in our virtual recreation was determined by bibliography research based on historical documentation. Numerous references indicate that, by the 15th century, the village's walls and defensive structures extended to the river’s edge. Additionally, many of the old entrances are still preserved today as part of the streets, which helps us understand the village’s limits.

Figure 123: Render of the main entrance to the watchtower.

Figure 124: Orthophoto of the village. The highlighted part shows the limits of the settlement by the beginning of the 15th century. Source: National Plan of Aerial Orthophotography (PNOA), Ministry of Transports and Sustainable Mobility, Government of Spain.

Figure 125: Aerial render of the virtual recreation.

Documentation related to a medieval and early modern tax known as the 'fogatge' was analysed to estimate the number of houses and the population at the beginning of the 15th century. This tax, levied in the Principality of Catalonia, required each community to pay the king an amount based on the number of households or hearths. Thanks to these records, we were able to estimate the number of houses. However, considering that tax evasion has been a common practice throughout the centuries, the number was set slightly higher than the records, with an estimated range of 90 to 150 houses.

There are no direct references regarding the defensive towers and their location. However, the ruins of the tower next to the church suggest the presence of additional defensive towers along the wall. The number of towers has been set to eleven as the oral tradition says that Guimerà was known as "the castle of the eleven towers", which is not reliable at all. This is why the uncertainty for the number and location of towers was set at Level 6 (71-86%) on the uncertainty scale.

Figure 126: Render of the highest part of the village.

Setting the Environment

Recapping what was said during the introduction, the environment and context around archaeological remains are crucial. Virtual reconstructions should reflect the complete historical context, including landscapes and ecological elements, avoiding lifeless or misleading portrayals.

A critical aspect when virtually recreating the environmental context of an archaeological site is comprehending its diversity and imperfection, as well as its diachronic dimension. This means computer-based visualisations should depict all historical phases, including periods of decline, rather than just an idealised, glorious past. As a result, buildings should be represented in various states of preservation, as human representation should be diverse in characteristics such as gender, age, social status, or role.

Figure 127: Close-up render view of two houses in different states of preservation. Also, a person can be seen leaving the left house.

The disposal of the vegetation needs to be realistic as well, considering the climate and biome where these elements are part of, as well as anthropic action over it. Therefore, in our example, there should be a higher density of trees and bushes next to the river, as well as the disposal of crop fields and agriculture as an anthropic action.

Figure 128: render view of the Corb river and its surroundings.

The accurate positioning of the Sun can offer a new perspective on the recreation as well. It can give us a better understanding of the site and its surroundings. To set the Sun's position, the Open-Source software Blender includes an add-on called Sun Position, which allows us to illuminate the scene by simulating solar radiation at the exact spot where it was at a moment of the day of a specific year. This add-on, based on real astronomical data from the U.S. Government, only requires the user to input the World coordinates of the place, which can be extracted from other open or public GIS data.

Figure 129: the Sun position at 8 am on 25th of May 1400.

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