# 3D ArchiVHR – Glossary

## 3D Architectural Virtual Hypothetical Reconstruction

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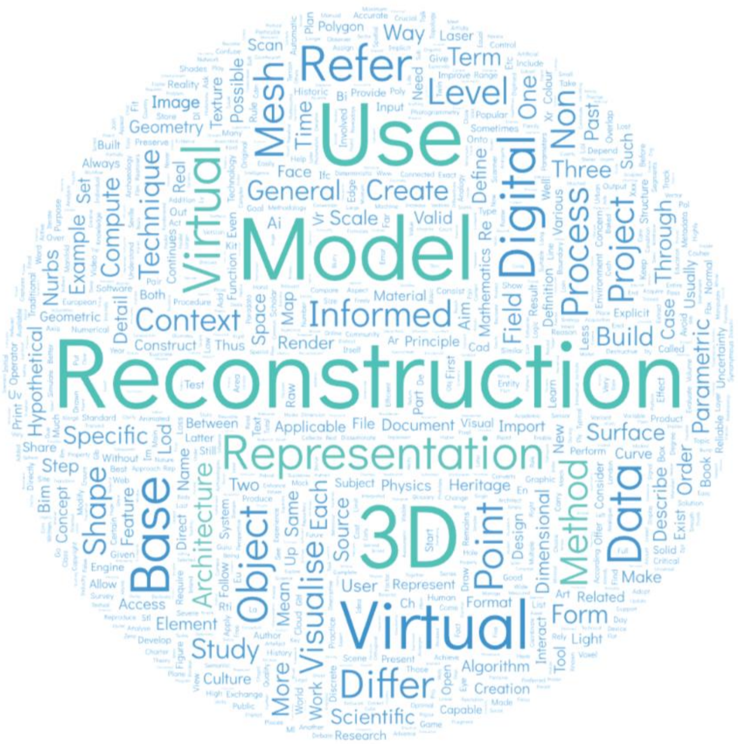


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# Introduction

## 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 world and the domain of digital entertainment (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 are no reference standards at the academic level designed to evaluate their 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. For the latter objective, to build a valid CVCH model, it 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

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 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 have never been built or have been destroyed. The goal is to create a digital 3D repository that can transmit, together with the finished product (3D model), also 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 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, constructing, 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 Case Studies 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 Case Studies Book (3D ArchiVHR – Case studies).

The *glossary book* collects some fundamental terms (sorted in alphabetical order) for the topic of architectural virtual hypothetical 3D reconstructions of the past. The terms listed here are the theoretical framework of the *Case studies book*. The definitions presented in this 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.

This 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 other hierarchical or chronological order. This choice is due to two fundamental reasons. The first is the fact that this book is complementary to a second book of case studies that has a more hierarchical/chronological structure which presents and illustrates case studies from start to finish intended as good practices of reference applied in different contexts; therefore, this first book has to be intended as a theoretical basis of reference to be used together with the second book. The second reason is that this book can also be intended as a manual of reference that can be read jumping from one concept to the other freely and according to one's needs. This allows the scholar or the amateur to read and further study only the needed terms according to their cultural backgrounds.

## 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).

Some of the definitions were developed from scratch by the research group in order to clarify those concepts that missed a clear naming and a shared definition. Other conceptual and technical definitions were inherited from the scientific literature and were included to avoid ambiguity and mystification.

Artificial Intelligence tools (i.e. Open AI Chat GPT https://chat.openai.com/) were also used in minor parts of the text. It is true that the neural network architecture, which allows the AI tools to generate coherent and contextually relevant responses, already proved in the past to give often inconsistent or wrong results, however with a human-driven professional verification and validation of the automatically produced texts, these tools can be an effective way to explore alternative grammatical forms or synthesising complex concepts. Probabilistic reasoning is a key aspect of AI tools and, rather than absolute facts, they give answers based on advanced probabilistic algorithms, which is sometimes a useful strategy to have a first hypothesis of what could be the most popular meaning of a specific term in a specific context.


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## Acknowledgements

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# Glossary of Terms and Concepts

## 3D Model

In computer graphics, a 3D model is a digital representation of an entity in a virtual three-dimensional space. It is a computer-generated or digitally sculpted model that captures the shape, form, and spatial characteristics of the subject. 3D models can have different taxonomies, for example, we can classify them according to the 3D digital representation method used, which concerns (refer to Figure 1):

- their geometric continuity (discrete/continuous, mathematical/numerical 3D models);
- their mathematical parametrisation (parametric, non-parametric 3D models);
- their formal mathematical formulation (implicit, explicit 3D models);
- the spatial configuration/morphology (Solid, Surface, Wireframe, Volume);
- the specific representation method adopted (e.g., NURBS, mesh, Voxel-based 3D models);

In the case of 3D hypothetical virtual reconstruction of architectural heritage, we are implicitly talking about digital/virtual 3D models created in a computer environment. Such models, stored as zeroes and ones (digits), are accessible to users (for example, visually) thanks to computer interfaces. There is also the possibility of transforming the digital record into a physical one, such as in the case of 3D printing.

Digital models have features that make them particularly useful in the process of creating 3D hypothetical virtual reconstructions of the past. These features stem from the nature of new media. These are, according to Lev Manovich [2001, pp. 21–46][1]:

- numerical representation
- modularity
- automation
- variability
- transcoding

The numerical representation features allow easy communication and replication of the model record without loss of quality. The *modularity* feature makes it possible to isolate individual parts and analyse or work on them individually and makes it possible to differentiate by colour (e.g., uncertainty/reliability scale) and/or assign appropriate meanings to individual parts of the model (i.e., semantic segmentation). *Automation* is a feature which speeds up certain activities employing algorithms. *Variability* is a feature of digital models that allows them to exist in an infinite number of versions, which are modifications of the original. Each of them can be changed by modifying some of its parameters while keeping the changes reversible (something that cannot be said of most physical models). Finally, *transcoding* is a feature that manifests itself

[1] Manovich, L. (2002). The Language of New Media. Screen. Cambridge, Massachusetts: MIT Press. http://books.google.com/books?id=7m1GhPKuN3cC

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at the technological level through the ability to save the model in different formats allowing different uses; but also at the cultural level, where the model can carry different concepts and meanings. The model can then be explored in different contexts and different ways: visualisation, Virtual Reality, augmented, and mixed reality. It can be a research or popularisation tool; it can be an element of a fictional world or a scientifically valid attempt at hypothetically reconstructing the past. In extreme cases, the transcoding feature can lead to going beyond the digital world, (e.g.) with the creation of mock-ups based on the model using 3D printing.

## 3D Modelling

In computer graphics, 3D modelling is the process of creating a three-dimensional representation of an object or scene using specialised software. 3D modelling can be classified according to the 3D digital representation method that the software uses for the creation of shapes, or according to the practical 3D modelling technique used by the operator (refer to Figure 1). In the context of virtual hypothetical 3D reconstruction 3D models can also be classified according to their level of interpretation (Raw Model, Informative Model).

## 3D Modelling Technique

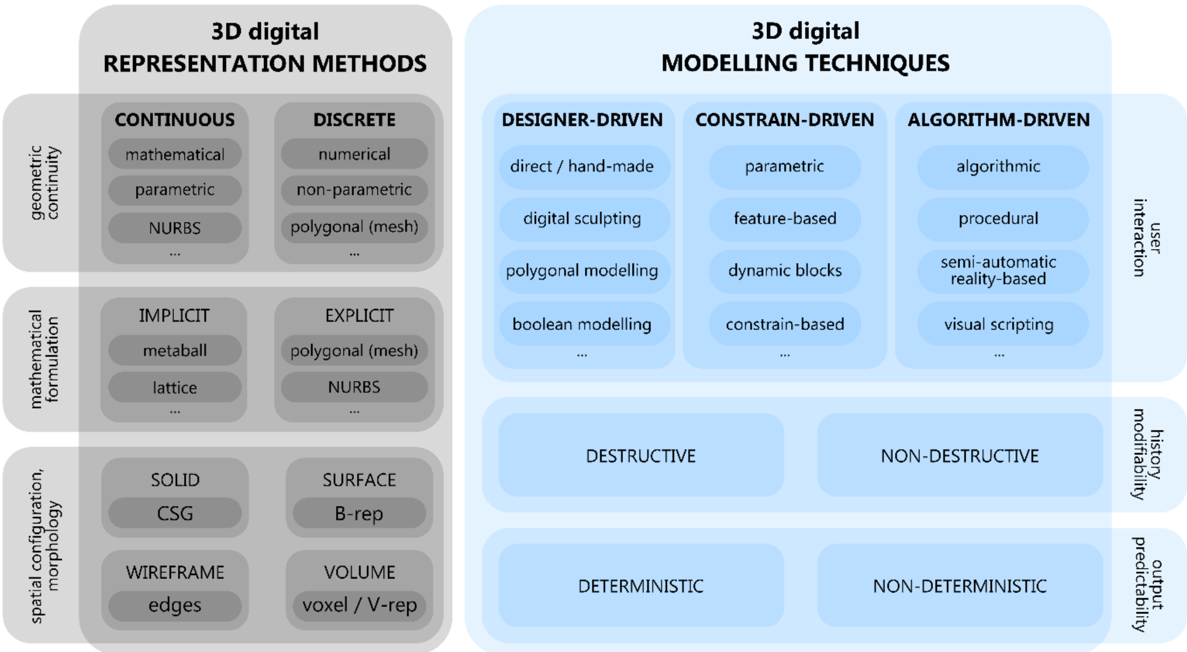


*Figure 1: taxonomic scheme of 3D digital modelling techniques compared with 3D digital representation methods.*

A 3D modelling technique concerns the step-by-step processes to create 3D models. The 3D modelling technique describes the act of constructing the shapes and must not be confused with the 3D digital representation method that defines how the computer mathematically/geometrically represents the 3D models. The following analogy with the traditional methods and techniques of representation in classical descriptive geometry should clarify the distinction between 3D digital representation


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methods and 3D modelling techniques. A traditional drawing technique (e.g., watercolour technique) can be used to add a shading effect to a drawing realised with any of the traditional representation methods (e.g., perspective projection, axonometric projection). Analogously, 3D modelling techniques (e.g., algorithmic 3D modelling) can be used to generate models described with different 3D digital representation methods (e.g., algorithmic 3D modelling can be used to generate 3D models that are defined with NURBS or mesh representation methods). There is no official taxonomy of 3D modelling techniques because new ones are created day by day. Sometimes the boundaries that divide one technique and the other are blurry, and there could be overlapping and subcategories however the scheme shown in Figure 1 can help orienting in this vast field.

Some technique's names take the term directly from the representation method that they use (e.g., mesh 3D modelling, NURBS 3D modelling, mathematical 3D modelling, etc.) To avoid any confusion, as a rule of thumb in this book we refer to the technique when the naming is in the form "XXX 3D modelling" and to the representation method when the naming is in the form "XXX representation method".

## 3D Printing

3D printing is the construction of a three-dimensional physical object from a reference digital 3D model by using various technologies and materials. There are different 3D printing technologies and new ones are being invented and improved day by day, but the most popular nowadays are the following: material extrusion, vat polymerisation, powder bed fusion, material jetting, binder jetting, directed energy deposition, and sheet lamination. In synthesis the 3D physical object can be created by melting a specific polymeric or compounded material and extruding it through a nozzle that moves in 3 axis and deposits it layer by layer on a static or movable rigid bed; or by melting/glueing the powder of a specific material which is deposited and processed layer by layer; or by stacking and cutting thin sheets of material and gluing/melting them on top of each other; or by curing a specific liquid polymer (resin) with light which is precisely pointed only on the areas that need to solidify.

## 3D Scanning

3D scanning is the process of collecting three-dimensional data of a physical object to reconstruct its shape and appearance in digital form. In this context, the word scanning is considered synonymous with the terms digitisation, surveying, and acquisition.

3D scanning can be performed with many different technologies and methodologies, each with pros and cons. Some of the most popular technologies and methods for 3D scanning are: digital photogrammetry, tomographic scanners, structured-light scanners, and Time of Flight scanners (e.g., LiDAR, laser scanners, ToF cameras).

While digital photogrammetry does not use an active sensor to scan directly the 3D information like a laser scanner or a structured light scanner, it is still considered a form of 3D scanning because it deduces 3D information by analysing a series of 2D images captured through a passive sensor.

3D scanning methodologies are divided into two broad families which are passive systems (e.g., photogrammetry, photometric stereo, RTI) and active systems (e.g., laser scanning). The first family of technologies do not emit any signal directly, they simply read the data already present in the environment (e.g., by comparing and triangulating multiple points of view of the same object), the latter emits a signal and compares it with its own reflected signal.

## Accuracy

Accuracy, in a technical sense, refers to the degree to which the result of a measurement, calculation, or specification conforms to the correct value or standard. The Community Standards for 3D Data Preservation define accuracy as "the proximity of a measured value to a standard or known value. High accuracy, similar to high precision, implies that the difference between the values is small. The term is commonly misused." This definition does not explicitly address the specific dimensions of accuracy in the context of 3D models. These dimensions include geometric accuracy, accuracy of scale and units, architectural or surface detail fidelity, and the reliability of source materials.

Geometric accuracy describes how precisely a 3D model replicates the shapes, dimensions, and spatial relationships of the real-world object. Accuracy of scale and units refers to how well the model's proportions correspond to the actual size of the original object, often depending on architectural scales such as 1:100 or 1:50 in conceptual designs. Architectural or surface detail fidelity relates to the level of detail captured or represented, such as intricate textures or ornaments, which may vary based on the modelling method. Additionally, the accuracy of a model depends on the reliability and completeness of the input materials. For example, models based on contemporary photographs or laser scans are typically more precise in representing the actual form than those relying on fragmented historical texts or speculative reconstructions.

These aspects of accuracy can vary independently, meaning a model may achieve high geometric precision but rely on uncertain or incomplete source materials, or vice versa. For models created through direct measurements, such as photogrammetry or laser scanning, accuracy is primarily determined by the precision of the measurement tools and the quality of input data. For instance, the Leica RTC360 3D Laser Scanner, according to its technical specifications, can capture measurements with varying levels of accuracy depending on the range. At a measurement range of 10 metres, the accuracy of the captured point cloud is 1.9 millimetres. This accuracy directly translates into the reprocessed 3D model, provided the modeller has not simplified the geometry, which would otherwise reduce the fidelity of the original measurement.

Conversely, models derived from architectural drawings or other conceptual resources have an accuracy level determined by the intended level of detail for the project's scale. In hypothetical reconstructions, especially those based on historical sources, determining accuracy is often challenging due to uncertainties in the reliability of the sources, such as photographs, paintings, or written descriptions. In such cases, it is crucial to evaluate the trustworthiness of the source materials and acknowledge the limitations in determining exact accuracy, allowing the model to serve as a foundation for further interpretation and discussion. Transparency about these limitations ensures the model's value in fostering understanding and encouraging reuse.

It is also worth noting that accuracy in this context can sometimes only be evaluated by providing a counterexample to the value under investigation. For instance, a model created at a 1:1 scale based on real-world dimensions offers geometric accuracy of 1:1. However, a model created from architectural drawings at a scale of 1:100—where the smallest legible detail on the drawing is approximately 0.1 mm—would correspond to a design accuracy of around 1 cm in real-world terms. Despite this geometric accuracy, the overall accuracy of the model may still be low in terms of historical truthfulness if the source materials lack detail, are inconsistent, or contain inaccuracies.

## Algorithmic 3D Modelling (3D Modelling Technique)

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. 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. Thus, based on this distinction parametric 3D modelling is a subset of algorithmic 3D modelling.

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.

## Anastylosis (Virtual/Digital)

Anastylosis is a term that comes from ancient Greek and means "to erect", it is a term mostly used by archaeologists to describe the process of restoring the original shape of a manufact. There is a difference between physical anastylosis and virtual/digital anastylosis. Virtual/digital anastylosis can be produced by statistically and geometrically matching preserved and digitalised fragments. Assembling a whole object from pieces is usually called *mosaicing* [Kampel and Sablatnig 2004][2].

In synthesis the pieces are put together by comparing their geometric shape as if they were pieces of a puzzle; or by referring to the shape of other still intact coeval references (if the pieces are far away from each other and do not have matching sections). Traditionally this process was performed directly on the physical remains by a manual trial and error procedure. Now, thanks to modern technologies, this process can be carried out virtually by acquiring the pieces through digital scanning (e.g., photogrammetry, laser scanning) and manually or automatically aligning them through digital 3D modelling applications or automatic algorithms which iteratively try to find the best fitting between neighbourhood pieces (e.g., Artificial Intelligence and Machine Learning techniques can improve the research of the proper joining between parts).

Not only the shape but also the superficial features (e.g., the colour, the figured elements) can be used for matching fragments and joining them together. In this domain, the term *registration* refers to the establishment of geometric correspondence between a pair of fragments depicting similar content. The term *reprojection* refers to the alignment of individual fragments into a common coordinate system. The term *stitching* refers to the joining of the fragments on a larger canvas by merging overlapping portions and retaining fragments where no overlap occurs. Errors propagated via geometric and photometric misalignments often result in undesirable object discontinuities and seam visibility around the boundary between two images.

## Archaeology

Archaeology is the discipline that studies human history and prehistory through the excavation, analysis, and interpretation of material remains and artefacts. Archaeology is a multidisciplinary field that draws on knowledge and methods from many other disciplines, including history, anthropology, geology, and biology. It plays an important role in understanding the human past, from the earliest human societies to the present day. By studying artefacts and other physical remains, archaeologists can reconstruct past environments, social structures, and economic systems, as well as trace the development of technology and artistic expression. Archaeology also helps us to better understand how different societies have interacted with each other, and how they have influenced one another over time Archaeology is distinct from palaeontology, which is the study of fossil remains.

[2] Kampel, M., & Sablatnig, R. (2004). 3D puzzling of archeological fragments. In Proceedings of 9th Computer Vision Winter Workshop (Vol. 2, pp. 31-40). Slovenian Pattern Recognition Society.


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## Archaeology of Architecture

The archaeology of architecture is a subfield of archaeology that focuses on the study of architectural remains and the built environment of past societies. This includes the analysis of buildings, structures, and other architectural features, as well as the materials, technologies, and social and cultural practices that went into their construction. Archaeologists of architecture use a range of methods to study architectural remains, including fieldwork, surveying, mapping, and excavation.

## Architectural 3D Model

An architectural 3D model is a physical or digital three-dimensional representation of an environment, building or structure that serves to present, visualise and communicate design concepts, formal and spatial relationships, and other architectural qualities and concepts. Typically, the architectural 3D model is a small-scale representation of the actual or design model. Refer to the voice model for more information.

## Architectural Remains

Architectural remains are physical traces of past architectural structures and features that have survived to the present day. These remains can include buildings, walls, foundations, floors, roofs, and other elements of the built environment.

Archaeologists and architectural historians study architectural remains to better understand past societies, their cultures, and their ways of life. The analysis of architectural remains can reveal important information about social, political, economic, and religious systems, as well as the technological and artistic achievements of past cultures.

Architectural remains can be found in a wide range of settings, including urban and rural areas, archaeological sites, and historic buildings. In some cases, architectural remains are still in use today, such as ancient temples that have been repurposed as churches or mosques. In other cases, they may be preserved as ruins or archaeological sites, offering valuable insights into past cultures.

## Architecture

Architecture is the art and technique of designing and constructing buildings, or other physical environments or structures that meet the functional, aesthetic, and technical requirements of human habitation, work, and leisure. Architects work to balance the needs of the occupants of an particular space with the constraints of the site and the budget available for construction. Architecture involves a broad range of disciplines, including engineering, construction, urban planning, interior design, and landscape architecture.

Architecture encompasses the whole process behind the realisation of an architectural object from its conceptualisation (e.g., ideating, sketching, designing) to its realisation (e.g., planning, constructing). The architectural practice began in the prehistoric era and characterised civilisations up to our days, despite that the first real treatise on architecture was the “De Architectura” written by the roman architect and military engineer Marcus Vitruvius Pollio where it was defined, for the first time, the discipline itself and the figure of the architect.

## Artificial Intelligence (AI)

Artificial Intelligence (AI), nowadays, refers to all those digital applications that perform complex tasks once doable only with human interaction. Most of the time it is used to refer to applications based on Machine Learning (ML) or Deep Learning (DL), which are usually non-deterministic approaches, however, it is not exclusive to these. Sometimes it is also used to describe much simpler deterministic algorithms, most probably for marketing reasons.

## Augmented Reality (AR)

Augmented Reality (AR) is the real-time enhancement of a real-world scene with digitally generated graphics (e.g., texts, images, 3D models). The enhanced scene can be a composition of a naked-eye viewed scene overlapped with digital content through the use of special prismatic glasses (e.g., HoloLens by Microsoft), or it can be real-time compositing of a live-captured video acquired with traditional camera sensors and visualised through a display where it is overlapped in real-time with additional digital content (e.g., smartphone/tablet AR, Apple Vision Pro, Meta Quest2). Both solutions require the real-time tracking of the movements of the user and can be achieved through various sensors integrated directly into the visualisation device or anchored to the surrounding environment. AR continues to evolve with the development of new hardware, software, and technologies. It offers exciting possibilities for enhancing perception, interaction, and understanding of the real world, enabling new forms of user experiences, and transforming various industries.

## Axonometric Projection (Traditional Representation Method)

An axonometric projection is one of the traditional representation methods of descriptive geometry and it is a special type of orthographic projection used in technical and architectural drawing to represent three-dimensional objects in a two-dimensional space. Unlike perspective projections, axonometric projections maintain the parallelism of the lines (which are parallel in three-dimensional space) and do not create a sense of depth or foreshortening.

We can distinguish between oblique and parallel axonometric projections depending on the angle between the projection plane and the projecting direction.

There are different types of orthogonal axonometric projections: isometric, dimetric, and trimetric. In Isometric projection the three axes are equally foreshortened, in dimetric only two are equally foreshortened, in trimetric, all of them have different foreshortening.

The oblique axonometric projections can be subdivided into different typologies: in the *Militar* axonometric projection the angle between the x-axis and the y-axis is projected in 90 degrees; therefore, the plan can be drawn without distortion. In *Cavalier axonometry*, it is generally the elevation that can be drawn without apparent


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distortions, where the x and z axis for example form an angle of 90 degrees. There is also the so called *special axonometry* where both the plan and the elevation show no apparent distortions.

Pohlke's theorem is the fundamental theorem of axonometry. It was established 1853 by the German painter and teacher of descriptive geometry Karl Wilhelm Pohlke. Three arbitrary line sections in a plane originating at point, which are not contained in a line, can be considered as the parallel projection of three edges of a cube. The practical consequence of this theorem on oblique axonometry is that any triad chosen on the sheet of paper can represent a correct axonometry of three edges of a cube.

## Blueprint

An early plan or design that explains how something might be achieved. The name comes from the use of a photographic print in white on a bright blue background (or vice versa) used especially for copying maps, mechanical drawings, and architectural plans.

## Boolean 3D Modelling (3D Modelling Technique)

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. 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 who was the mathematician that theorised mathematical logic which is the foundation of addition, subtractions, and intersections of shapes.

## Boundary Representation (3D Digital Representation method)

Boundary representation (or B-rep) is a 3D digital representation method where the 3D shapes are represented by defining their outer limits. 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 thier outer boundaries, other times it also includes opened or non-manifold poly-surfaces (Grasshopper for Rhinoceros). B-reps can be both NURBS or meshes but some applications assign the B-rep status only to NURBS models. So in order to avoid misconceptions we refer to the initial most general definition.

## Box 3D Modelling (3D Modelling Technique)

Box modelling is a digital 3D modelling technique commonly used in computer graphics for creating 3D models. It involves starting the modelling process by creating a basic shape (typically a simple box/cube, but also cylinders, spheres, pyramids, etc.) and then refining and sculpting it by adding detail and manipulating the vertices, edges, and faces of the initial shape. Box modelling is a subgroup of polygonal/mesh 3D modelling, and overlaps with extrusion 3D modelling, and SubD 3D modelling.

## Building Information Modelling (BIM)

The acronym BIM stands for Building Information Modelling. The National Institutes of Building Science defined it as "the digital representation of the physical and functional characteristics of an object". In practical terms, it defines a computer-aided methodology aimed at optimising the process of construction of a Building from the conceptualisation (design) to the realisation, with a strong emphasis on preserving the connection between the 3D digital model and related data. The optimisation is achieved through the implementation of several automatisms (such as the creation families of premade parametric architectural elements), the standardisation of the documentation process and the addition of the possibility to link metadata and paradata to specific parts of the model, in order to simplify subsequent manipulation and interrogation of the model also by different professionals. Differently from traditional CAD-based workflows, the BIM-based workflow allows the operators to embed into the model metadata (e.g., materials, costs, amount) or extract from the model data useful for the latter phases (e.g., the total area of the windows, the total amount of paint needed, the eventual collision between pipes and walls).

BIM has become widely adopted in the architecture, engineering, and construction (AEC) industry due to its potential benefits, including improved design coordination, cost estimation, clash detection, and facility management. It enhances collaboration, reduces errors, improves project efficiency, and supports better decision-making throughout the entire project lifecycle.

## CAD 3D Modelling (3D modelling technique)

CAD 3D modelling refers to the use of specialised software to create three-dimensional models. CAD applications provide a digital environment where designers, engineers, architects, and other professionals can create, modify, and analyse projects. CAD is the acronym for Computer Aided Design, so etymologically it is a general term that refers to whatever involves digital design with a computer. However, CAD modelling has acquired a more specific meaning over time. CAD modelling, nowadays, is usually used to refer exclusively to highly accurate modelling that relies on precise snapping and where the geometries are described with mathematical formulas (e.g., NURBS). Most polygonal modellers specialised in VFX or rendering (e.g., Maya, Blender, Cinema 4D, 3D max) are not usually considered CAD applications because they are not aimed at designing highly accurate objects, but rather visualise them.

## CityGML (Exchange File Format)

CityGML (City Geography Markup Language) is an open data model and XML-based encoding standard for representing and exchanging 3D city models and urban environments. It provides a common framework for describing the geometric, semantic, and topological aspects of urban spaces, including buildings, terrain, vegetation, transportation networks, and more. The standardisation and adoption of CityGML promote interoperability and facilitate the sharing and exchange of 3D urban data, allowing for enhanced urban planning, analysis, visualisation, and decision-making processes.


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## Colour Space

Colour spaces define how colours are represented numerically and provide a reference framework for accurately communicating and reproducing colours across different devices and media. The most popular colour spaces are: RGB, CMYK, HSB/HSV, LAB, each of them is further subdivided according to the mathematical model they follow and according to the number of shades of colour they can describe.

## Computational 3D Modelling (3D Modelling Technique)

Etymologically the term computational means "referring to the process of computing" or "made with a computer", however in the 3D modelling field the term computational in the 3D modelling field has assumed a more specific meaning. Computational 3D modelling, also known as computational design or generative design, nowadays refers not only to 3D models generated with the help of a computer, but more specifically to the approach of 3D modelling that involves using algorithms, scripts, or computer programs to generate or manipulate 3D models automatically or semi-automatically. It combines elements of computer science, mathematics, and design to create complex and innovative designs. In this sense, it is a term that is often considered synonymous with algorithmic 3D modelling.

## Continuous Representation (3D Digital Representation Method)

Continuous (or smooth) representation is the counterpart of discrete representation. It describes the forms by a mathematical equation with geometric continuity and curvature. A continuous/smooth representation can be easily discretised by extracting points from its surface and connecting them with triangular faces. NURBS models are examples of continuous/smooth representations.

## Copyright

Copyright is a legal concept that regulates intellectual property. In simpler terms, Copyright protects the right of not being copied by someone else and gives the owners of the rights the exclusivity to copy, distribute, sell, perform, adapt, modify, display, and exhibit, their creative work.

This means that anyone that wants to use a specific creative product must ask for permission from the original author first (or another legitimate right holder). In different fields, Copyright is regulated differently, but more importantly, it varies between countries. All over the world Copyright protect the creative products between 20 to 100 years from the creation/publication of the product or the death of the author. The differences depend on the country's regulations and on the type of work. Since the differences are so impactful it is important to study the Copyright legislation in the country of application before using any authorial creative work.

In Europe, Copyright protection is granted automatically upon the creation (with proved authorship) of the creative product, and lasts up to 70 years after the death of the author. Thus, most of the historical sources (e.g., drawings, paintings, sculptures, medals, texts) that are usually used in 3D hypothetical virtual reconstructions of architecture should lie in the public domain. However, the identification of the right holder might have some exceptions based on the single case or the specific European country.

Let's take the example of a historic blueprint or a painting of an old building, even if the original author of the work died more than 70 years ago, the digital image of the work, for German legislation, is considered a duplication (*Vervielfältigung*) of the original work and the author of said acquisition (in this case the operator/institution that digitised the original) holds its Copyrights. However, this practice is highly criticised within scientific communities.

Another example concerns modern measurement campaigns (e.g., SFM, laser-scanning, photogrammetry) and their derivates used for digital 3D reconstructions. Even if these types of works are still in a grey legal area, it is always preferable to not only ask for permission before proceeding with the acquisition, but it is suggested to sign a mutual contract to prove said permission in advance, in order to avoid legal issues later on. The legal contract should also concern future uses of the acquired data and the allowed forms of publication.

If photographs are considered most of the times creative original works, there is a debate on whether 3D digitisations (e.g., point clouds, photogrammetric models) fulfil, in the same way, all requirements of producing an original, with all related Copyrights and properties or if it is to be considered as a mere copy like a scan of a document, and therefore creating only non-original works, without such rights.

Because 3D hypothetical virtual reconstructions are created on the basis of authorial historical sources, it is important to consider the aspects related to Copyrights before acquiring or publishing any data.

## Critical Digital Model (CDM)

The Critical Digital Model (CDM) is a 3D model aimed at restoring the original form of the object of study, as complete and as close as possible to the will of the author/s in a given period, based on a comparative study of all the available sources (direct or indirect) that are provided as appendices, while losing as little information as possible from reference documentation [Apollonio et al. 2021][3]. It is a subset of the broader family of Informative Models (IM) and its name derives from its analogies to the critical edition of books. In a case study where multiple variants existed over time, each variant has to be considered as a separate Critical Digital Model and eventually attached as an appendix to the other CDMs.

[3] Apollonio, F. I., Fallavollita, F., & Foschi, R. (2021). The critical digital model for the study of unbuilt architecture. In Workshop on Research and Education in Urban History in the Age of Digital Libraries 2019 (pp. 3-24). Cham: Springer International Publishing.

## Decimation

The decimation of a 3D model concerns the polygon count reduction of the model. There are various algorithms more or less robust that perform this task. This is the first and most important step when optimising a Raw Model. When the Raw Model is created, it usually has the maximum possible detail according to the acquired raw data, this is the most accurate representation and the highest scientific rigour based on the available data, however for most uses, in the visualisation or dissemination contexts, models that are too densely tessellated would not be manageable by many game/render engines thus decimation would be necessary.

## Deep Learning (DL)

Deep Learning (DL) is a subset of Machine Learning (ML) and Artificial Intelligence systems (AI) that tries to imitate how the human brain works using digital neural networks (NN). Deep Learning algorithms are particularly good at finding hidden patterns in unstructured input data sets.

## Descriptive Geometry

Descriptive geometry is a branch of mathematics that studies, represents and communicates the shapes and relationships between them in space through the tool of drawing.

Gaspard Monge gave the name to this discipline (géométrie descriptive is the original French name) and is considered the father of descriptive geometry (even though orthogonal projection and perspective projections were probably known before him) because he defined, extensively studied, and systematised this field.

## Destructive 3D Modelling (3D Modelling Technique)

Destructive 3D modelling is a 3D modelling technique where the construction history is lost while modelling. Traditional CAD 3D modelling applications usually adopted partially or totally destructive approaches. It is the counter part of non-Destructive 3D modelling which is preferable for all those situations where the production of variants is needed. Usually, destructive workflows are preferred to non-destructive ones because they are faster to set up (at the first iteration) and the models generated with this approach are usually more interoperable.

## Deterministic 3D Modelling (3D Modelling Technique)

Deterministic 3D modelling is a 3D modelling technique where the same sets of input parameters correspond to the same output results. Deterministic 3D modelling is the counterpart of non-deterministic 3D modelling. This naming is generally used in the context of algorithmic 3D modelling. For example, direct handmade 3D modelling is deterministic.

## Digital

In the most general sense *digital* means something expressed as a series of 0s and 1s (digits). In the context of computer graphics, the 3D digital model is a three-dimensional representation created and experienced with a computer. In the context of 3D hypothetical virtual reconstruction, the digital 3D model almost always overlaps with the concept of the virtual 3D model, so, even if *virtual* and *digital* have slightly different definitions, they are often used interchangeably in this field.

## Digital Cultural Heritage (Based on ICOM-Italia Definition[4])

ICOM-Italia defines the Digital Cultural Heritage (DCH) as "the new discipline that explores the evolution of the web to imagine new forms of storytelling and enchantment for museums and cultural institutions". It relates the cultural heritage with digital technology and puts the accent on the long-term value produced by digital means.

## Digital Heritage (Based on UNESCO Definition[5])

Digital heritage is made up of computer-based materials of enduring value that should be kept for future generations. Digital heritage emanates from different communities, industries, sectors and regions. Digital heritage is frequently ephemeral and requires purposeful production, maintenance and management to be retained. Not all digital materials deserve to be maintained, but many of these resources have lasting value and significance and therefore constitute a heritage that should be protected and preserved for current and future generations. This heritage may exist in any language, in any part of the world, and in any area of human knowledge or expression.

## Digital Repository

Digital repositories are information systems designed to store, archive, manage, preserve, and share digital data. They can be online (accessible through the internet) or offline (accessible only from specific machines, or local networks, in specific physical locations). Digital Repositories especially if shared online as open-access services, are crucial instruments to provide visibility and accessibility to knowledge.

## Digital Sculpting (3D Modelling Technique)

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. 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.

[4] ICOM-Italia "Digital Cultural Heritage". https://www.icom-italia.org/gruppo-ricerca-digital-cultural-heritage/

5 UNESCO (2003). "Charter on the Preservation of Digital Heritage". https://en.unesco.org/about-us/legal-affairs/charter-preservation-digital-heritage. Accessed: 02 August 2023.

## Digital Twin

A digital twin is the virtual/digital representation of any physical entity (animated or unanimated). The Digital twin can receive data, from its physical counterpart, through a complex network of sensors that communicate with the digital system, or they can exchange data asynchronously through the manual input carried out by an operator over time. In the architectural field, the digital twin is mostly used as a tool to monitor the lifecycle of a building or to preserve and maintain a monument in ruins.

## Digitalisation

Digitalisation is often considered synonymous with digitisation however they have distinct meanings. Digitalisation goes beyond converting analogue to digital, it involves rethinking and redesigning traditional analogue processes to take full advantage of the potential offered by digital technologies. In its meaning, it entails also the concept of adopting digital technologies to improve efficiency, effectiveness and innovation (e.g., internet of things, automation, Artificial Intelligence, web services).

## Digitisation

The conversion of a physical/analogue input into a digital form (e.g., the digital scanning of a book into a PDF format, the 3D acquisition of a Roman theatre in the form of a digital point cloud) The word digital comes from the word digitus (the Latin word for finger which are often used for counting). It is different from digitalisation.

## 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. Digital 3D sculpting is considered a subfamily of direct handmade 3D modelling, it adopts this more specific name because the tools that are mainly used in digital sculpting specifically resemble the tools of a sculptor (e.g., scalpels, brushes, scrapers).

## Discrete Representation (3D Digital Representation Method)

Discrete representation is a 3D digital representation method where the digital entities are represented as discontinuous data (e.g., concerning curvature continuity).

In mathematics, the word discretisation refers to the process of transforming a continuous/smooth function into its non-continuous (discrete) counterpart. In 3D modelling, for example, the discretisation of a model can refer to the process that converts a NURBS continuous/smooth curved surface into a discretised/faceted polygonal mesh. Thus, in the context of 3D modelling, discrete representation refers to those 3D models that describe the shapes with a set of discontinuous entities (e.g., point clouds, voxels, triangular faces) as opposed to continuous representation (e.g., a NURBS surface).

## Dissemination

There are many output possibilities to disseminate cultural heritage with 3D models apart from the basic interaction through a 3D viewer. Once the model is ready, it can be converted to various formats (e.g., an image, a video), it can be 3D printed, animated, included in a videogame, or XR experience, or it can be used for dynamic storytelling through a web interface, etc. The list below shows the most popular methodologies and technologies to disseminate a 3D model (with a focus on the optimisation required and the most used exchange formats in the various contexts):

- **Renders**: a rendered image (or simply a render) can be done in applications like Blender, Maya, or Cinema 4D. If the image has only visualisation purposes, it is often not necessary to dedicate much effort to the optimisation of the model other than the one needed to improve render times without loss of quality. All the most popular render engines nowadays can only work with polygonal geometries, so in order to import the models in the render engine of choice, it is preferable to use mesh-based exchange formats that possibly support also the texture parametrisation (e.g., OBJ, FBX, GLB, glTF).
- VR **and videogames**: Virtual Reality and videogames are popular options for dissemination, as they enable the user to interact with the model in a more free way. Depending on the device and the game engine used, severe optimisation (concerning geometry and textures) might be needed before uploading the model in the 3D environment as the experience must be rendered in real-time and it has to offer good performance on many devices (modern game engine like Unreal engine recently developed tools to automatically optimise the geometries but in some cases, they still fail, and most importantly they are not compatible with all the devices, so, if possible, it is still preferable to optimise the models in advance). The most popular exchange formats to bring 3D models into game engines are those that support meshes and texture mapping (e.g., FBX, GLB, glTF, OBJ) because they not only import the geometry but also the shaders, the textures, and their parametrisation (and in some cases also other properties such as animations and scene assets like cameras and lights).
- **AR**: Augmented Reality is another common output for 3D models. Usually, the digital model is presented alone overlapped and tracked onto a real-world scene. The models need to be optimized according to the AR visualisation devices of choice (e.g., headsets, HoloLenses, smartphones).
- **3D printing**: printing is gaining importance in dissemination, especially as a response to blind people's accessibility needs in museography and exhibitions. In the case of 3D printing of Raw Models, it is recommended to

decimate them only up to the resolution of the 3D printer in order to avoid loss of detail; and in the case of 3D printing of Informative Models, it is recommended to model to a Level of Detail compatible with the resolution of the 3D printer to avoid modelling details that will not be visible in the final print. All the geometric details baked and embedded only into bump maps or normal maps are not considered in the 3D printing process, a good rule of thumb would be removing all the normal and bump maps before printing in order to have a more realistic preview of the result. The standard exchange formats for 3D printing are STL and PLY as printers most often work only with mesh geometries without textures.

- **Animation**: animation offers the opportunity to add the time dimension to the 3D space, making it a 4D model. It is an interesting output for reconstructions, as the virtual anastylosis or geometric complexion processes can be shown in a 3D timeline. Animations can be exported in various video formats, the most popular and widely supported is the MP4 with H.264 codec. Some 3D export formats recommended for 3D animated models are FBX, GLB and glTF, which support not only the model and its parametrised textures but also its animations.
- **Web Storytelling**: 3D models freely navigable in real time on the web can be implemented with additional information like texts and audio in order to add knowledge interactively to the experience (3D viewers like Sketchfab or Poly Viewer have plugins to insert the models in web pages that offer this kind of tools). This offers the possibility to elaborate storytelling through the 3D Model. Depending on the web service of choice, is possible to program the user navigation experience and synchronise it with the displaying of texts and images or the reproduction of audio tracks, to enhance the narrative and offer a meaningful experience.

## Documentation

In the field of 3D hypothetical virtual reconstructions, the documentation process concerns the careful and extensive description of the gathering and evaluating the sources used for the reconstruction, and the methods, techniques and working steps carried out to build the 3D digital model. More in general it concerns the gathering and publication of all the metadata and paradata concerning the hypothetical reconstruction.

It provides the foundation for transparency and reproducibility of the study which are cornerstone features of the scientific practice. Good documentation should take care not only of the textual descriptions but also the references of the available sources used. Digital reconstructions are based on visual aspects, so it is desirable to include in the documentation other visual materials that can help to understand the research process. These can be multimedia materials (images, presentations, video, etc.) complementing the 3D reconstruction with additional information concerning the authenticity, hypotheses, source materials and their analysis, as well as archival, historical, archaeological and architectural research that has been conducted. For digital documentation, standardisation of the documentation process is crucial for the creation of an efficient research environment. The use of open exchange file formats capable of embedding metadata and paradata and relating them directly to the 3D elements is nowadays the best solution available for documenting the reconstruction process. Documentation prepared in this way should also be made available to others through publication in appropriate repositories that comply with FAIR Principles[6].

## Exchange File Format (CityGML, IFC, OBJ, glTF, PLY, IGES, STEP, STL, ...)

An exchange file format, in the field of 3D modelling, refers to a 3D model file format that does not refer to any particular application. They are more effective than proprietary exclusive formats to store and share 3D data for future uses because they are most of the time open source and they should guarantee a better long-term preservation of the data. However, exchange file formats could lose specific proprietary data in the conversion process (e.g., specific metadata, modifiers, elements, filters), thus it is crucial to investigate which data a given exchange file format can carry before using it as the only vehicle of transmission of our 3D models.

- **FBX**: stores a wide range of 3D data, including mesh geometry, animation, cameras, rigs, lights, and textures. Useful for games, XR and web visualisation.
- **GLB/glTF**: store mesh geometry, animations, and textures using a small and compressed file size. Useful for games, XR and web visualisation and more supported by software and online viewers than FBX.
- **OBJ**: stores mesh geometry and textures in separate files. Useful for storing the data and modifying textures.
- **STL**: stores mesh geometry data without textures. Useful for 3D printing.
- **PLY**: stores mesh geometry data and vertex colours. Useful for 3D printing but less supported than STL.
- **IGES / STEP**: store NURBS geometries.

## Explicit Representation (3D digital representation method)

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 either 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.

In practice, explicit representation methods describe the shape directly, by defining its outer boundary (e.g., through numerical meshes or parametric NURBS surfaces for example).

[6] Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., ... & Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. Scientific data, 3(1), 1-9.

Explicit functions are the basis of most CAD-based applications. This approach 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.

## Extended Reality (XR)

Extended Reality (XR) is a macro-family of technologies that enhance, augment or replace the user's view of the physical world. It includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), which share some overlapping characteristics as well as some technical requirements; however, each of them serves different purposes.

## Extrapolation

Extrapolation is a method for geometric completion. In mathematics, extrapolation is a type of estimation, beyond the original observation range, of the value of a variable on the basis of its relationship with another variable [Sidi 2003[7], Brezinski and Redivo Zaglia 2020[8]]. Image extrapolation extends pixels beyond image borders [Bowen et al., 2021[9]]. It is a much more challenging task since there is much less information available; while inpainting methods are given the entire boundary of the missing region, in image extrapolation we only know one border. This less constrained problem means the method needs to extrapolate both textures and structures in a convincing manner. 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. 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

[7] Sidi, A. (2003). Practical extrapolation methods: Theory and applications (Vol. 10). Cambridge University Press.

[8] Brezinski, C., & Redivo-Zaglia, M. (2020). Extrapolation and rational approximation. The Works of the Main Contributors, Cham: Springer Nature.

[9] Bowen, R. S., Chang, H., Herrmann, C., Teterwak, P., Liu, C., & Zabih, R. (2021). Oconet: Image extrapolation by object completion. In Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (pp. 2307-2317).

is extrusion [Vollertsen et al., 1999[10]]. Techniques such as spline interpolation or polynomial fitting are commonly employed to achieve smooth extrapolation. Extrapolation may also mean an extension of a method, assuming similar methods will be applicable. Extrapolation can apply to human experience to project, extend, or expand the known experience into an area not known or previously experienced so as to arrive at a (usually conjectural) knowledge of the unknown [Armstrong 1984[11], Steel 2007[12], Nikulchev and Chervyakov 2023[13]]

## Extrusion Modelling (3D modelling technique)

Extrusion modelling (also called extrusion-based modelling) is a 3D modelling technique used in 3D computer graphics to create geometric shapes by mainly pushing and pulling faces or surfaces of a primitive shape along a path or a direction. It is a subgroup of NURBS 3D modelling, and polygonal/mesh 3D modelling and also overlaps with other techniques such as box 3D modelling.

## FAIR Principles

The FAIR Principles [Wilkinson et al. 2016][14] are a set of guidelines aimed at improving the Findability, Accessibility, Interoperability, and Reusability of digital assets, particularly in the context of scientific data management and research. The principles refer to three types of entities: data (or any digital object), metadata (information about that digital object), and infrastructure. The principles were first published in a 2016 by a group of scholars and experts in data management, and have since gained widespread recognition in the scientific community. The FAIR Principles are intended to enhance the ability of machines to automatically find and use data, in addition to supporting its reuse by individuals.

## Feature-Based 3D Modelling (3D Modelling Technique)

Feature-based 3D modelling is a 3D modelling technique where the 3D model is created by means of features which represent the geometric components/characteristics/parts of the model. The designer does not only specify the shape, and dimensions of the model but also relevant information about its features. Feature-based CAD systems allow the users to change the parameters of some of the features at any point of the modelling process and sometimes it is even

[10] Vollertsen, F., Sprenger, A., Kraus, J., & Arnet, H. (1999). Extrusion, channel, and profile bending: a review. Journal of Materials Processing Technology, 87(1-3), 1-27.

[11] Armstrong, J. S. (1984). Forecasting by extrapolation: Conclusions from 25 years of research. Interfaces, 14(6), 52-66.

[12] Steel, D. (2007). Across the boundaries: Extrapolation in biology and social science. Oxford University Press.

[13] Nikulchev, E., & Chervyakov, A. (2023). Prediction intervals: A geometric view. Symmetry, 15(4), 781.

[14] Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., ... & Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. Scientific data, 3(1), 1-9.

possible to rearrange the modelling history, thus it is a subset of parametric or algorithmic/procedural 3D modelling.

## Gamification

Gamification is a neologism that comes from the word game which is used to describe the act of exploiting playful strategies to engage a specific audience and transmit specific content or reach certain objectives. This approach is widely used in museums to improve the engagement of the visitors, increase the interaction between them and the exhibited objects, and simplify the comprehension of complex concepts.

## Geometric Element

A geometric element is an element in space about which some transformation can be performed. Geometric elements are classified based on the dimensionality N of the space on which they act, the upper limit on the dimensionality of the symmetry element being N-1.

- Point: the minimum element we can visualise. It represents a single exact position and has no dimension in Euclidean space.
- Line is the trace of a trajectory between two points; this trajectory can be straight or curved. It has a single dimension in Euclidean space.
- Plane: a set of points with just two dimensions.
- Surface: the graphical element linking a series of points. Surface is also the term we generally use when we refer to the global boundary delimiting the outermost or uppermost layer of a physical object or space. Planes can be seen as a particular kind of surfaces: a flat surface, and surface as a generalisation of planes. Edges can be defined as a particular type of line segment delimiting different planes or surfaces.
- Manifold is a collection of points, lines or surfaces forming a certain kind of set, such as those of a topologically closed surface or an analogue of this in three or more dimensions.
- Volume: a particular combination of planes and surfaces closing a particular space.

## Geometric Properties

Spatial properties - location, size, distance, direction, separation and connection, shape/form, pattern, and movement of a solid body or moving particle that can be expressed quantitatively.

## Generative 3D Modelling (3D Modelling Technique)

Generative 3D modelling is a 3D modelling technique. Where the 3D shapes are created by a list of rules/operators/processing steps. It is often used as synonymous with algorithmic/procedural 3D modelling.

## Headset VR

A VR headset is an electronic device designed to fit a person's head that allows the user to explore virtual environments. It is usually provided with a pair of screens one in front of each eye of the user who looks into them through two lenses (usually Fresnel lenses). The VR headsets are improving year after year and some of them are now capable to visualise scenes at human eye resolution. Sometimes they also integrate headphones, cameras, and other sensors to track the hands, the eyes, the head and body movements.

## Heritage Building Information Modelling (HBIM)

Heritage Building Information Modelling (HBIM), is a specific variation of BIM technology used in a cultural heritage context. For example, HBIM applications can be used for documenting and maintaining manufacts during or after restoration campaigns.

## Hologram

An intangible three-dimensional image produced through the use of intersecting light beams or other light sources. Sometimes the term hologram is improperly used to refer to various figures that appear to be three-dimensional through the careful exploiting of optical illusions or the projection of bi-dimensional images onto almost invisible media (e.g. glasses, thin cloths, rotating fan-like displays). The most advanced of these "fake" holograms can also react to the position of the observer, through the use of mirrors or sensors, and simulate the parallax effect typical of a three-dimensional object. Most of the commercial technologies that claim to create holograms belong to this latter category.

## Hypothetical reconstruction

In the context of architectural cultural heritage, a hypothetical reconstruction is a general term which refers to the simulation of a lost past based on an inference process which makes use of various available direct or indirect sources and the critical evaluation of an expert. Because of that the hypothetical reconstruction always has some degree of subjectivity. Hypothetical reconstructions can be in various forms: oral, textual, pictorial, sculptural; static or animated; physical or virtual; and so on.

## IFC (Exchange File Format)

IFC (Industry Foundation Classes) is an exchange open file format aimed at the interchange of 3D models, produced with a BIM-based workflow, with the minimum loss of geometrical data, metadata and paradata. An IFC 3D model can be navigated and interrogated in order to read specific metadata and paradata connected to specific elements of the 3D model, furthermore, new properties can be added per element if the preset ones are not suitable to describe the needed data. This format is the most complete format nowadays available (together with CityGML format for urban-scale cases) capable of documenting the whole reconstructive process directly into the 3D model.


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## Implicit Representation (3D Digital Representation Method)

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

In practice, 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.

Implicit functions can describe the inside of a volume through mathematical formulas, this makes it suitable for applications where changes in the volume matter (e.g., creation of variable density 3D printing lattices, modelling of metaballs with marching cubes algorithms, reconstructing a surface from point clouds with the Poisson surface reconstruction methodology). The trade-off of this latter approach is that it is less suitable for visualisation purposes or for generating exact replicas of the boundaries of digital objects.

In the context of 3D hypothetical virtual reconstructions, solutions that use only implicit representations are of minor interest. Implicit representation is usually used in sub-steps of the reconstruction processes which are then converted into explicit representations for reproduction, manual manipulation, and visualisation purposes.

## Informative Model (IM)

Digital reconstructive architectural 3D models can be divided into two broad categories: Raw Models (RM) and Informative Models (IM).

The Informative Model (IM) is a digital information-enriched 3D model where the relevant information is available and accessible (Informed Model or Information Enriched Model are similar to informative models but have slightly different meanings because they do not require the information to be available and accessible).

An example of IM is any architectural source-based virtual hypothetical 3D reconstruction which is documented and published. Another example of IM is an architectonic survey that starts from raw data obtained through a laser scanning campaign which is then automatically processed to make an objective mesh model (RM), such mesh is then polished, rectified, segmented and redesigned by an author through a CAD software (IM).

The main difference between RM and IM is conceptual: the RM represents only dimensional data (and sometimes also colourimetric data) acquired from physical objects independently of any previous scientific interference. The IM, on the other hand, represents the complex interpretation process of various sources. The IM is a model obtained through a reverse engineering operation. There is also a technical difference. The RM is always discrete (numerical or polygonal). On the contrary, the IM can be represented with different digital representation methods (continuous or discrete) and built with various modelling techniques (e.g., parametric modelling, direct handmade modelling, polygonal modelling).

To sum up, the IM provides many types of information, such as metric, colorimetric, geometric, source-based. On the contrary the RM provides only metric and colorimetric information (e.g., if a chunk of a point cloud is interpreted to be interpolated with a cylindrical/planar/conical NURBS surface that interpolated 3D surface is already an IM).

## Informed Model / Information Enriched Model

Digital reconstructive architectural 3D models can be divided into two broad categories: Raw Models (RM) and Informative Models (IM).

Informed Models (or Information Enriched Models) are 3D digital models that contain information processed and interpreted by an author. These terms are often used interchangeably with Informative Model, however the Informed Model is not always transparent and accessible. Therefore Informative Models are a subset of Informed Models (or Information Enriched Models).

## Interoperability

A concept that describes the ability of a product or a system to exchange information with other products or systems without loss of data. In the context of the hypothetical 3D virtual reconstruction of architectural heritage, it is particularly important to aim for the interoperability of the 3D model because this would guarantee better long-term preservation of the data and easier access to the knowledge embedded into the model.

## Interpolation

Interpolation is the simplest method for shape completion. 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 [González and Patow 2016][15]. This is commonly used in various fields such as numerical analysis, computer graphics, and data science to approximate values and make predictions (see also 3D surface modelling)"

## Kit-Bashing (3D Modelling Technique)

Kit-bashing is a popular model-making technique that refers to the practice of taking parts from different model kits and assembling or modifying them to create a new custom and unique model. In the digital realm kit-bashing is commonly used to add details, or create entire environments, by 3D artists or concept artists.

## Laser Scanning

3D laser scanning is a technology capable to acquire three-dimensional data from the physical world by targeting the object of the survey with laser beams and

[15] Gonzalez, F., & Patow, G. (2016, February). Continuity and interpolation techniques for computer graphics. In Computer Graphics Forum (Vol. 35, No. 1, pp. 309-322).


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measuring the distance by evaluating the time needed by the reflected light to return to the scanner. Laser scanning is usually a more expensive methodology compared to photogrammetry, and usually produces less accurate textures. For this reason, laser scanning and photogrammetry are often used together to take the best features from both methods and compensate for the deficiencies of each of them (e.g., 3D models from laser campaign and texture from photogrammetry).

## Level of Definition

Level of Definition is a standard terminology associated with BIM systems and encapsulates the concepts of Level of Information (LoI) and Level of Detail (LoD) at once. In the later European standard EN-ISO-19650 (2020) the naming Level of Definition was abandoned and replaced with the naming Level of Information Need (LoIN), which adds to the concepts of *Information* and *Detail* already present, also the concept of *Unstructured* documentation.

Sometimes this standard is defined, interpreted and used in slightly different ways by the scientific and professional communities, based on the context or the countries. For an exhaustive discussion about this topic refer to the literature review by Abualdenien and Borrmann in 2022[16].

In the context of hypothetical 3D reconstruction, to avoid confusion, it is not recommended to refer to the concept of Level of Definition because its acronym overlaps with the Level of Detail which is a much more popular and less ambiguous concept.

## Level of Detail (LoD)

In computer graphics, the Level of Detail (LoD) refers to the amount, complexity and dimension of the elements that constitute a 3D model. In video games multiple LoDs are produced for every asset and visualised according to the distance from the viewer, in this way, the scene can be optimised and rendered in real-time more efficiently with minimal loss of perceived quality. The LoD is usually defined by a number, starting with the maximum detail representation which is always labelled as LoD 0, as shown in Figure 2.

In BIM 3D modelling the concept of LoD might be blurry because sometimes it not only encapsulates the concept of geometric detail but also the alphanumeric information added as metadata and paradata to the 3D elements. Some BIM professionals use the terms Level of Detail, Level of Definition, and Level of Development, interchangeably because they have the same acronym, however, all these definitions have slightly different meanings. For an exhaustive discussion about this topic refer to the literature review by Abualdenien and Borrmann in 2022[4].

In BIM framework the LoDs numbering is standardised as follows:

- LoD 100 (conceptual model where only the volumes are drafted, it is at the pre-design phase where only the designers interact);

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[16] Abualdenien, J., & Borrmann, A. (2022). LEVELS OF DETAIL, DEVELOPMENT, DEFINITION, AND INFORMATION NEED: A CRITICAL LITERATURE REVIEW. Journal of Information Technology in Construction, 27.

- LoD 200 (a schematic model where the dimensions, shapes, orientation and positioning are approximated, this LoD enables basic analysis of the design and preliminary coordination with other stake holders);
- LoD 300 (a developed model useful for a more accurate estimation of costs, this LoD enables coordination with the contractors and fabricators);
- LoD 350 (this intermediate LoD adds the construction documentation to the previous LoD);
- LoD 400 (model accurate not only in its shape and dimensioning but also with regards to construction requisites, this LoD enables the production);
- LoD 500 (as-built, this LoD report all the information coherent with the constructed building, it is used for maintenance and facility management).

It is important to not confuse the LoD with the concept of the scale of representation, however, they are concepts that can be put into relation. Higher LoD (more complexity) can be related to representations at larger scales (e.g., 1:20, 1:10, 1:2), and lower LoD (less complexity) can be related to smaller scales (e.g., 1:100, 1:200, 1:300).

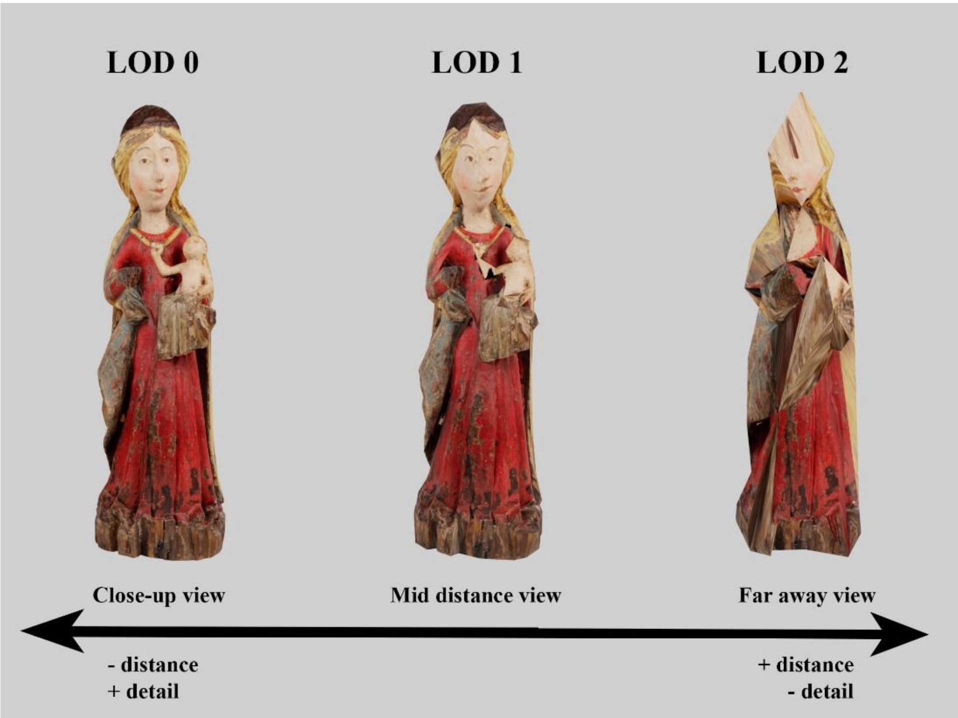


*Figure 2: 3D model and its behaviour, recreation when using LoD. Model: "Mare de Déu amb el nen", Girona History Museum. Programa Giravolt. Author: Pol Guiu Alargé (La Tempesta). Reference: https://skfb.ly/oIWGF*

## Level of Development

Level of Development is a terminology associated with BIM systems and refers to the articulation that the 3D model, and associated information, has reached during the designing process. As observed by Abualdenien and Borrmann[4] there are inconsistent definitions and uses of the Level of Development depending on the sources, context or country. Sometimes it is considered synonymous with the Level of

Detail since they also share the same acronym (LoD), however, another definition proposed in "Level of Development (LOD) specification part I & commentary" (2020)[17] defines it as "The degree to which the element's geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model" which clearly differentiates it from the Level of Detail.

In the context of hypothetical 3D reconstruction, to avoid confusion, it is not recommended to refer to the concept of Level of Definition because its acronym overlaps with the Level of Detail which is a much more popular and less ambiguous concept.

## Level of Information (LoI)

Level of Information (LoI) is associated with BIM systems and describes the amount of non-graphical data that a BIM element contains at a specific time (e.g., dimensions, materials, costs).

## Level of Information Need (LOIN)

Level of Information Need (LOIN) is a terminology associated with BIM systems introduced as a new European Standard by the EN-ISO-19650 (2020) and later as an updated standard and defines the extent and granularity of information considering three different aspects, the geometric data, the alphanumeric data, and the unstructured graphical data (documents, sources). The standard was introduced with the goal to overcome the limitations of existing LoD definitions. With this standard, the International Organisation of Standardisation asks to limit the use of acronyms as much as possible in order to reduce misinterpretations. An exhaustive literature review about this topic is the one by Abualdenien and Borrmann in 2022[4].

The use of the LOIN concept in the context of hypothetical 3D reconstruction is not very popular.

## London Charter

The London Charter[18] is a document that aims to establish internationally recognised principles for the use of computer-based visualisation by researchers, educators and cultural heritage organisations. It was conceived, starting in 2006, to ensure the methodological rigour of computer-based visualisation as a means of researching and communicating cultural heritage. It also aimed at contributing to widespread recognition of this method.

The London Charter principles are the following and are valid whether the computer-based visualisation is applied to research or dissemination of cultural heritage:

[17] Jim Bedrick, FAIA, Will Ikerd, P.E., Jan Reinhardt (2020). "Level of Development (LOD) specification part I & commentary – For Building Information Models and Data" . https://bimforum.org/resource/level-of-development-specification/.

[18] Denard, H. (2009), The London Charter. For the Computer-Based Visualisation of Cultural Heritage, Version 2.1. https://www.londoncharter.org

- implementation
- aims and methods
- research sources
- documentation
- sustainability
- access

The principle of *implementation* deals with the awareness that the computer-based visualisation should follow the London Charter principles in order to be transparent and transmissible; furthermore, the costs of implementing of such a strategy should be considered from early stages in relation to the outputs. The principle of *aims and methods* illustrates that computer-based visualisation should be used only when it is the most appropriate for that purpose. The *research sources* principle illustrates the importance of properly research, analyse, structure, and communicate the sources to ensure intellectual integrity. The principle of documentation describes how to properly document and disseminate sufficient information about the process of reconstruction to make the computer-based visualisation understandable concerning its context and purposes. The principle of *sustainability* highlights the importance of ensuring the long-term sustainability of cultural heritage-related computer-based visualisations and relative documentation to avoid loss of knowledge. The *access* principle, lastly, illustrates the importance of ensuring the maximum possible benefits from the study, understanding, interpretation, preservation and management of cultural heritage and how this work of reconstruction can enhance dissemination, access and understanding.

## Machine Learning (ML)

Machine Learning is a subfamily of Artificial Intelligence systems (AI) which refers to all those algorithms capable of learning from reference data without needing specific instructions. This approach is mainly based on training the model by inputting huge data sets and setting some rules to evaluate the quality of the input and the output. The model is then set up to run millions of times to allow the machine to learn from its failures.

## Manifold

In mathematics, a manifold is a topological space that locally resembles Euclidean space near each point[19]. Examples of one-dimensional manifolds are (e.g.) the line and the circle. Examples of two-dimensional manifolds are (e.g.) the sphere and the torus.

In 3D modelling practice, manifold geometries are important because they can be rendered, 3D printed, and manipulated without errors. Non-manifold geometries in 3D modelling are for example two cubes attached only with an edge or a cylinder with an off-centred hole (with its axis parallel to the axis of the cylinder) that is tangent to the lateral face of the cylinder from the inside. Another example of non-manifold

[19] Hirsch, M. W. (1976). "Differential topology". Springer Verlag: New York, Heidelberg, Berlin.


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geometry is a mesh where three faces are attached to the same edge, in a manifold mesh each edge has two and only two faces attached.

## Mathematical Representation (3D Digital Representation Method)

Mathematical representation refers to the use of symbols, equations, and mathematical constructs to represent concepts and relationships. It is useful for formalising and analysing symbolic and abstract concepts. NURBS geometries are often called mathematical representations since they are described by mathematical equations (and not numbers like meshes). Mathematical representation is often used as synonymous with parametric representation and is the counterpart of numerical representation. When 3D modelling applications implement tools based on the mathematical representation method, we can also talk about mathematical 3D modelling which is the 3D modelling technique based on this representation method.

## Mesh Representation (3D Digital Representation Method)

A polygonal mesh (or simply mesh) is a 3D digital representation method where the three-dimensional shapes are described with collections of vertices, edges, and polygonal faces. Meshes always consist of triangular planar faces, nevertheless, most 3D modelling or rendering applications nowadays allow to hide some edges from the view in order to work with polygonal faces. Meshes composed mainly by quadrangular faces are often preferred to triangulated ones because they behave better in specific contexts, for example for visualisation purposes, in subdivision-based workflows, in soft body simulations, and in non-rigid animations. Mesh representations are described only with the coordinates of their vertices and by defining which vertices are connected with which other, this is why this way of representing a 3D model is considered a subset of discrete and numerical representation. Modern graphic cards are only capable of shading and rendering mesh models, thus mathematical continuous models such as NURBS must be converted into discretised polygonal meshes for any visualisation purpose. Meshes are more efficient for real-time rendering applications compared to NURBS models, especially if they have a low number of polygons, for this reason, they are preferred for computer games and any other real-time-rendering applications. Mesh models also have major cons, they are not capable of describing concepts like curvature and tangency since any curved surface in mesh 3D modelling is approximated with flat faces. Converting a NURBS model into a mesh model is an easy task that a computer can perform automatically because it is just a matter of placing points on the curved surface and connecting them with flat triangular faces. Doing the opposite is much harder, because there is no robust fully automatic algorithm capable of always accurately converting a mesh into a NURBS model yet.

The digital 3D modelling technique that uses meshes to represent three-dimensional shapes is the polygonal 3D modelling technique (sometimes also called mesh modelling).

## Metadata

Metadata is data that provides information about something else. Simple examples of metadata are the information about the resolution, the format, and the date of creation of a digital image (part of this data is visible by opening the file into a text editor, or by accessing the properties of the image). Another example is the cataloguing of information written in the database of a library aimed at describing and indexing specific books. In the context of 3D hypothetical virtual reconstructions, it is very important to organise carefully the knowledge about the model (e.g., sources, uncertainty, modelling process) in the form of linked metadata in order to keep track of the reconstruction process.

## Mixed Reality (MR)

Mixed Reality (MR) indicates the parallel and complementary coexistence of computer-generated images and real-world objects/environments in the user's view/, therefore, the type of interaction is both human-computer and tangible interaction. The objects are actually transformed into interfaces.

## Mock-up

A mock-up is an early visual representation of a design concept usually static. Mock-ups are used to present the general design idea; they differ from prototypes because they are usually non-interactive and do not have functional elements.

## Model

In the most general sense, according to modelling and simulation theory, a model is an approximation/representation of a selected part of reality (a system) reduced to a form that facilitates its understanding, bringing out only those features that help formulate and solve the problem. Models, therefore, always occur as a certain simplification to facilitate understanding and such a model will not be an attempt to create an exact replica of something that exists or existed. The key is the selection of those meaningful features that we want to represent in our model, and which are crucial in solving our problem. Models are created when there is a need to test systems or experiment on them. Models are also built when the real system cannot be engaged, when it is simply unavailable or, for example, it would be dangerous or unethical to test some solutions. Designing a building is a particular case in which we build a model to test a system that does not yet exist; a 3D hypothetical virtual reconstruction is a particular case where the real object is partially or entirely no longer available. In this latter case, we can also talk about simulations since one of the purposes of creating such reconstructions is the desire to learn how they functioned in the past. In this way, we can perform observations of them and derive some conclusions. Besides simulations, there are recording and presentation purposes, since a physically non-existent building is an idea that needs to be materialised in order to be shared with others.

## Native File Format


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Native file format, in 3D modelling, refers to the file format used by a specific 3D modelling software. This format is designed to store all the data that the software can handle, such as 3D models, textures, animations, lighting information, and other scene data. It could also be called a proprietary file format. It means the specifics of how the data is encoded in the file are often kept secret and owned by a company or individual. Different 3D modelling programs have their native file formats. For example:

- .blend for Blender
- .max for Autodesk 3ds Max
- .ma or .mb for Autodesk Maya
- .c4d for Cinema 4D
- .skp for SketchUp

These native file formats are often the best choice for saving work in progress because they retain all the data and attributes specific to the software. However, they are typically not compatible with other 3D modelling software directly. Therefore, data exchange formats are used for sharing models across different platforms.

## Non-Destructive 3D Modelling (3D Modelling Technique)

Non-Destructive 3D modelling is a 3D modelling technique where the construction history is memorised by the software and the user is allowed to access and modify it during or after the 3D modelling process. For example, algorithmic, parametric, and procedural 3D modelling usually adopt partially or totally non-destructive processes. It is the counterpart of Destructive 3D modelling, which is preferred for all those applications where the fast production of variants is not needed.

## Non-Deterministic 3D Modelling (3D Modelling Technique)

Non-deterministic 3D modelling is a 3D modelling technique where the same set of input parameters might not correspond to the same output results. It is the counterpart of deterministic 3D modelling and they are terms usually used in the context of algorithmic 3D modelling. Non-deterministic algorithms can be found in Artificial Intelligence (AI) and the benefit of this latter approach is that they might find solutions hard to be predicted.

## Non-Parametric Representation (3D Digital Representation Method)

The non-parametric representation is the counterpart of the parametric representation. In the non-parametric representation, the digital entities are described without the use of parametric equations, thus they are simply described with discrete lists of points defined with their coordinates and their topological connections (edges and faces). For example, meshes are non-parametric representations.

In the context of virtual hypothetical 3D reconstruction, even if this terminology is valid, we suggest using it with caution because it might be confused with the parametric 3D modelling technique which has a different meaning and is used more often. To avoid confusion, the naming continuous representation (or mathematical representation) and discrete representation (or numerical representation) can be valid alternatives for parametric representation and non-parametric representation respectively.

## Non-Photorealistic (Shading/Rendering)

Non-photorealistic shading/rendering refers to all those styles of rendering a scene that produces effects that do not try to mimic reality. Non-photorealistic shading/rendering (also called abstract shading/rendering) can be used not only for artistic purposes but also for transmitting various information visually using false colours. One of the most popular examples in the context of 3D hypothetical virtual reconstruction is the false colour shading/rendering used to visualise the level of uncertainty/reliability.

## Normal Map

A normal map is a raster image (texture) which is used to simulate fine surface details without adding actual geometry to the 3D models. The RGB channels on each pixel of the image represent the xyz vector components of a reference normal vector on each pixel of the image which will be UV mapped on a 3D geometry and will vary the directions of the original normal vectors of the surface, point by point, only at the visualisation stage. This strategy is not a hardware-intensive process and thus it is very effective to give the illusion of highly detailed 3D models in real-time rendering environments.

*Figure 3: the model on the left shows the mesh without the normal map applied, the model on the right shows the mesh with normal map applied. Model: "Capitell de les Sirenes", Museums of Sant Cugat. Programa Giravolt. Author: Pol Guiu Alargé (La Tempesta). Reference: https://skfb.ly/oEJLo*

## Normal Vector

In computer graphics, a normal vector (or simply a normal) is an oriented direction, of magnitude one, that is perpendicular to a given face or surface. It provides information about the orientation and direction of the surface at that point. 3D models with flipped normal might not be rendered properly. In solid 3D models, the normal should always be pointed outward. Some modelling techniques (e.g., polygonal 3D modelling) enable the manipulation of normal vectors independently from the face (or vertex) to which they refer in order to achieve unnatural or artistic shading effects.

## Numerical Representation (3D Digital Representation Method)

Numerical representation concerns the use of numbers and their manipulation to represent quantities and convey information related to them. Numbers allow for the exact measurements, calculations, and comparison and are easily readable by computers which by definition are only able to compute quantities. Mesh geometries are often called numerical representations since meshes are described only by the coordinates of their vertices expressed with numbers (and not mathematical equations like NURBS). The numerical representation is often used as synonymous with non-parametric representation, and discrete representation.

## NURBS (3D Digital Representation Method)

NURBS is an acronym which stands for *Non Uniform Rational B-Spline* which is a mathematical model capable of describing free-form curves, as well as straight segments, and conical curves accurately (circles, parabolas, hyperbole, ellipses). NURBS math is the evolution of the simpler spline and Bézier models that were capable of describing certain families of free-form curves but were not capable of describing conical curves. Older CAD applications used different mathematical models to draw conical and free curves which caused problems such as the impossibility to join curves described with a different math into one single poly-curve. The fortune of NURBS modelling, other than being able to represent all fundamental shapes in 2D and 3D in a continuous (non-discretised) way, resides in its capability to manipulate easily the shape of the curves through a control polygon which passes through several control points (each point can have a different weight in order to attract more or less the curve to its control polygon). The first two points of the control polygon on each end of the curve coincide with the direction of the tangent of the curve at its endpoints, this allows the users to control the geometrical continuity accurately when joining multiple curves at their endpoints. The order of the NURBS curve represents the number of the control points of said curve, the degree of the NURBS curve can be equal at most to the order of the curve minus one. Higher-degree curves are usually smoother than lower-degree curves, a NURBS curve with a degree equal to one is a polygonal chain made with straight segments that pass through the control polygon itself, this is the strength of this mathematical construct since it enables the drawing of all these shapes without changing formulation. NURBS curves can be analysed for the extraction of the osculating circle and the curvature graph, both are useful tools for designers because they give them full control over the geometrical shape of the 3D model.

In the context of 3D hypothetical virtual reconstructions of architecture, NURBS modelling is useful in order to have full and accurate control of the geometry of each element of the building, NURBS models allow the operators to keep under control (e.g.)

the tangency of the arches, the curvature of the vaults. Furthermore, NURBS modelling applications usually provide a wider range of snapping aids and a wider range of tools to check the topological/dimensional correctness of the model. The drawback of NURBS modelling in this context is that it is less suitable for real-time visualisation and interaction, because modern graphic cards are only capable of rendering polygonal meshes, thus in order to visualise NURBS surfaces any software requires an additional conversion step (which is performed internally in the case of real-time viewport visualisation, or exposed to the user when exporting into mesh exchange formats). This issue is easily solvable because the automatic conversion from NURBS to mesh is easily achievable automatically by software, while the opposite (from mesh to NURBS) almost always requires human interaction.

The NURBS 3D modelling is a 3D modelling technique that uses NURBS representations for the creation of three-dimensional shapes.

## Object-Based 3D Modelling (3D Modelling Technique)

Object-based 3D modelling is a 3D modelling technique that focuses on representing real-world entities known as objects and their interactions within a system. In object-based 3D modelling, the whole system is viewed as a collection of interacting objects, where each object has its unique properties (attributes/instances of classes), behaviour (invoking methods and exchanging messages), inheritances (allowing classes to inherit properties and behaviours from other classes), encapsulations, polymorphisms, associations, aggregations and compositions (which means having a semantic structure capable of encapsulating a level of knowledge of how the various objects are related to each other). In an object-based model, each component is represented as an individual entity. The spatial resolution of the model can be set at any desired level (see LoD) and thus describe a given system in many ways. In a building (or artefact) modelled with an object-based approach, i.e. made up of explicit spatial objects, even from a technical/physical point of view, the spaces and enclosing structures of which it is formed are implicitly determined. This result, in fact, springs from the principle of the complete physical boundary and the separation of space from other spaces, identified through (e.g.) the walls, floors, ceilings, that surround them.

## Orthogonal Projection (Traditional Representation Method)

The orthogonal projection is one of the traditional representation methods of descriptive geometry that consists of projecting a three-dimensional object into a two-dimensional space in a way that the projecting rays are parallel to each other and perpendicular to the projection plane. In architectural representation, the double orthogonal projections consist of projecting the object on planes that are orthogonal to each other (e.g., side/front, top/front).


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## Paradata

Paradata is the information about the data-making process. In the context of 3D hypothetical virtual reconstructions of architecture, it refers to the documentation process of sources interpretation. The accurate incorporation of paradata (and metadata) into the 3D reconstruction, is crucial to ensure the scientific transparency, reproducibility, and reusability of the reconstructive works by other scholars. Metadata and paradata can be both communicated and appended to the 3D model as external texts (e.g., PDF, DOC, TXT) but more effectively they can also be embedded into the model itself and connected to specific elements of the 3D model through the use of BIM systems, and exported as IFC or CityGML exchange formats.

## Parametric 3D Modelling (3D Modelling Technique)

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.

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. For example, in some 3D modelling applications which define themselves as parametric modellers, it is possible to create a 3D object and change the initial parameters (e.g., size, position, generative curves, the radius of a hole) at any time, which is a typical feature of parametric modellers; however, it is not always possible to access and modify every operational step performed to build the model, and it is not always possible to change the order of the construction history, which on the contrary is a typical feature of algorithmic 3D modelling. 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.

Parametric 3D modelling is useful in various scenarios: to guarantee consistent outputs while varying the input parameters; to speed up the process of producing variants; for shape-finding and shape-searching iterative processes.

## Parametric Representation (3D Digital Representation Method)

Parametric representation must not be confused with the parametric 3D modelling technique, since it has a completely different meaning. Parametric representation concerns the way the software describes mathematically the digital entities, namely they are described with parametric functions defined in a certain domain. A parametric surface can be represented by the following formulation:

f(u,v)=(x(u,v),y(u,v),z(u,v)). It is the counterpart of the non-parametric representation, where the digital entities are described with points defined with their coordinates and their connections (i.e., which pair of points are connected with an edge, which groups of edges delimit a face). NURBS-based representation is an example of parametric representation (the u and v parameters represent values parametrised from one end of the surface to the other, they are analogous to x and y for the cartesian plane), while mesh-based representation is an example of non-parametric representation.

In the context of virtual hypothetical 3D reconstruction, even if this naming is valid, we suggest using it with caution because it might be confused with the parametric 3D modelling technique which has a different meaning and is used more often. The parametric 3D modelling technique concerns the way the 3D model is constructed and not the formulas that describe its inner shape (the parameters that give the name to the technique are not the u and v along the surfaces, but are for example the dimensions of its features, its width, the radius of one of its holes, the height of the extrusion). To avoid confusion, the naming continuous representation (or mathematical representation) and discrete representation (or numerical representation) can be valid alternatives for parametric representation and non-parametric representation respectively.

## Perspective Projection (Traditional Representation Method)

The perspective projection is one of the traditional representation methods of descriptive geometry and consists of a type of projection where the projecting rays, passing to the projection plane, converge to a point named viewpoint. In a perspective projection, parallel lines in the three-dimensional scene converge towards one vanishing point. Perspective projection simulates the way the human eye perceives the world and creates a sense of depth and foreshortening as if the projected scene was in fact a three-dimensional space seen from a bi-dimensional window. The perspective projection is the queen of all the projection methods because other traditional representation methods can be derived from perspective's special cases. For example, axonometry is obtained when the centre of projection moves away indefinitely from the picture plane; then the projecting rays will be parallel to the picture plane.

## Photogrammetry (Digital)

Digital photogrammetry is a technique used to create 3D models or measurements of objects or environments by analysing multiple 2D images taken from different angles. It involves the use of specialised software to process the images and extract geometric data. The most advanced photogrammetric methodologies rely on computer applications that process large sets of pictures (image acquisition) of the same object and automatically recognise homologous points in several photos, these homologous points are triangulated in order to find the position of the viewpoints (image alignment), then the photos are re-processed to generate a 3D dense point cloud which can be used to produce a 3D model (textured or untextured). Photogrammetry usually provides better texture outputs, and sometimes even denser


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point clouds/meshes compared to laser scanning, however, they are less reliable in terms of geometric accuracy. Photogrammetric surveys usually give highly unreliable results (or fail entirely) in the presence of highly glossy reflective surfaces or transmitting/transparent objects. Laser scanning and photogrammetry are often used in conjunction to take the best from both words (e.g., 3D model from laser campaign and texture from photogrammetry).

## Photometric Stereo

The photometric stereo is a survey methodology capable of acquiring three-dimensional information by capturing multiple pictures from a single point of view while changing the lighting conditions (raking light from at least three different directions). This methodology is less robust for the accurate acquisition of the overall shape of an object compared to (e.g.) photogrammetry and laser scanning because it relies on the assumption that the surface of the object of survey is Lambertian (which is rarely the case in real cases). However, it is low cost, and it is capable of qualitatively describing much tinier superficial details in the form of normal mapping. For this reason, it is more suitable for the analysis of the high-frequency details of the surface of the object of study, while it is not suggested for the acquisition of the low-frequency details (macrostructure). To improve the quality of the survey, this technique is often used in conjunction with other survey technologies (photogrammetry, laser scanning).

## Photorealistic (Shading/Rendering)

Photorealistic shading refers to all those methods of rendering a scene that aims to produce a physically plausible rendition of light and materials. In the context of 3D hypothetical virtual reconstructions, photorealistic rendered views are often paired with abstract shaded views of the same 3D scene/model because ultra-realistic visualisations, if not properly communicated, might mislead the observer to think that the reconstruction was 100% accurate and compliant to the reality. On the other hand, photorealistic renderings help the observers to immerse into the reconstructed context and imagine better how it could have been.

## Point Cloud

It is a collection of points in 3D digital space. 3D scanning methods and technologies such as laser scanning and photogrammetry produce point clouds that can be processed and interpolated to generate 3D models.

## Polygonal 3D Modelling (3D Modelling Technique)

Polygonal 3D modelling is a 3D modelling technique that consists of generating a three-dimensional shape using discretised geometries made by polygonal faces (polygonal meshes).

# Principles of SEVILLE

The Principles of Seville[20] is a charter of basic principles developed at the international level, aimed at establishing and governing good practices in the growing field of computer-based visualisation for archaeological heritage. The Principles of Seville aims to increase the conditions of applicability of the London Charter in order to improve its implementation specifically in the field of archaeological heritage[21]. Even if its focus and implications are mainly in the archaeological field, it is one of the most important and influential documents in the academic field of 3D hypothetical virtual reconstructions.

The Principles of Seville implements the principles already presented in the London Charter as follows:

- Interdisciplinarity
- Purpose
- Complementarity
- Authenticity
- Historical rigour
- Efficiency
- Scientific transparency
- Training and evaluation

The first principle, *interdisciplinarity* illustrates the importance of engaging professionals from different fields. The *purpose* principle highlights the importance of clarifying the purpose of computer-based visualisation before its development in order to set the Level of Detail and accuracy required. The principle of *complementarity* highlights the importance of using computer-based visualisation only as an additional tool to more traditional management instruments and not as a substitute. *Authenticity* regards the importance of clearly indicating which parts of the model are based on real remains and which are hypotheses. The principle of *historical rigour* illustrates the importance of supporting computer-based visualisation with solid research and documentation. The principle of *efficiency* illustrates that the key to efficiency concerns using fewer resources to achieve steadily better results and depends on economic and technological sustainability. *Scientific transparency* deals with the importance of making computer-based visualisation verifiable, capable of being tested, and reproduced by other experts in the field. Finally, the *training and evaluation* principle concerns the importance of following and promoting training and evaluation programmes at the academic level dealing with virtual archaeology which has its own specific language and techniques and thus requires trained operators in order to output high-quality results.

[20] Principles of Seville (2017). International Principles of Virtual Archaeology. Ratified by the 19th ICOMOS General Assembly in New Delhi. http://sevilleprinciples.com/

[21] Lopez-Menchero, V. M., & Grande, A. (2011). The principles of the Seville Charter. In CIPA symposium proceedings (Vol. 2011, pp. 2-6). https://www.semanticscholar.org/paper/THE-PRINCIPLES-OF-THE-SEVILLE-CHARTER-L%C3%B3pez-Menchero-Grande/fd40fcf0dc510322f079b1a873f46ead382b3211


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## Procedural 3D Modelling (3D Modelling Technique)

Procedural Modelling is a 3D modelling technique that generates a model through the definition of a procedure. It is often considered synonymous with algorithmic 3D modelling.

## Prototype

A prototype is a functional, interactive model that simulates the behaviour and functionality of a product or system. Prototypes are created to test and validate design concepts, gather user feedback, and explore the feasibility of the proposed solution. They can be developed using various techniques, ranging from low-fidelity paper prototypes to high-fidelity interactive digital 3D models. Prototypes typically focus on the user experience, functionality, and interaction flow. They allow stakeholders to interact with the design, test specific features, and identify potential issues or improvements. They differentiate from mock-ups because they are not exclusively aimed at reproducing the visual appearance of the design.

## Publication

Publication is a public release of our resources. It can be carried out in various ways, however, the most effective way would be online publication on reference platforms used by the reference community in open access format. Making it freely accessible would improve the dissemination of knowledge. Data set for publication can consist of a 3D reconstruction model in native format or data exchange formats, available 2D or 3D visualisations, video materials, available documentation and other media. The publication should always have specific objectives, which may be exploration, validation or use of the 3D model by a specific target group. Based on these objectives, we decide what resources will be published and with which tools. If we want to ensure reusability of our model by others, it is crucial to publish the3D reconstructive model together with the documentation. However, Copyright legislation might play against the open-access publication of images and 3D models provided by third-party individuals and organisations. It is always preferable to study the Copyright legislation of the country of reference and the conditions required in order to publish any kind of material before including it in the open-access publication (refer to the Copyright section for more information).

## Raster Image

A raster image is a digital picture composed of a grid of pixels each with its individual colour in a range of colours defined by a specific colour space.

## Raw Data

In the context of architectural virtual hypothetical 3D reconstruction, raw data is defined as the unprocessed information instrumentally acquired from reality (e.g., from the preserved remains of built heritage through laser scanning or photogrammetry) necessary to create the Raw model (e.g., the photos for a photogrammetric campaign).

The raw data is independent of the user's subjective influence by definition, namely, Raw data only represent metric and colourimetric information (that is objective up to the accuracy of the acquisition technology used) and does not contain any interpretative or creative addition by any author. If two different users acquire the same physical object through the same instrument with the same input settings and environmental/boundary conditions, the data from the two campaigns would be analogous. The difference between Raw Data and Raw Model is that the Raw Data does not necessarily have to be three-dimensional (e.g., the photographic set for photogrammetry before processing is raw data).

## Raw Model (RM)

Digital reconstructive architectural 3D models can be divided into two broad categories: Raw Models (RM) and Informative Models (IM).

The Raw Model is a digital 3D model obtained through quasi-automatic procedures starting from raw data captured from physical sources with minimal subjective interpretations by the operator (e.g., digital photogrammetry, laser scanning). For example, possible sources may be archaeological remains (e.g., the ruins of a Roman theatre) and in this case the RM could be a point cloud or a textured mesh model.

The main difference between RM and IM is conceptual: the RM represents only dimensional data (and sometimes also colorimetric data) acquired from physical objects. The IM, on the other hand, represents the complex interpretation process of various sources. The IM is a model obtained through a reverse engineering operation. There is also a technical difference. The RM is always discrete (numerical or polygonal). On the contrary, the IM can be represented with different digital representation methods (continuous or discrete) and built with various modelling techniques (e.g., parametric modelling, direct handmade modelling, polygonal modelling).

To sum up, the RM provides only metric and colorimetric information and not geometric interpretations (e.g., if a chunk of a point cloud is interpreted to be interpolated with a cylindrical/planar/conical NURBS surface that interpolated 3D surface is already an IM).

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

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 reproduces digitally the object of the survey. 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.


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## Real-Time Rendering

Real-time rendering refers to the process of generating and displaying computer-generated graphics in real time. It is a popular technique used (e.g.) in the video game industry, entertainment industry, architectural visualisation, and product design.

## Reconstruction (ICOMOS)

Reintegrating the past appearance of any entity from the evidence preserved in the present (ICOMOS). It is distinguished from restoration because of the introduction of new material and/or data. In the context of digital humanities virtual hypothetical 3D reconstruction has a different meaning, refer to the relative definition in this book.

## Recreation

The new creation of a presumed earlier state of a given entity, based on surviving evidence and on deductions drawn from that evidence. It's not the construction that existed in the past, but a new entity in the present; a model that represents the entity that existed in the past generating all the necessary elements. Also among the definitions proposed by the Principles of Seville (p. 3), the term Virtual Recreation focuses on recovering a specific moment of the entity under study in the past, including material culture (movable and immovable heritage), environment, landscape, customs, and general cultural significance.

## Reflection Transformation Images (RTI)

Reflectance Transformation Imaging (RTI) (or relightable imaging) is an acquisition technique, of quasi-planar manufacts, that captures the surface colour and surface ruggedness of an object and produces an enhanced 2D visualisation that enables the interactive re-lighting of the subject from any light direction[22].

The advantage of having relightable images is that the modification of the light conditions can help to visualise and analyse certain features readable only under certain and different raking light conditions (e.g., geoglyphs, bas-reliefs, coins' engravings). The acquisition procedure is very similar to that of the photometric stereo technique, however, the output in RTI systems is usually not a normal map or a 3D modelled surface, but it is simply an image that cannot be rotated freely in space but can only be relit through the click (or drag) of the mouse. RTI technology uses an acquisition methodology similar to the one used in photometric stereo, however in RTI systems the 3D model of the object is not available and the relighting happens by calculating view-dependent per-pixel reflectance functions, which is a less computation-intensive process and requires lower-performance hardware for the visualisation.

## Reliability

Reliability refers to the consistency, dependability, and trustworthiness of a system, process, or object to perform its intended function or deliver the expected results over time. It is an important aspect in various fields, including engineering, manufacturing,

[22] An example of an open source RTI application https://vcg.isti.cnr.it/relight/

software development, and even human behaviour. In engineering and technology, reliability is often associated with the ability of a system or product to function without failure for a specified period under specific operating conditions. In the context of hypothetical reconstruction, reliability refers to the degree of trustworthiness and credibility associated with the reconstructed scenario or interpretation of historical events. It pertains to the consistency, coherence, and robustness of the reconstructed narrative, evidence, and arguments presented. Reliability, in 3D hypothetical virtual reconstructions, refers to the degree of confidence and trustworthiness associated with the reconstruction based on the available evidence, methodologies, and expert assessment.

## Rendering (3D)

In computer graphics, 3D rendering is the process, performed by a computer, of converting a 3D digital model/scene into a 2D raster image through more or less advanced algorithms. There are several commercial or open-source render engines on the market capable of reproducing a physically plausible photorealistic effect or an abstract non-photorealistic style. The render engines can be standalone applications or can be integrated as plugins in the most popular 3D modelling applications.

## Replication

The construction of a physical copy of a structure or building usually on a different physical location.

## Representation Method (3D Digital)

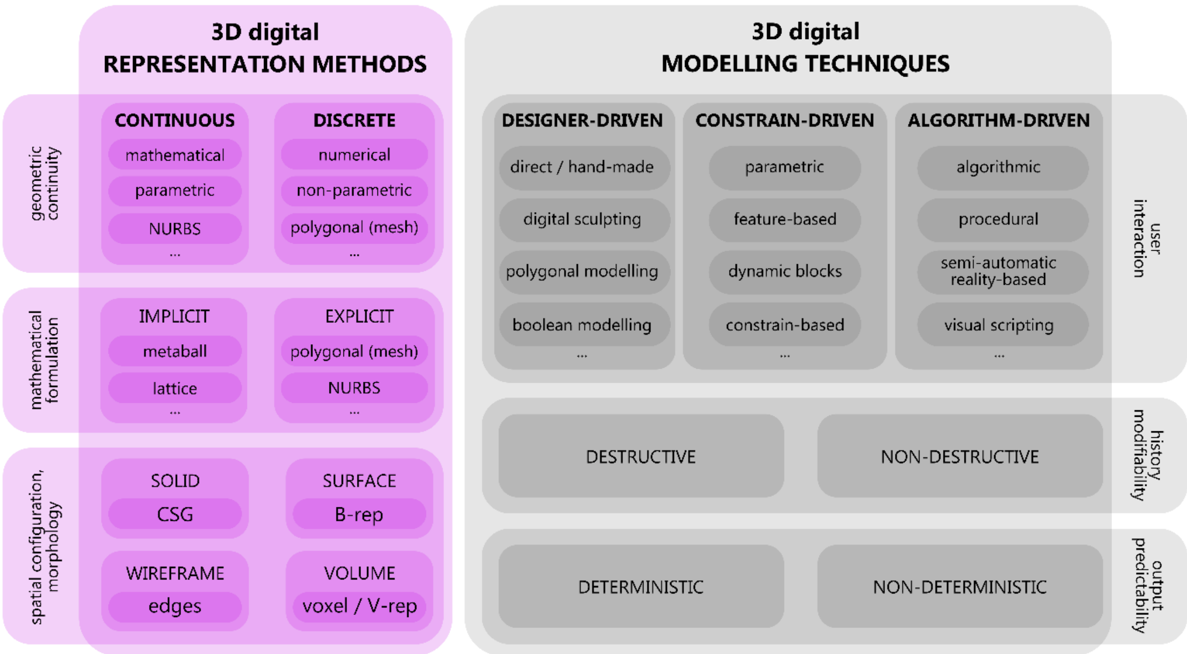


*Figure 4: taxonomic scheme of 3D digital representation methods, compared with 3D digital modelling techniques.*


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The 3D digital representation method concern the intrinsic mathematical/geometrical nature of the 3D models, namely they are the languages (or set of rules) that the software uses to represent shapes in a three-dimensional space.

The naming 3D digital representation methods comes from their analogies with the traditional representation methods. The main analogy concerns the fact that both digital and traditional methods are sets of mathematical/geometrical rules developed to represent shapes, the former in 3D space, and the latter in 2D space. There are also analogies in the way they are used. For example, orthogonal views and axonometric projections are used to describe precisely the shape and dimensions of an object; on the other hand, perspective projections are used to describe how humans perceive space with sight. In the same way, the continuous/mathematical/parametric representation methods, for example, are used to precisely describe the shape and are more suitable to accurately control the geometric shape, while the discrete/numerical/non-parametric representation methods are used to approximate curved shapes and are more suitable for visualisation purposes (renderings).

The most relevant classification of representation methods used in the field of virtual hypothetical 3D reconstructions considers two methods: continuous representation (e.g., NURBS, Bézier, spline) and discrete representation (e.g., mesh, point clouds, voxels). Continuous and discrete representation methods are also known as, parametric representation and non-parametric representation respectively, however, we will suggest not using this latter naming in this context to avoid ambiguity with the parametric 3D modelling technique which has a completely different definition.

Another possible classification of the digital representation methods confronts the mathematical representation from the numerical representation. Since mathematical representation concerns equations (described with parameters), and numerical representation concerns numbers (coordinates), In the context of hypothetical virtual 3D reconstruction this classification overlaps with the continuous/parametric and discrete/non-parametric classifications.

Another possible classification of digital representations considers the forms of the equations used to describe the digital shapes: implicit representation, and explicit representation, this latter classification is not analogous to the previous ones, however, it is less interesting in the context of hypothetical virtual 3D reconstructions because it does not correspond to specific geometrical features of the models. For example, a curved smooth NURBS model and its mesh approximation can be both explicit representations of the same object, however, they have a very different geometrical nature, the former is a continuous smooth accurate description of the shape, while the latter is its approximation with flat faces (discretisation).

There are many possible ways to classify representation methods, the last presented here concerns the differentiation of methods that represent the 3D models as boundary representations, solids, volumes or wireframes.

Sometimes the boundaries between representation methods and 3D modelling techniques are blurry, because some techniques take the name directly from the representation method that they use (e.g., mesh 3D modelling, NURBS 3D modelling, mathematical 3D modelling, etc.) To avoid any confusion, as a rule of thumbs in this book we refer to the technique when the naming is in the form "XXX 3D modelling" and to the method when the naming is in the form "XXX representation method".

## Representation Method (Traditional)

The traditional representation methods are those methods, typical of the descriptive geometry field, that are used to represent three-dimensional shapes onto a bi-dimensional media (e.g., the paper, the computer display). The traditional representation methods are the following: double orthogonal projections, axonometric projection, perspective projection, and topographic terrain projection.

## Reproducibility

In the context of 3D hypothetical virtual reconstruction, the term reproducibility refers to the possibility of reproducing the same virtual hypothetical 3D reconstructive model by following the same steps described by the scholar responsible for the creation of a 3D model. Reproducibility is a foundational feature of a valid scientific process. This assertion alone should highlight the importance of the careful description of each step, in particular the use of the sources and the subjective choices, and the importance of sharing a model interoperable, and easily and extensively inspectable.

## Research Environment

The research environment is the virtual or physical setting where scientific/academic activity is carried out. Research environments typically provide infrastructures, tools and guidelines to help scholars and researchers to bring forward their research in a scientific and optimal way. Scientific research environments are based on the sharing of knowledge, the process of sharing is regulated by standard procedures accepted and applied by all their participants.

## Restoration

Returning a place to a known earlier state by removing accretions or by reassembling existing elements without the introduction of new material. The shape, content and functionality of the –virtually or physically- restored object or building must not be modified in a way that the restored entity will no longer be identifiable. Legibility is considered as a fundamental prerequisite for cultural transmission (Pietroni & Ferdani, 2021)[23].

## Retopology (3D Modelling Technique)

Retopology is the process of modifying or recreating a 3D mesh model in order to improve its geometric structure (e.g., edge flow, quadrangular faces, loops and rings), for future processing that requires a specific configuration/organisation of the model topology (e.g., subdivision surface, soft-body animation).

[23] Pietroni, E., & Ferdani, D. (2021). Virtual restoration and virtual reconstruction in cultural heritage: Terminology, methodologies, visual representation techniques and cognitive models. Information, 12(4), 167.


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While the decimation of a 3D model means the reduction of the polygon count of the model, the retopology implies the re-creation of a new and cleaner mesh from scratch, for this reason is considered a 3D modelling technique. It is highly recommended for improving hardware performances and visual quality, especially if the model comes from automatic or semi-automatic digitisation methodologies (photogrammetry and laser scanning). The reason is that digitisation automatic and semi-automatic procedures produce triangulated 3D models, while for visualisation and animation, quadrangular faces are preferred. Quads-based meshes provide improved behaviour in UV mapping, smooth shading, subdivision surface workflows, and soft body animation.

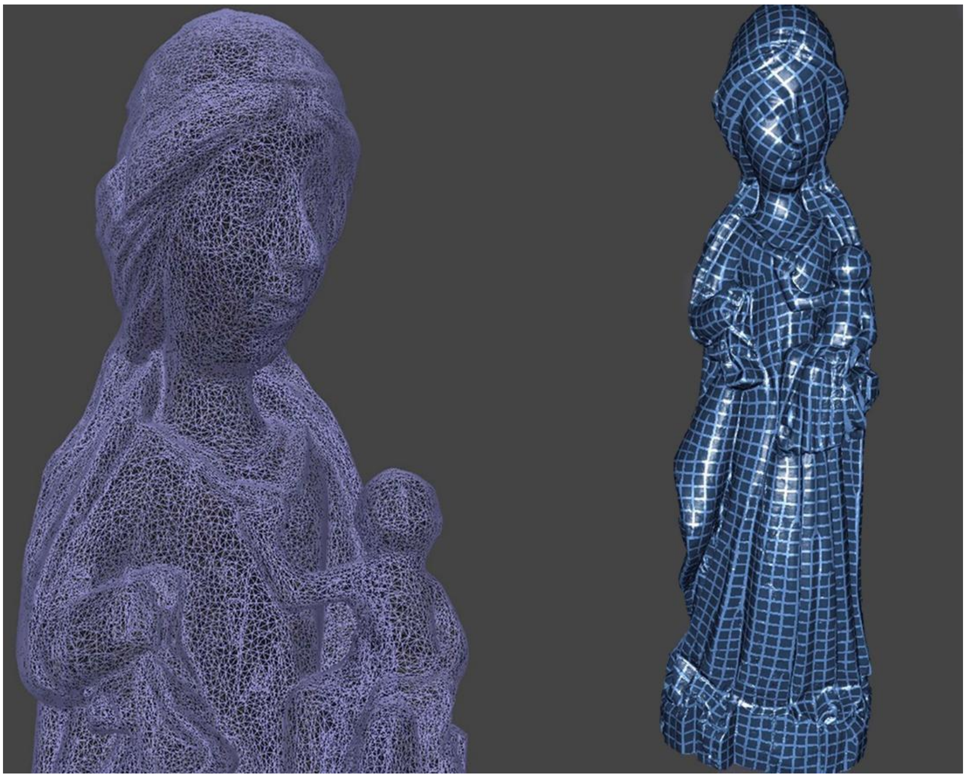

*Figure 5: the model on the left shows the original wireframe, made of triangles. The model on the right shows the quad remeshing performed in Instant Meshes, also reducing the polygon count by 99%. Model: "Mare de Déu amb el nen", Girona History Museum. Programa Giravolt. Author: Pol Guiu Alargé (La Tempesta). Reference: https://skfb.ly/oIWGF.*

## Reusability

In the context of 3D hypothetical virtual reconstruction, the term reusability refers to the possibility of reusing the model by other scholars for the same or different purposes. In order for that to be achievable the users that are not the creators should be put in the condition to properly understand the documentation, open and inspect the file without loss of data, and backtrack the creation process in order to verify the steps performed by the first creator. Due to the different nature of the 3D models, there will be models not reusable for specific purposes without heavy modifications, however, the reusability feature does not require the model to be reusable in every possible context, but at least reusable by others for the same use it was originally created for.

## Reverse Engineering

Reverse engineering is the process of analysing, deconstructing, and extracting knowledge from a product, system, software, or anything manmade, often with the aim of reproducing the object of study. It is a form of backward inference from the end state to the beginning state of a product or system. The process starts with the final product and then follows the design process, but in the opposite direction compared to the formation process (i.e. backwards), in order to arrive at the original product specifications. Reverse engineering is usually conducted to obtain missing knowledge ideas and the design philosophy when such information is unavailable. This concept has been around since long before computers or modern technology and dates back to the days of the Industrial Revolution.

## Scale of Representation

In architectural drawing, the scale of representation is used to determine the size of the object or architectural space based on its drawn reproduction on a bi-dimensional media (e.g., a sheet of paper). In this context, the representation scale of 3D models has a direct analogy with the representation scale of 2D drawings. Generally, when building a 3D model, it is necessary to set a reference unit of measurement in the virtual space (for example, one unit of the virtual system corresponds to one centimetre of the metric system). Furthermore, it is necessary to set a tolerance which establishes the software's accuracy when performing the calculations.

The choice of the reference unit of measurement (centimetre, metre, kilometre, Roman feet and more) must be based on the target Level of Detail. Therefore, for example, the reference unit will be centimetres if the target scale of the details is equivalent to a 1:50 scaled print; or the reference unit will be kilometres if the target scale of the details is equivalent to 1:10000 scaled print. In conclusion, when working in a digital 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, it would be related to 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".

## Scientific 3D Hypothetical Reconstruction

In the context of 3D hypothetical virtual reconstruction, the subjectivity of the operator is an unavoidable factor. For this reason, the use of the adjective *scientific* in this contest is widely debated.

Defining the word *scientific* can be a big challenge because it covers a vast number of subjects and many scientists, thinkers, and philosophers have given innumerable definitions with slight differences which we cannot enumerate all here for reasons of space. However, a good synthesis is given by the AI tool Chat GPT[24]: "The term scientific pertains to anything that is related to or based on the principles and

[24] https://openai.com/blog/chatgpt.

methods of science. Science is a systematic and organised approach to acquiring knowledge and understanding the natural world through observation, experimentation, and logical reasoning. It involves formulating hypotheses, conducting experiments or making observations to test those hypotheses, and analysing the data to draw conclusions."

The canonical steps of the scientific process consist of:

- defining a question to investigate,
- making predictions,
- gathering data,
- analysing the data,
- drawing conclusions.

Some authors also add a further step, which is the sharing of the results with the reference scientific community which validates them by reproducing the experiment/procedure and comparing the results.

Thus, *scientificity* doesn't have anything to do with *correctness* or *completeness* but can be defined instead as the methods of accessing knowledge through the discovery/creation of reproducible models that give answers to questions that are consistent with what was or will be observed in the real world. The scientific models of the past are constantly put to test as soon as new evidence is available, and if the evidence is compatible with the theory, the theory itself remains valid, otherwise, it is updated, refined or rejected. The longer a theory holds, the stronger the theory is.

Scientific does not mean exact, the proof is that most of the theories of the past developed following the scientific method are now outdated. Based on this, the 3D hypothetical virtual reconstruction can be scientific as long as it strictly follows the steps of the scientific method. The biggest challenge is guaranteeing reproducibility because it involves subjective hypotheses. In order to make a scientifically valid 3D virtual reconstruction, thus, the process of documentation and publication of the results are the most crucial aspects that cannot be overlooked or conducted in an approximate, ambiguous, or unclear way.

Several initiatives tried to clarify and improve the dissemination of the aspects that make a hypothetical reconstruction transparent and reproducible, for example, the Principles of Seville and the London Charter are two of the most important documents with these objectives.

## Scientific Reference Model (SRM)

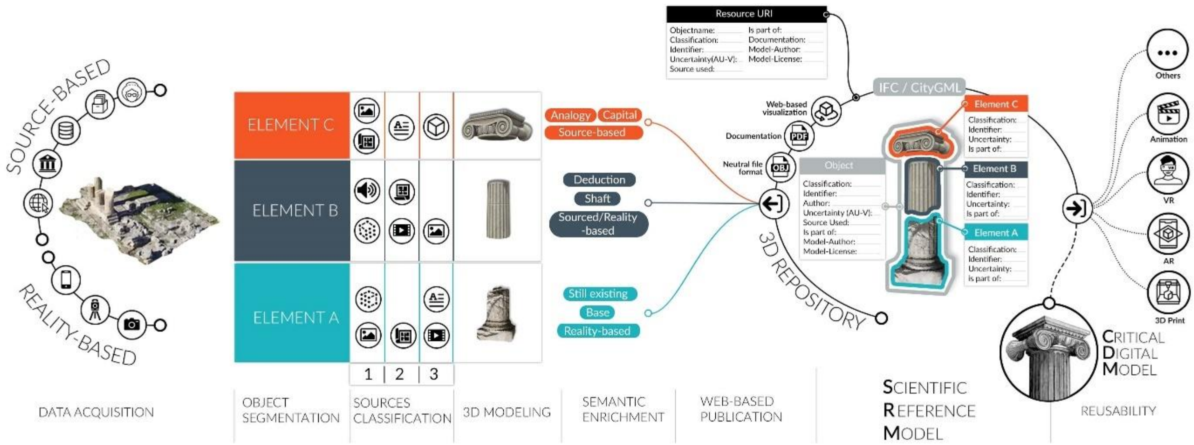


*Figure 6: Scientific reference model framework*

The Scientific Reference Model (SRM) aims to establish an applicable methodology within hypothetical 3D reconstruction that meets scientific requirements and enables referencing and re-using the results. In most cases, the SRM provides an initial reference model available for further re-use. This approach follows the insight that the majority of the hypothetical 3D re-constructions are used for (visual) mediation in high-quality renderings, animated films, (serious) games, Augmented Reality, Virtual Reality, 3D printing, etc. and thus has to meet a wide range of (technical) requirements in the final result. The SRM anticipates this dilemma by publishing the 3D model earlier, which guarantees standardisation, interoperability and sustainability of a core knowledge framework. The SRM is a reference model from which various derivatives can be derived for further applications. SRM can be considered a predecessor of CDM that focuses on the visual representation of the model, its appearance and materiality as a result of texturing and exposure.

## Semantic Enrichment

Semantic enrichment refers to the process of adding additional meaning, context, or information to the geometric representation of a 3D model, semantically structured or segmented. It involves attaching semantic attributes, such as functional properties, spatial relationships, building systems and components, historical data sources, behavioural properties or metadata, paradata and attributes, to the 3D geometry to enhance the understanding, analysis, and use of the building or artefact modelled.

## Semantic Segmentation

Semantic segmentation is the process of subdividing the object of study (e.g., 3D model, point cloud, raster image) into sub-elements, organising them hierarchically - while assigning to every element a specific name and/or one or more families/classes, and defining their mutual spatial and topological relationships. Semantic segmentation is a crucial step in any scientific knowledge-oriented process, and it is fundamental for the comprehension of the object of study, for the analysis of its parts, and for the unambiguous transmission of the study results. Semantic segmentation can be performed by using object-oriented computer applications (e.g., BIM software,


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CAD), if the software does not support grouping and hierarchical organisation of the model it is always possible to embed the hierarchical relations by defining an efficient naming system (based on a precise architectural vocabulary), or by assigning colours through materials and/or layers, however, this latter solution is less efficient and it is not always interoperable with other applications. For an effective and unambiguous semantic segmentation of 3D architectural models and for easy identification of their sub-elements, it becomes particularly important to try avoiding intersections between different elements and/or open/non-manifold geometries. A useful approach to ensure these characteristics of a 3D architectural model is based on taking care of the physical objects and structures of a building (see: object-oriented design/modelling), which means considering: building objects/elements; connections, relations or dependencies between these objects; composition levels/structures; building systems.

## Shape/Form

In the visual arts shape is a flat, enclosed area of any visual entity, and it can be represented through lines, textures, or colours, or an area enclosed by other shapes, such as triangles, circles, and squares. In mathematics, shape refers to the structure of the localised field constructed "around" an object [Koenderink and Van Doorn 1992[25], Kosslyn 1994[26], Paindaveine 2008[27], Leymarie 2011, Barceló 2014, Klingenberg 2016[28]]. The word shape should be limited to the 2D world of planes. The term form is to a 3D representational framework what shape is in 2D: a cube is to form what a quadrangle is to shape [Cooke and Terhune 2015[29]].

## Shading

In 3D rendering, shading refers to the process of determining the surface colours or the variation of their level of darkness/lightness in a three-dimensional scene, it is a crucial step in the rendering pipeline that simulates how light interacts with the 3D objects, considering their material, and creates the illusion of three-dimensionality.

## Simulation

The term simulation covers a vast diversity of aspects. In general, it refers to the imitation of a situation or process. In the context of 3D hypothetical virtual reconstruction, the users can simulate different scenarios, such as how the building might have looked in the past, by changing conditions, adding or removing elements, or simulating the impact of different types of weather on the building. However, in 3D graphics, the term *simulation* is often used to refer to a specific class of effects that are

[25] Koenderink, J. J., & Van Doorn, A. J. (1992). Surface shape and curvature scales. Image and vision computing, 10(8), 557-564.

[26] Kosslyn, S. M. (2005). Mental images and the brain. Cognitive neuropsychology, 22(3-4), 333-347.

[27] Paindaveine, D. (2008). A canonical definition of shape. Statistics & probability letters, 78(14), 2240-2247.

[28] Klingenberg, C. P. (2016). Size, shape, and form: concepts of allometry in geometric morphometrics. Development genes and evolution, 226(3), 113-137.

[29] Cooke, S. B., & Terhune, C. E. (2015). Form, function, and geometric morphometrics. The Anatomical Record, 298(1), 5-28.

produced by imitating physical properties on digital objects, such as smoke and fire, fluids dynamics, hair movement, rigid bodies, and interaction between particles.

## Solid Representation (3D Digital Representation Method)

Solid representation or CSG (Constructive Solid Geometry) is a 3D digital representation method where the 3D shapes are represented as closed watertight sets of non-intersecting surfaces (with only manifold edges).

When you consider the technique of constructing shapes with solid representation, it is usually based on stacking Boolean operations onto 3D solid primitives (e.g., spheres, cones, pyramids, prisms, toroids, ellipsoids) or based on the iterative modification of a base solid that never loses its water-tightness. In solid 3D modelling, it is always possible to identify if a point is inside or outside of a certain object, this makes solid modelling a robust method for designing geometries that must be physically prototyped and always guarantees the correctness of closed three-dimensional shapes preventing geometrical errors such as flipped normals, self-intersections, zero-thickness elements, non-manifold geometries, and so on.

## Source

Each 3D hypothetical virtual reconstruction relies on sources. The sources can be direct and indirect or primary and secondary. Direct sources refer directly to the object of study (e.g., a paint of a specific building, the remaining of a Roman theatre), while indirect sources refer to different objects or events that might be related or might be analogous to the object of study (e.g., coeval objects, objects from the same geographical area, or by the same author). Primary sources provide first-hand information about the object of study (sources by authors directly involved or related with the object of study), while secondary sources provide second-hand information about the object of study (sources by authors not directly involved or related to the object of study). The interpretation of sources always requires a certain level of interpretation, however, direct/primary sources are often more reliable sources. Most of the time in 3D hypothetical virtual reconstruction both direct/primary and indirect/secondary sources concur to achieve the completion of the reconstruction, however since the construction of models is always dependent on a certain level of interpretation or schematisation by the operator, it is crucial to keep track of these choices and document them properly by documenting and providing accurate metadata and paradata.

The most popular types of sources used in the context of 3D hypothetical virtual reconstruction are the following:

- graphical/iconographic sources (e.g., drawings, sketches, paintings, photographs, frescoes),
- textual sources (e.g., treaties, letters, parcels, receipts, judicial acts, books),
- oral sources (e.g., testimonies of eyewitnesses, traditional songs),
- sculptural/objectual sources (e.g., original remains, statues, bas-reliefs, medals, coins).

## Space

A boundless, three-dimensional extent in which objects and events occur and have relative position and direction. In geometry, it is a set containing selected mathematical objects that are treated as points, and selected relationships between these points. According to Alan Dix [Dix et al., 2005[30]], there are three types of spaces:

- real space - actual objects in actual physical space;
- measured space - the geometric representation of that space though a model making emphasis on locations of objects;
- virtual space - electronic spaces created to be portrayed to users, but not tied explicitly to the real world.

Taking into consideration the conceptual distinction between space and place, based on and according to cultural constructs space is transformed by its inhabitants into a unique place. Champion and Dave [2007][31] state that in a virtual environment a place can be defined as "a region recognisable to a user as a culturally coded setting". The notion of place (both physical and virtual) is something more than just the spatial setting around people/users. Champion and Dave put emphasis on the engagement with the place, considering that a place is "particular, unique, dynamic, and memorably related to other places, peoples, and events, and it is hermeneutic". In other words, we virtually reconstruct 3D spaces, in order to create virtual places. It is an interesting distinction, especially when the emphasis is put on the use of our models/spaces for dissemination purposes.

## Storytelling

Storytelling is a communication strategy used in several fields, based on the transmission of concepts through the narration of a story. It is often used to present 3D hypothetical virtual reconstructions, to engage the audience and convey knowledge in a more effective form easier to enjoy also by youngers. The term Digital Storytelling already appeared during the 1990's referring to the use of multimedia in the narration of a story. From 2000 onwards the element of interaction was added to the definition. Digital Interactive Storytelling is plot/character-based, and it has been transformed into an interdisciplinary field between Computer Science and Humanities.

## Structured-Light 3D Scanners

Structured light scanners are devices capable of acquiring 3D information using projected light patterns captured through a camera sensor and analysed with algorithms that compare the expected pattern configuration with the captured one. It is considered an active 3D scanning technology.

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[30] Dix, A., Friday, A., Koleva, B., Rodden, T., Muller, H., Randell, C, Steed, A. (2005). Managing multiple spaces. In Turner, P., Davenport, E. (eds.) Space, Spatiality and Technologies. Kluwer.

[31] Champion, E., Dave, B. (2007). Dialing Up the Past. In Cameron, F., Kenderdine, S. (eds.) Theorizing Digital Cultural Heritage: A critical Discourse. MIT Press.

## Subdivision Surface 3D Modelling (3D Modelling Technique)

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 a control cage and converts it into a smoother geometry (a denser higher resolution mesh). 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.

## Surface 3D Modelling (3D Modelling Technique)

3D surface modelling is a 3D modelling technique that concerns the process of generating a three-dimensional shape by using tools capable of constructing the shapes starting from the single surfaces that can be modified, manipulated, and connected to form opened zero-thickness surfaces (or poly-surfaces) or closed solids. Rarely an application is exclusively a surface modeller or a solid modeller, modern CAD applications usually implements both representation methods.

## Tessellation

In computer graphics the term tessellation means the discretisation of a surface into planar faces (polygons). Thus it is usually a process that converts a continuous/smooth surface into a discrete polygonal surface. A coarse mesh is a polygonal model tessellated with a low amount of polygons, a fine meshis a model densely tessellated.

## Texturing

Texturing is the process of applying images to the 3D models. Textures can be created from photos, or procedurally. Texturing improves the visualisation of the surfaces of the model not only in terms of colour information but also in terms of how the material reacts to light. It is also possible to embed geometrical information into specific types of textures (e.g., normal mapping, bump mapping, and displacement mapping), this is useful to keep the geometry of the model simpler and lighter while giving the impression of a higher resolution model only at the visualisation stage.

## Texture baking

Texture baking is the process of capturing various data (e.g., material data, light data, geometric data) into a raster image UV mapped onto a 3D model. Texture baking can be used to increment the efficiency of a 3D scene in the case of video games or XR outputs. For example, texture baking is often employed to avoid using extra lighting in the scene by baking the lights and shadows directly in the object's diffuse texture (base colour). This highly improves the performance, as the ambient illumination implies the real-time calculation of lights and shadows, which should be always minimised, however, baked lights can not be moved without recalculating the baking. Another example is the conversion of small-scale geometric information into


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normal maps from a high poly model to its low poly version. This process is aimed to simplify the mesh geometry without loss of perceived detail.

## Topographic Terrain Projection (Traditional Representation Method)

Topographic terrain projection refers to the process of representing the three-dimensional surface of a terrain or landscape onto a two-dimensional plane while preserving spatial relationships and elevation information. It is commonly used in cartography, and architectural drawing to create maps and plans. The most important elements of topographic terrain projections are the contour lines which are curves connecting points with equal elevation on the terrain above the reference level. Adjacent contour lines on the same topographic terrain representation are usually drawn with equal elevation distance.

## Topology

In mathematics, topology is a branch of geometry that focuses on the properties of space that are preserved under continuous transformations (e.g., stretching, bending, and twisting, but not tearing or glueing). It studies the fundamental concepts of continuity, connectivity, and neighbourhood relationships. A typical question to understand intuitively if two objects have the same topology is: "How many holes do these two objects have?". If the answer is: "Both objects have the same number of holes", then the two objects might have the same topology. A typical example of two objects with the same topology is "a cup with a handle" and "a doughnut", they have the same topology because one can transform into the other with continuous (stretching) transformation without tearing or gluing any part.

In network theory, the network topology refers to the schematic description of the arrangement of the physical and logical elements of a communication network or a graph.

In computer graphics, the term topology encapsulates both meanings and refers not only to the shape of an object but also to the way a 3D model is geometrically structured, namely, how its sub-elements are connected and related to each other (e.g., adjacent vertices, edges, faces). For example, a 3D mesh model with a good topology is a model where there are no geometrical errors (e.g. there are only manifold edges, there are no overlapped faces, no flipped normals, etc.) and with good edges flow (e.g., the rows of quadrangular faces are organised in a way that they follow the main features of the 3D model).

## Traceability

In the context of 3D hypothetical virtual reconstruction, the concept of traceability refers to the possibility of following the development of the reconstruction process while keeping track of every subjective choice made by its creator. This feature is crucial for the scientific validation of the 3D model. Traceability is only achievable by documenting the reconstruction process through the redaction of a detailed relation, and/or the compiling of extensive metadata and paradata embedded into the 3D model itself.

# Uncertainty

Uncertainty refers to epistemic situations where we have imperfect or unknown information about a particular topic. It is relevant in various fields such as insurance, philosophy, statistics, economics, and financial markets (Knightian uncertainty). In scientific modelling, uncertainty arises when predicting future events can have a range of possible different outcomes. The Heisenberg uncertainty principle in physics is an example of how uncertainty is fundamental to our understanding of quantum mechanics. In science and engineering notation it is involved in every measurement or can be used in the context of validation and verification of material modelling. The concept of uncertainty also plays a significant role in the hypothetical virtual 3D reconstruction process. When reconstructing historical events, there are inherent limitations in the available data, making it difficult to have a complete understanding of the past. Uncertainty arises due to factors such as the lack of direct observation, incomplete information, the need for assumptions and approximations, the presence of multiple hypotheses, the changing historical context, and the interpretation and bias involved in analysing historical data.

# Uncertainty Scale

| 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). |

*Figure 7: an example of an uncertainty scale where the uncertainty is related to the type, authorship and quality of the reference sources used. This scale is conceived for 3D hypothetical virtual reconstruction of architectural heritage. In cases where authors are unknown (such as in some*



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*archaeological periods) the five-levels scale presented in [Apollonio et al., 2024[32]] could be more appropriate.*

The uncertainty scale (sometimes it is called the reliability scale which is opposite to uncertainty) is an analysis and visualisation strategy for hypothetical source-based reconstruction aimed at evaluating the level of accuracy and consistency of interpretation and historical plausibility based on some related data (e.g., historical documental sources). Different scales could exist based on the different objectives of the reconstruction.

The uncertainty scale is based on the definition of a multi-step sorted list, where every item of the list is related to a certain level of uncertainty described textually and/or numerically and assigned to specific elements/areas of the hypothetical reconstructive model (an example of uncertainty scale is in Figure 6). In order to visualise the assigned levels of uncertainty the textual definitions are usually paired with colours (or other similar graphical artifices: e.g., different patterns, level of transparency, silhouette lines), that are assigned to the various elements of the model through false-colour shading. Over the years several scales have been developed, for example, some measured the uncertainty based on the type of sources, others by following fuzzy logic approaches, others by relating their levels to the amount of available physical ruins.

The various one-dimensional scales developed over the years (simple lists of elements) sometimes evolved into n-dimensional matrices (tables with multiple entrances). Uncertainty matrices are able to cross-reference multiple factors at the same time, this approach is harder to read and apply but is capable of transmitting more information.

In the context of scientific 3D hypothetical reconstruction, the scale/matrix of uncertainty must be as objectively applicable as possible with minimal overlapping between different levels and minimal ambiguities in their definitions. A scale/matrix of uncertainty in order to be usable in a scientific context should be able to give consistent results. A scale/matrix of uncertainty should return operator-independent results. A scale based on objective data, (e.g., the type of sources, the authors, the state of preservation, the consistency, the year of construction) is less subject to personal interpretation and thus the results between the analysis and visualisation of uncertainty of two reconstructive models are more easily comparable and readable, thus scientifically sounder.

## UV Unwrap/Parametrisation/Mapping

UV unwrap (or UV mapping or UV parametrisation) is the process of projecting the surface of a 3D model into a bi-dimensional plane. The letter U and V represent the parameters X and Y in the texture space (some applications uses also the letter W to represent the texture Z axis). Texture parametrisation is a fundamental step to define how to wrap a bi-dimensional image onto a three-dimensional object.

[32] Apollonio, F. I., Fallavollita, F., Foschi, R., & Smurra, R. (2024). Multi-Feature Uncertainty Analysis for Urban-Scale Hypothetical 3D Reconstructions: Piazza delle Erbe Case Study. Heritage, 7(1), 476-498.

## Validation

The assurance that the solution to the reconstruction problem meets the needs of the entertainment, educational or scientific project. It implies making a particular re-creation of some built heritage element 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-constructions or re-creations of the past implies exploring the use of such replica, and the goals we had when beginning the re-construction or re-creation process. Validation often involves acceptance and suitability with the model users, according to the different ways the model can be used with an entertainment, educational or scientific purpose.

## Variants (3D)

In the creation process of 3D hypothetical virtual reconstructions of architectures or manufacts from the past multiple plausible solutions for the same case study are often available. These different versions of the same manufact are called variants. They can be different possibilities with different levels of uncertainty related to the same historical moment, or they can be variations of the same building over time. In the academic field, the variants are usually referenced/connected to each, in order to keep track of them.

## Verification

The evaluation of whether or not the solution to the reconstruction problem complies with requirements, specifications, or imposed conditions for the proper recognition of the solution as deducible from problem statement (Artemov and Fitting 2019[33], Grellert and Pfarr-Harfst 2019[34]). That implies that the way new information has been added during the re-creation process is made explicit, and the reliability of structural (in)dependencies between perceived (raw) and inferred (re-created) elements. Verifying a physical, a textual, a visual or a computational model representing a particular re-creation of a past building is just the reverse of the re-creational process. A re-creation can be verified in terms of how it has been produced, but it cannot be tested for truth content because our knowledge of the re-created target is very far from us and only partially known.

## Virtual 3D Model

The virtual 3D model indicates a digital entity which does not physically exist as such, but it is made possible by software and exists or operates in a computer-generated simulated environment. In the context of virtual hypothetical 3D reconstructions, it almost always overlaps with the concept of digital 3D model.

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[33] Artemov, S., & Fitting, M. (2019). *Justification logic: reasoning with reasons* (Vol. 216). Cambridge University Press.

[34] Grellert M., Pfarr-Harfst , M., (2019) Die Rekonstruktion – Argument – Methode: Vorschlag für einen minimalen Dokumentationsstandard im Kontext digitaler Rekonstruktionen. In: Kuroczyński P., Pfarr-Harfst, M., Münster, S. (eds.) *Der Modelle Tugend 2.0: Digitale 3D-Rekonstruktion als virtueller Raum der architekturhistorischen Forschung*.arthistoricum.net: Heidelberg.


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## Virtual Hypothetical 3D Reconstruction

Virtual hypothetical 3D reconstruction refers to the process of digitally recreating or constructing a three-dimensional representation of an object, structure, or environment that may no longer exist or is inaccessible in its original form. It involves using available data, such as historical sources, photographs, archaeological findings, or physical remnants, to create a virtual representation of the object.

The process of virtual hypothetical 3D reconstruction usually involves the following steps:

- Data Collection: relevant historical or archaeological data, including photographs, drawings, measurements, or written accounts, are collected to provide a basis for the reconstruction. This data serves as a reference for understanding the original form and characteristics of the subject.
- 3D Modelling: using specialised software, a 3D model is created based on the collected data. This involves recreating the shape, structure, and appearance of the subject using various 3D modelling techniques and methods of representation.
- Texture mapping and definition of material properties: sometimes the 3D model is further enhanced by applying textures, colours, and material properties to enhance the visual appearance of the subject; textures can be derived from historical images or artistic interpretations. Sometimes this step is completely skipped if the initial sources do not provide enough information, and a neutral mono-material is applied instead (white, grey).
- Addition of contextual assets: sometimes additional elements such as characters, furniture, products, and vegetation, are added in order to achieve a better placemaking and depict the atmosphere of the represented time by adding a further layer of complexity considering perception and/or social relations between people and artefacts.
- Presentation/visualisation and interaction: the reconstructed 3D model can be presented/visualised by means of various methods and technologies. It can be rendered as static images depicting it from different angles; animated and presented in a video fort; or presented in an interactive virtual environment.

Virtual hypothetical 3D reconstruction plays a significant role in disciplines such as archaeology, cultural heritage preservation, architecture, history, and education. It allows researchers, historians, and the public to experience and understand historical or archaeological subjects that may no longer exist in their original form. Virtual hypothetical reconstructions help visualise and communicate the past, provide insights into lost civilisations, architectural marvels, or significant historical events, and contribute to the preservation and documentation of cultural heritage.

In this field, the word *hypothetical* is sometimes omitted without changing the meaning. According to the Principles of Seville, *3D Virtual Reconstruction* is defined as "…using a virtual model to visually recover a building or object made by humans at a given moment in the past from available physical evidence of these buildings or objects, scientifically reasonable comparative inferences and in general all studies carried out by archaeologists and other experts in relation to archaeology and history". This definition is well recognised in the archaeological field, however in the larger field of Digital Cultural Heritage, this naming acquired a larger meaning. The word *reconstruction* etymologically means "constructed again", thus Seville's definition is perfectly coherent; however, in the academic field, this term is often used to define all kinds of digital visualisations that reproduce a hypothetical version of the past starting from documental sources even if no physical remains are available and the object of study was never physically built in the first place. Because the academic community is aligned in using this naming consistently, we adopt the larger significance of the term. To avoid this ambiguity some scholars use the following variants of the term *reconstruction*: (re)construction, or re-construction.

## Virtual Reality (VR)

Virtual Reality (VR) is the real-time simulation of a computer-generated scene/experience that is visualised and interacted with through advanced electronic equipment (e.g., VR Headsets, haptic VR gloves, VR treadmills). VR creates a cognitive multi-sensory environment, where both the computer system and the user are focused only on digital stimuli, while the physical world around them is never considered (in contrast to Mixed Reality or Augmented Reality, where the physical world is considered and actually forms part of the experience). The immersivity of the user into the virtual world is a foundational aspect of VR applications, the level of immersivity depends on the technology, the effectiveness of the designed user's experience, and the sophistication of the software in use.

## Virtual Recreation (3D Digital)

According to the Principles of Seville (2017) the 3D Virtual Recreation "involves using a virtual model to visually recover an archaeological site at a given moment in the past, including material culture (movable and immovable heritage), environment, landscape, customs, and general cultural significance". In a broader architectural scholarly context (not only archaeological) this naming often overlaps with 3D virtual reconstruction where the latter is used more often.

## Visualisation (3D)

3D Visualisation is the multistep process of creating 3D shapes, environments, animations, and events and showcasing them in various forms that are perceivable and understandable by human observers. The process of conversion of machine-readable numerical data written in the form of bits (zeroes and ones) into data perceivable by a human observer is called rendering. This conversion happens through a multistep process that relies on advanced algorithms capable of producing raster images that will be visualised on an electronic display or printed on physical media.


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## Volumetric Representation (3D Digital Representation Method)

Volumetric representation (or V-rep) is a 3D digital representation method where the 3D shapes are represented as three-dimensional regions of space defined point by point. Often they are represented through the use of dense point clouds (voxels). Volumetric models are for example generated through tomographic acquisitions and are used in the medical field to visualise and analyse the composition of specific parts of the human body, or in the engineering field to quantify defects in manufactured pieces. Volumetric models are conceptually different from 3D solid models.

## Voxel-Based 3D Model

Voxels are the three-dimensional counterparts of bi-dimensional pixels. In point clouds, the points take the name of *voxels*, usually when they are arranged in a regular three-dimensional grid and visualised as cubes. Voxel-based 3D models are volume-filling shapes and are the main 3D digital representation method used in volumetric 3D modelling.

## Wireframe Representation (3D Digital Representation Method)

Wireframe representation is a 3D digital representation method where the 3D models are represented as cages of vertices connected with straight segments. Wireframe representation is different from the mesh representation because in wireframe representation there are no faces and thus edges in front or behind the 3D shape are visible all at once without any hierarchy.