I introduction

A general overview of the main issues related to the scientific digital reconstruction for cultural heritage is here traced, before focusing on the main topic of the research. Here the dichotomy between model and reality is analysed, especially in order to define a methodology and some principles for documentation at a level of metadata and paradata. Before agreeing upon these issues, an investigation involving terminology is necessary: this constitutes a large part of this chapter.

In hypothetical reconstructions of lost or never built heritage, sources like images and texts are integrated, leading to partially hypothetical reconstructions. Therefore, this introduction emphasises the need for critical analysis, documentation, visualisation techniques, and model reusability in order to ensure the scientific validity and transparency of the digital 3D reconstruction, primarily targeting academics and researchers.

'What do you consider the largest map that would be really useful?'

Lewis Carroll, *Sylvie and Bruno Concluded*, London: Macmillan and Co., 1893.

I

introduction

object, aims, methods

A.
OBJECT OF THE RESEARCH: SOME DEFINITIONS

As declared in the title, this study considers digital 3D reconstruction as a tool for research in the field of cultural heritage, especially in art and architecture history. In particular, we refer to source-based models of destroyed or never built artefacts, reconstructed not – or just partially – from reality, which is the reason why they have to be integrated with other sources such as images, drawings, written texts: this means that they remain, to some extent, hypothetical.

The issue of "right" and "wrong", or "certain" and "impossible", intended not just as a binary opposition, but as the two poles of a continuous gradient of possibilities, is the driving force of every reconstruction process of this kind, even though an analysis from this point of view is often lacking.

In this context, reconstructions should be scientifically grounded, documented, accessible and shareable. That's why the documentation of the process, indicating the choices we make while reconstructing an object, becomes vital, as well as the definition of the level of uncertainty of our reconstruction, which will be based on a value scale and translated into a graphical representation. This will be the focus of our research, which will deal with the classification and visualisation of uncertainty, especially with the aim of making data interoperable.

Let's start with some definitions explaining the object of the research and its context.

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A.1. Virtual reconstruction

With the term "virtual reconstruction" we refer to the process of creating a simplified copy (a model) of an object in a space that is different from the original – "real" – one in which the object is, or was, or should have been situated.

In our case, which is very common nowadays, by "virtual" space we mean a "digital" one, created with the aid of computer graphics to highlight particular features of a model and especially, in this study, to re-construct[1] something lost in order not only to present it, but also to study it and improve our knowledge of the past.

We know that virtual reconstructions in the form of digital models are a widely used solution to communicate a step of an ongoing process or to summarise the results obtained in a certain period of time or during a project (Demetrescu 2018). However, we should keep in mind that the concept of "virtual reconstruction" existed long before the use of digital technologies (Piccoli 2017): among the most famous examples we can mention the *Envois de Rome de l'Académie de France*, which were the reconstruction exercises that the winners of the *Prix de Rome* had to do. We have recordings of them dating back to the 17th century; they became then mandatory from 1778 (Pinon and Amprimoz 1988).

In our research the word "virtual", similarly to "potential", also expresses the «likelihood of a certain artifact having existed in the past» and obtained by "reconstruction", which is «part of research from the earliest stages»: since it influences reasoning, it has to be considered «a scientific tool to improve the understanding of a phenomenon» (Demetrescu 2018). This is the reason why it is important to create validated contents.

This constitutes a crucial topic, since the field of virtual reconstructions obtained with digital tools, with which this study deals, has enormously grown up in the last thirty years, but without defining actual standards for

1 As we will see further in this study, what we call "reconstruction" should be more precisely considered a "construction" of something lost that we don't completely know (Clark 2010).

methodology (and, even before, terminology) that would lead to a scientific use of these models.

A.2.
Reality-based and source-based (hypothetical) 3D models

A virtual reconstruction can be reality-based (based on physically existing objects) and/or source-based (based on documents depicting objects – or parts of them – that do not physically exist).

Reality-based 3D models are thus grounded on data that can be collected during a survey. In this case, accuracy is mainly expressed in usual units of measure or as a human error in the measurements.

Source-based 3D models deal with artefacts that were partially or totally destroyed or have never been built. Therefore, the digital reconstruction should take into consideration all the available sources, for instance pictures, drawings, written texts, which can help virtually restore it as far as possible.

The research here presented refers to totally or partially source-based 3D models, thus to reconstructions that remain to some extent hypothetical. Accuracy here derives from the uncertainty degree of the used sources, which is the central issue of this work.

A.3.
Geometry of the model

3D models can be based on different types of geometry, partially depending on the software used, which sometimes gives a range of possibilities in this regard. Nowadays reality-based models are often built starting from a point cloud and then creating a mesh. The most used techniques are, in this case, laser scanning[2] and photogrammetry[3].

It is clear that these procedures cannot be applied to source-based models, where the reconstruction, manly obtained starting from archival documentation, is made through design software that may use different kinds of geometries. Here the main difference is between the use of continuous curves to create the objects (NURBS and curve modelling[4]) or the use of discrete surfaces (polygonal modelling[5]). Other techniques that can be used, alone or together with the previous ones, are object-oriented modelling[6], Boolean modelling[7], digital sculpting[8] and procedural modelling[9]. The 3D model can also be integrated with a conceptual data model through the so-called conceptual modelling, that is

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2 In this technique, a real object is laser-scanned to create a digital representation of it, in a quick process in which, however, the generated geometry has to be cleaned up before use. <https://dreamfarmstudios.com/blog/a-quick-guide-to-3d-modeling/> (accessed 31.10.2024).

3 A camera, in this case, is used to photograph an object multiple times from all angles in an even lighting condition. The collected images are then uploaded to a program that interprets them and generates a 3D representation of the object. <https://artisticrender.com/10-different-types-of-3d-modeling-techniques/> (accessed 31.10.2024).

4 NURBS is a shorthand for non-uniform relational B-spline. This kind of model uses basis splines (B-splines) to represent curves and surfaces and it is suited when a high degree of geometric accuracy is required. <https://dreamfarmstudios.com/blog/a-quick-guide-to-3d-modeling/> (accessed 31.10.2024).

5 This type of modelling builds 3D objects out of smaller components called “tris” (triangles) or “polys” (polygons). Each poly or tri is a flat shape defined by the position of its vertices (or points) and its connecting edges. <https://blog.spatial.com/the-main-benefits-and-disadvantages-of-polygonal-modeling> (accessed 31.10.2024).

6 Object-oriented modelling is based on the manipulation of ready-made components, such as walls, roofs, windows. <https://www.techopedia.com/definition/28584/object-oriented-modeling-oom> (accessed 31.10.2024).

7 Here the geometry of an object is created by taking two objects and making them a new one; either by cutting one out of the other, combining the two, or using the negative space of the intersection as the new object. <https://dreamfarmstudios.com/blog/a-quick-guide-to-3d-modeling/> (accessed 31.10.2024).

8 Sculpting is a process akin to clay modelling, where a digital brush has an influence area and more organically reshapes the geometry based on the brush type and settings. <https://dreamfarmstudios.com/blog/a-quick-guide-to-3d-modeling/> (accessed 31.10.2024).

9 Procedural modelling creates 3D models and textures from sets of rules, instructions, or algorithms. The set of rules may either be embedded into the algorithm, configurable by parameters, or be separate from the evaluation engine. <https://en.wikipedia.org/wiki/Procedural_modeling> (accessed 31.10.2024).

the creation of a database with metadata about the different elements of the model[10]. In this study the used software is based, in some cases, on NURBS, curve modelling and Boolean modelling (*Rhinoceros*), in other cases on polygonal modelling (*SketchUp*); eventually, it has also been translated into conceptual modelling (*CityGML*, through the *CityEditor* plugin for *SketchUp*).

A.4.
Photorealistic and non-photorealistic models (and the audience we refer to)

Photorealistic models are very popular in the entertainment field; however, from a scientific point of view, they are rarely free of subjective interpretations. This is why, if they are used for research purposes, they have to be clearly documented both at a level of modelling and at a level of texturing (Apollonio, Fallavollita, and Foschi 2021).

The choice of the type of model here depends on our goal: it is clear that, if we address to a wide non-specialist audience with products such as movies, games, but also applications for cultural sites that should result appealing and captivating, a higher level of photorealism is required.

Karen Kensek (2007) takes as an example the city of Troy, which, in the collective imagination, is mainly connected to its representation in the 2004 movie.

We must nonetheless remember that there are many different "Troys", among which, first of all, we should mention the city discovered by Schliemann (1872–1874), composed at least of eight different stratifications, and the one described by Homer (8th century BC). Kensek also mentions a reconstruction of Troy that was done, in the same years as the movie, by CERHAS[11] (Center for the Electronic Reconstruction of Historical and Archaeological Sites), composed of a group of archaeolo-

10 This is the case of BIM, HBIM, CityGML. <https://www.ogc.org/standards/citygml>, <https://www.bimframework.info/conceptual-model/> (accessed 31.10.2024).
11 See <http://cerhas.uc.edu/troy/about.html> (accessed 22.10.2024).

gists from the Cincinnati University, even though it has obviously had a minor impact on the public's perception.

Computer visualisation is a powerful tool that can influence a large number of people, who have potential access to a wide selection of representations of the past, but are somehow subject to the intention of the creators of these models, in a field in which «there are big differences between research, education, entertainment and propaganda, but it is not always easy to draw sharp lines between them» (Miller and Richards 1994).

The present study mainly addressed to a public of academics, students and in general people who intend to use digital models for heuristic purposes, asking to which extent a model can be considered likely and accurate, which is the historical period that has been reconstructed, with the aim of potentially making new discoveries. To answer these questions, it is better to focus on non-photorealistic models, because photorealistic ones would be misleading, giving the impression that the reconstructed reality is indubitable.

Conversely, non-photorealistic models might be used to obtain more transparent and replicable reconstructions and to convey more information through the use of several visual techniques.

The models produced during this research have been uploaded to the *DFG Repository*[12] that is being developed by AI Mainz for the dissemination of historical 3D reconstructions. Non-photorealistic representations have been primarily used for this purpose.

A.5. *Scientific approach*

This work focuses therefore on a scientific approach for the documentation and visualisation of source-based 3D models, with the aim of increasing our knowledge. Consequently, these models, as we said in the

12 See <https://3d-repository.hs-mainz.de/> (accessed 30.10.2024).

previous paragraph, should have a heuristic dimension, rather than being just produced for entertainment.

By "scientific model" we generally mean an accurate digital representation of an object; sometimes by "accurate" we mean "authenticated by experts" (Frischer et al. 2000). The scientific approach will be discussed in general in **PARAGRAPH C** and, more specifically related to the hypothetical 3D reconstructions, in **PARAGRAPH C.2**.

In this context «scientificity doesn't mean that the result must be 100% correspondent to the original one, because no matter the efforts and the number of sources the reproduction will always be an approximation of the original artefact. Scientificity means that the process is documented so that any other researcher that follows the same process based on the same sources would end up with the same result. So given this definition we can certainly assert that, yes, photorealistic texturing can be scientifically acceptable as far as uncertainties and subjective conjectures are clearly identified and documented» (Apollonio et al. 2022, draft)[13].

"Scientificity" depends therefore on four main factors: critical analysis of sources, accurate documentation, visualisation techniques and reusability of the model[14] (see **PARAGRAPH C.2**).

A.6. Interpretation

The central topic on which this dissertation focuses is uncertainty. Uncertainty arises in the creation of source-based models, i.e. models of destroyed or never built artefacts, when we have to interpret the sources we have found according to their type, quantity and quality, but also to

13 Apollonio et al., draft of the visualisation chapter of the DFG network book, June 2022.

14 In the description of Jan Lutteroth's dissertation project, they are mentioned as follows: "Der wissenschaftliche Anspruch an die digitale 3D-Rekonstruktion einzelner Bauphasen wird dabei an vier Themenkomplexen festgemacht: 1. Quellenkritik; 2. Dokumentation der 3D-Rekonstruktion; 3. Visualisierungsstrategien; 4. Nachnutzbarkeit der 3D-Modelle". <https://deckenmalerei.badw.de/personen/junge-wissenschaft/jan-eric-lutteroth-ma.html> accessed 30.10.2024.

our knowledge. This leaves some space to subjectivity, which should be limited as far as possible.

The problem that arises reminds the opposition between the sentence by Nietzsche (1901), according to which «there are no facts, only interpretations», which had great success in the postmodern culture (going far beyond the initial declaration by Nietzsche), and the statement by Wittgenstein (1922) defining the world as «the totality of facts», adding that «the facts in logical space are the world» and «the world divides into facts».

A realistic point of view, for which an object exists independently from us, collides with an anti-realistic one, that assumes reality as a cognitive construct that can be subjective or collective.

Anyway, in our field, we are considering a reality that we cannot completely know and that is bound to generate, to some extent, ambiguities – this would be closer to the topics of the more mature production by Wittgenstein (1953). So how do we act when we have to interpret a series of documents related to a past stage of our world?

When multiple (we would virtually say "infinite") interpretations are allowed and it is impossible to choose the best one, the only applicable criteria we can use are grounded on common sense and on the principle of minimum effort: we should limit our useless loss of energy through an economy in reading. There aren't any other ways to grasp the intention of a text, when it is, at the same time, object and parameter of its interpretation.

The principle of minimum effort is also the one that could be accepted by a community of interpreters aiming at reaching some agreement, if not on the best interpretation, at least on the refusal of the obviously unacceptable and unsustainable ones (Eco 1990).

At this point, we can consider more than one acceptable interpretation: this is why uncertainty assessment is an operation that is difficult to standardise. The same element can be differently evaluated depending on the aspects that we tend to privilege or on the scale we use; sometimes we also have to take into account more variants related to a particular element or even to the entire model; when a stratification of phases is present, we should also try to attribute them to different epochs and reconstruct more models related to as much temporal stages. All these choices should be documented in order to declare the extent of subjectivity and in order not to lose the connection between source and reconstruction: in this way transparency can be ensured. This is the reason why documentation of uncertainty is a central topic in source-based digital 3D reconstructions.

B.
AIMS AND METHODS

In 2000 – about ten years after the prediction by Howard Rheingold (1992) – the exploration of virtual worlds was becoming a mass phenomenon. However, the digital reconstructions were made by anonymous creators who didn't consider accuracy or authenticity a primary issue (Frischer et al. 2000).

Frischer et al. (2000) made themselves another prediction, which turned out to be true: «in 2011 there will be a variety of virtual worlds that people will explore through different devices». They also predicted a growth, in the following ten years, of the models made by scholars and researchers for scientific purposes.

This has happened to some extent, but still, after twenty years from that publication, standards for a scientific 3D digital reconstruction are missing.

The general aim of this research is therefore setting some guidelines for the publication of reconstruction projects in the field of cultural heritage, considering them research tools. Consequently, it concerns the creation of a workflow that can lead to the increase of the scientific quality of 3D digital reconstructions. This process has to be documented and accessible in a way that all the choices can be retraced.

This has been discussed since the 1990s, but without reaching uniformity, neither in the terminology used, nor in the process behind the reconstruction.

Moreover, when speaking of hypothetical reconstructions, i.e. reconstructions of buildings that have been destroyed or have never been built, based on different kinds of sources that can be more or less accurate, uncertainty should always be declared. There have been many attempts to do this, but this hasn't become a standard yet.

The state of the art will be analysed according to the notion of uncertainty (starting from terminology issues) and, on the basis of this, a workflow will be proposed to evaluate hypothetical reconstructions, with the aim of publishing them in online platforms and consequently avoiding the creation of digital cemeteries.

Uncertainty is just a part of a wider issue related to the scientific quality of 3D digital reconstructions. Therefore, before focusing on visualisation and classification of uncertainty and on 3D viewers, a brief introduction about challenges, terminology and documentation of these reconstructions is necessary, being this the framework in which this study is included.

C.
MODELS AND REALITY IN THE FIELD OF DIGITAL RECONSTRUCTIONS

When we speak of "models", we refer to 3D digital models for cultural heritage and to the data models embedded. However, it is important to remember that this term is used in a variety of fields (for mathematicians, a model is an equation) and that there are some concepts and definitions that apply to almost all of them, especially those concerning the epistemological difference between models and reality.

It is clear that we have advanced tools for making 3D models, but every model remains an idealisation and, consequently, a "falsification", as Alan Turing wrote (Turing 1952).

Anyway, we should – and we will – focus on the usefulness (Box 1976)[15] of these idealisations. Moreover, it's in this difference between model and reality that uncertainty mostly arises.

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15 We refer to the famous sentence by George Box: «All models are wrong, but some are useful».

The fact that a model will never be as precise as reality is not to be considered a flaw, but rather its primary quality – otherwise, it wouldn't be necessary.

A model only makes sense if it remains a reduction, as two very famous short stories explained (Carroll 1893; Borges 1946):

> "What a useful thing a pocket-map is!" I remarked.
> "That's another thing we've learned from your Nation," said Mein Herr, "map-making. But we've carried it much further than you. What do you consider the largest map that would be really useful?"
> "About six inches to the mile."
> "Only six inches!" exclaimed Mein Herr. "We very soon got to six yards to the mile. Then we tried a hundred yards to the mile. And then came the grandest idea of all ! We actually made a map of the country, on the scale of a mile to the mile!"
> "Have you used it much?" I enquired.
> "It has never been spread out, yet," said Mein Herr: "the farmers objected: they said it would cover the whole country, and shut out the sunlight! So we now use the country itself, as its own map, and I assure you it does nearly as well."
>
> Lewis Carroll, *Sylvie and Bruno Concluded*, Chapter XI, London, 1895

> Del Rigor en la Ciencia
> En aquel Imperio, el Arte de la Cartografía logró tal Perfección que el mapa de una sola Provincia ocupaba toda una Ciudad, y el mapa del Imperio, toda una Provincia. Con el tiempo, estos Mapas Desmesurados no satisficieron y los Colegios de Cartógrafos levantaron un Mapa del Imperio, que tenía el tamaño del Imperio y coincidía puntualmente con él.
> Menos Adictas al Estudio de la Cartografía, las Generaciones Siguientes entendieron que ese dilatado Mapa era Inútil y no sin Impiedad lo entregaron a las Inclemencias del Sol y los Inviernos. En los desiertos del Oeste perduran despedazadas Ruinas del Mapa, habitadas por Animales y por Mendigos; en

> todo el País no hay otra reliquia de las Disciplinas Geográficas[16].
>
> Jorge Luis Borges, *Los Anales de Buenos Aires*, año 1, no. 3, 1946

A model, that is a representation of a selected part or aspect of the world, is essential for the acquisition of scientific knowledge and there is hardly a domain without models (used to describe objects and phenomena such as elementary particles, rational decisions, populations, artefacts, climate…). Through its investigation, a model allows users to form hypotheses about their target system, which exists independently from them (Frigg and Nguyen 2017). Thus, models are simplifications and approximations of the real world and they represent just a fragment of it based on defined criteria and complying with given properties: in this way, the behaviour of a system under certain conditions can be tested and evaluated. First of all, however, if we want to use our models to learn particular features of reality, we have to understand how they work, that is, how they represent.

The idealisation that leads to the creation of a cognitive construct of finite complexity starting from a portion of reality that is infinitely rich in information can occur in different ways[17]:

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16 On Exactitude in Science …In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.

17 Elaborated starting from the concepts explained during the seminar "What is a model? An evolutionary perspective" held by prof. Marco Viceconti at University of Bologna on February 12th, 2021.

(1) It can be of descriptive nature, focusing on the semantic relationships between the model and the object to which it refers;
(2) It can be integrative, based on holistic relationships between connected features;
(3) It can have a predictive function, if it studies and simulates the causal relationships between a series of objects, trying to understand the evolution of a system;
(4) When a model turns out to be successful, it can also become prescriptive: it can be used to prescribe a series of actions, as happens in linear programming, used by managers to decide, as an example, how to optimise time and money.

In our field, the models we refer are primarily of descriptive and sometimes integrative nature, whereas, being oriented towards the past rather than the future, they don't have any predictive function. They can become somehow prescriptive – and this is related to our purpose – when a successful process is standardised and proposed on a larger scale in order to optimise the obtained results and make them comparable on the basis of a scientific method. This can be done to some extent, without being too strict in prescribing a method, but rather a series of good practices.

Models, in this field, are done to study, but also to facilitate the understanding of an object or a phenomenon: they can be 3D models, but also 2D images, diagrams, written texts… and, according to operations research[18], they can be classified by structure as[19]:

(1) Iconic: models that try to be similar to the represented objects, by reducing (or also increasing) their size. It is the operation done with our 3D models, but also with photographs, drawings, maps, etc. They are the most specific and concrete models, aiming to be descriptive rather than explanatory, even though sometimes the boundaries between the two categories are blurred. What we can

18 <https://en.wikipedia.org/wiki/Operations_research> (accessed 31.10.2024).
19 This is just a classification by structure. Other classifications are possible: <https://prinsli.com/classification-of-modelling-in-operations-research/> (accessed 31.10.2024).

say is that, generally, they cannot be used to make predictions and study the evolution of a system;

(2) Analogue: here a model is intended as a set of properties that is used to represent another set of properties. Once obtained a solution, this is reinterpreted in terms of the original system. Examples of this kind of models are graphs used to represent a wide range of parameters such as time, weight, age, etc. In our field, this is used in parametric modelling, but also sometimes to describe the data model behind the actual 3D model (**PARAGRAPH C**), or in ontologies like CIDOC CRM (**PARAGRAPH G**) to connect entities and properties. In this research, graphs have been used in some cases to connect the collected data and study the relationships between them: this can be mainly seen in **PARAGRAPH E**;

(3) Symbolic: a set of mathematical symbols is used to represent the decision variables of a system and to study its behaviour by means of mathematical equations. These are the most general and abstract models. They are usually far from the more specific models with which we work; however, a reduction of the uncertainty levels into numbers, allowing the calculation of the average uncertainty of a model, is an already used technique in our field (Apollonio, Fallavollita, and Foschi 2021) that can be replicated (this operation is attempted in **CHAPTER III**).

Recalling what we have said before, hypothetical 3D digital reconstructions allow the discovery of a building or work of art that we cannot physically see and facilitate the communication of it among a network of interested people. In this context, photorealism is not an essential feature of the model, which privileges the critical analysis of the sources used for the reconstruction: it follows that they are iconic models, but with some analogue and symbolic elements.

3D digital models, as well as experiments that lead to scientific theories, can be (and in our case *should* be) based on the scientific[20] method, composed of the following phases:

(1) Observation of a phenomenon and description of the research questions;
(2) Formulation of hypotheses, through induction (see below), based on observation or *a priori* knowledge;
(3) Repeated experimental tests in a controlled environment to prove the evidence of our hypotheses;
(4) Confirmation (and/or refining) of our hypotheses by predicting a well-known phenomenon independent but correlated; elimination of our hypotheses if they are not confirmed.

The evaluation can take place through different methods. According to Charles Sanders Peirce (1935), three processes have been identified:

(1) Deduction (law-based): the application of solid, general principles;
(2) Induction (based on a collection of examples): the test of statistical assumptions, including the search for false cases;
(3) Abduction (based on "explanatory hypotheses"): a simple suggestion of what may be the explanation of a phenomenon. In other words, when a surprising fact is observed, we make inferences (hypotheses) to merely suggest that certain things may explain that fact. This concept is somehow connected to Bayes's theorem[21], which is used to know the probability that an event occurred, given the final effect. After listing the possible causes and determining the probability that each single one occurs, the probability that this effect occurs everytime is estimated.

20 The need for a scientific approach is also explained in **PARAGRAPH C.2**, where it is more specifically related to hypothetical 3D digital reconstructions; here we refer in general to the use of a scientific method – as firstly devised by Galileo in the 17th century – when reducing reality to any kind of model.
21 <https://en.wikipedia.org/wiki/Bayesian_probability> (accessed 31.10.2024).

In the definition by Peirce, who first introduces the term "abduction", «Deduction proves that something must be; Induction shows that something actually is operative; Abduction merely suggests that something may be»[22].

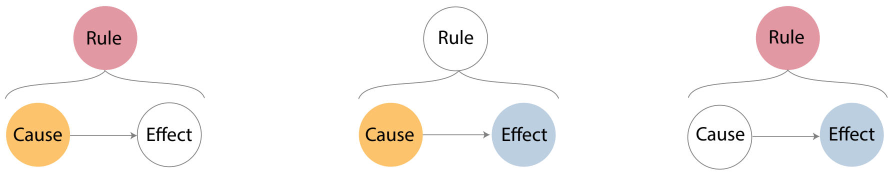

FIG. 1: Deduction: given the rule and the cause, deduce the effect; induction: given a cause and an effect, induce a rule; abduction: given a rule and an effect, abduce a cause. Author's elaboration based on <https://math.stackexchange.com/questions/619311/abductive-vs-inductive-reasoning> (accessed 25.10.2024).

In chronological order, we would say that, first of all, we make an abductive hypothesis. That abductive hypothesis is then followed by an inductive phase in which experiments are done attempting to confirm (or falsify) the initial hypothesis. Finally, the results are put together and, if they are consolidated, they can be used for deductive inference, as happens for scientific theories.

It has been also observed, especially by Karl Popper (1959) and critical rationalism, that there is an asymmetry between confirmation and falsification: lots of experiments cannot prove that a hypothesis is right; a single experiment can prove that it is wrong. Therefore, according to the falsifiability (or confutation) principle by Popper, progress doesn't derive from a collection of certainties, but rather from the progressive elimination of errors, similarly to biological evolution. The more we recognise (and exclude) wrong interpretations, the more we can trace the limits of what we call "truth", without taking it for granted: this is what we try to do with our models.

Creating models has always been part of the architects' work, in many

22 See also <https://www.cantorsparadise.com/c-s-peirce-on-abduction-the-logic-of-scientific-hypotheses-c29bac68cfab> (accessed 31.10.2024).

different forms, from drawings to maquettes: 3D digital models are just one of these possibilities, probably the most common and successful in these days.

This is primarily due to a range of features of 3D digital models, also useful in creating hypothetical representations, which have been listed by Lev Manovich (2001) in the "five principles of new media"[23]:

(1) Numerical representation: all new media are composed of a digital code (representing an image, a written text, a sound, etc.) that can be described mathematically and manipulated through algorithms. New media are therefore programmable: this constitutes a benefit for the communication and reproduction of documents among which our 3D models;

(2) Modularity: this quality has been defined by Manovich «the fractal structure of new media». The discrete samples that compose them (for instance pixels in an image) can be combined to form an object; more objects can be in turn combined to form even larger ones. It is then possible to independently modify these elements and to reuse them in other works. Modularity is also visible in the web structure, with independent sites and pages, each one formed by elements with a code that can be modified. Similarly, digital 3D models are composed of several elements that can be analysed at different levels of detail, according to their semantic segmentation (**CHAPTERS II–III**);

(3) Automation: a process through which users are allowed to create and modify media objects using templates or algorithms, resulting in the fact that creativity lies more in the selection and sequencing of elements than in the elaboration of an original object. An automated technique to create 3D digital models is parametric modelling; in hypothetical reconstructions we can think

23 The connections of the five principles by Manovich with the features of digital 3D models are in large part based on the draft chapter "What is a model?" written by prof. Krzystof Koszewski (University of Warsaw) for the *CovHer Handbook of Digital 3D Reconstruction* (Münster et al. 2024), introduced in **PARAGRAPH C.2**.

of creating in an automated way the parts of the model for which we don't have enough information;

(4) Variability: a new media object is not something fixed once for all, but something that can exist in different, potentially infinite versions. Here structure and content are not necessarily bound together, since a code allowing variability can generate random features. In the same way, digital models allow the creation of a huge number of versions corresponding to as many variants of the "original" one (meaning the first version that was created), a quality that is vital in source-based models, that often admit different interpretations;

(5) Transcoding: this is the most substantial consequence of the transition to digital media. It refers to the translation of new media from a format to another (for instance text to sound) or to the adaptation of content to different devices. In a broader context, it also concerns the way in which culture is being transformed by new media, i.e. the difference between traditional ways of modelling human culture and the means through which computers represent it. These two levels are recognisable also in 3D models, which – at a technical level – can be created with different software and saved in different formats and – at a cultural level – can convey information depending on their target: as an example useful in this field, they can be used for research or entertainment purposes.

Through new technologies and especially processes such as variability and transcoding, the model becomes accessible in different forms and by a potentially wide audience; however, we can understand that it is not automatic to use these (quite automated) techniques for scientific purposes.

Virtual reconstructions are too commonly considered the final step that synthesises the results of research, often without a traceable scientific study behind it: this generates «suggestive representations, suitable for a general public of non-experts», making 3D digital reconstruction an «aesthetic endeavour more than scientific tool» (Demetrescu 2018).

Therefore, there are different – and interconnected – problems that we should try to solve in order to recognise digital 3D reconstructions as research tools in the domains of architecture, art history and archaeology.

These considerations are at the basis – and will allow the development – of a workflow for 3D models based on the evaluation of features such as constructive aspects, accessibility, traceability, visualisation (Apollonio, Fallavollita, and Foschi 2021).

C.1.
Problems in the visualisation of reality

The unavoidable – intrinsic – "problem" of reducing reality to a model has been stated on many occasions, in discussions that initially began in fields such as mathematics and physics, to involve later other domains and processes, among which the 3D digital reconstructions for cultural heritage. We have collected, in this regard, a series of quotations that we present here below.

In the 1990s, the debate mainly concerned statistics and geography, especially in relation to the developments of the Geographic Information System (GIS), as in this case:

> «By definition, reality is continuous, while the observation of reality is discrete. Technology discretises measurement, as for example in satellite image 'snapshots' taken at regular intervals in comprehensive scanning paths. Perception also occurs in discrete 'chunks', is selective and easily masked or distracted. Digital organisation of data requires that models be fitted to observations and measured phenomena […] Because it is not possible to represent continuous phenomena completely, they must be approximated, or sampled as subsets» (Goodchild, Buttenfield, and Wood 1994)[24].

24 This refers, in particular, to the case of Geographic Information Systems (GIS).

Therefore, in the passage from reality to perception and then visualisation, something is lost and gives rise to what we would call "uncertainty":

> «Imperfection, be it imprecision or uncertainty, pervades real world scenarios and must be incorporated into every information system that attempts to provide a complete and accurate model of the real world. But yet, this is hardly achieved by today's information system products. A major reason might be found in the difficulty to understand the various aspects of imprecision and uncertainty. Is there imprecision and uncertainty in the real world? This is an open question. Whatever the answer, it must be recognized that our picture of the world, which corresponds to the only information we can cope with, never reaches perfection. Data as available for an information system are always somehow imperfect» (Smets 1996).

We know that ignorance and limited knowledge are immanent components of an architectural reconstruction and every reconstruction is a process of approaching reality (Heeb and Christen 2019). We can also say, in other – and stronger – words, that

> «All reconstructions carried out through the use of videos, infographics or three-dimensional models are intended to show an illusion, which may be more or less accurate but that in no case will become real» (Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018).

Anyway, the separation between fact and fiction, or "realism" and "magic", can sometimes be vague, as Richard Beacham suggests:

> «The relationship between realism and magic is not always as one might think at first, a straightforward dichotomy of opposites, but can involve as well a rather more subtle cognitive blending of various and ostensibly incongruent mental conceptions (and visual perceptions), and this blending itself has an extensive history in the history of "history" or more accurately, in historiography» (Beacham 2011).

Thus, even though "reality" can't be totally and faithfully recreated, we should try to get close to it and cope with that lack of information and objectivity that has been stated many times (Favre-Brun 2013; Landes et al. 2019). At this point, the concept of "scientificity" becomes relevant.

C.2.
Need for a scientific approach

The mistrust that is sometimes attributed to 3D reconstructions in Cultural Heritage is due to the fact that, as we have already observed, they have been largely used as entertainment tools rather than for their heuristic value, separating architectural representation from architectural scientific analysis (Blaise and Dudek 2004).

However, in recent years, many efforts have been made towards a scientific use of 3D digital models in architecture, archaeology and history of art. The issue has been pointed out by researchers and scholars at least from the 1990s, for example Strothotte et al. (1999) identify two main problems in scientific visualisations, namely the fact that they are too often considered a «correct, objective, and complete representation of the objects in question» rather than «situations in which there is considerable uncertainty associated with some features of a model» and that design decisions are not encoded, whereas «more information about geometric models should be representable and visualizable».

These features seem to be the requisites to define a digital reconstruction "scientific" and avoid the forms of criticism according to which 3D models, especially in fields such as archaeology, are

> «a closed box, with no possibility of evaluation and often without a particular aim, the emphasis being on computer graphics and artistic aspects, rather than on the wish to solve a particular archaeological scientific problem […] 3D modelling and virtual reconstruction are common tools of communicating Cultural Heritage. Many archaeological parks, museums, websites use them, but their contribution is commonly neglected by the archaeological community, as a stage designated for merely presenting

> to the public in a fashionably attractive way the results» (Hermon, Niccolucci, and D'Andrea 2005).

According to Rocheleau (2011) accurate documentation and visualisation is fundamental in order to obtain a "scientific" digital reconstruction. It is not necessary to reach a "complete" visualisation, full of special effects; we could say that it is more interesting, scientifically speaking, to show a "reliable" model, where everything is documented with the possibility of assessing the result:

> «Nowadays, VR models are numerous. However, most of them are mainly focused on showing the complete interpretation of the site, without any additional information, e.g. the reliability of its different components» (Perlinska 2014).

This requires a defined and accepted methodology, involving the presence of documentation in the form of "metadata" and "paradata"[25] and the possibility of validation of the results that should be shared as much as possible.

Moreover, scientific progress – to which also our field is subject – is not the mere application of a method, but, as the scientist Lee Smolin observed[26], the existence of a community of specialists (professionals) guided by common ethical principles, such as:

(1) Declaring the truth, debate, discuss;
(2) When data are not sufficient, encouraging opposition and competition, always without establishing *a priori* new paradigms.

Science is not made of continuous developments, but of discontinui-

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25 See the definition of "paradata" as the documentation of the «decisions made in the course of computer-based visualisation» given in the *London Charter for the computer-based visualisation of Cultural Heritage* (2006).
26 This paragraph has first of all been developed starting from the seminar on "Research assessment" held by prof. Fabrizio Apollonio at University of Bologna in May 2020. See also <https://www.macleans.ca/opinion/democracy-and-science-need-each-other-to-thrive/> (accessed 13.10.2024).

ties (revolutions) and quieter periods, during which a particular scientific community attributes a fundamental value to a set of theories consolidated in the previous years, which becomes a "paradigm" (Kuhn 1962).

The primary role of relationships according to the actor-network theory (Latour 1987) also leads to the consideration that the scientific fact, resulting from the interplay of several subjects and tools, forms a complex network whose mechanism is difficult to analyse (again, a sort of "black box") and in which there is no distinction between science and technology, defining a unique "techno-science". What is more, this domain cannot even be detached from aesthetics, as Gilbert Simondon pointed out with his definition of "techno-aesthetics" (Simondon 2012).

The scientific fact also has a rhetoric dimension that we have to take into account, as stated in the "laboratory studies" (Knorr-Cetina 2001), which analyse the discursive strategies, the representation techniques of the studied objects and the forms of presentation of data.

These are all central elements in our research, which considers, first of all, the social and cultural[27] dimensions of a scientific process that has to be validated, discussed and eventually accepted by a community of experts, knowing that it can always be subject to adjustments and this is the only way to enhance scientific progress. In this context, the work here presented has been developed starting from the discussions inside two international groups:

(1) The *DFG* Research Network *Digitale Rekonstruktion – Digital 3D Reconstructions as Tools of Architectural Historical Research*, in place since 2018[28];
(2) The *CoVHer (Computer-based Visualization of Architectural Cultural Heritage)* project, started at the end of 2021 and coor-

27 The "Science and technology studies" field deals with these topics: <https://en.wikipedia.org/wiki/Science_and_technology_studies>(accessed 13.10.2024).
28 <https://digitale-rekonstruktion.info>; <https://www.gw.uni-jena.de/en/faculty/juniorprofessur-fuer-digital-humanities/research/dfg-netzwerk-3d-rekonstruktion> (accessed 15.10.2024).

dinated by prof. Federico Fallavollita from University of Bologna[29].

These two networks have allowed the exchange between university research groups and members of companies located in different countries, among which Germany, Italy, Austria, Poland, Spain, Portugal, Cyprus.

C.3. Need for a defined methodology and validation tools

The gap between model and reality, or between “interpretation” and “original data” in the case of no longer or partially existing artefacts should be covered, as Apollonio (2015) writes, with «an appropriate theoretical and analytical study of virtual reconstruction practice [...] as well as a methodological approach to display the data-processing behind the 3D modelling practice» enabling «a multidimensional approach to knowledge on several levels». As a consequence,

> «To validate the entire 3D modeling reconstruction process and to facilitate the exchange and reuse of information and collaboration between experts in various disciplines, new standards are necessary, due to the reusability and accessibility of knowledge linked to 3D digital models. For a better interpretation of a digital heritage artifact, a comprehensive interpretive method is needed» (Apollonio 2015).

The problem is highlighted in many studies, which mention the main unresolved questions concerning certification, classification, annotation, storage and visualisation of 3D data sets (Kuroczyński, Hauck, and Dworak 2016), as well as a lack of standards in the production of data also due to the variety of sources:

29 <https://covher.eu/> (accessed 15.10.2024).

> «The first difficulty comes from the fact that there is often a lack of consistent methodology for restitution, mainly because of the lack of a standard in data production […] Indeed, metric data acquired on site might be completed with multitude of historical documents that often have non-metric properties (historical maps, old photographs, drawings, sketches, paintings) as well as archaeological knowledge based on deductions […]. Therefore the quality, accuracy and completeness of restitution depend on the way these heterogeneous data are combined» (Landes et al. 2019).

The heterogeneity of sources generates a range of problems and questions in uncertainty documentation, to which we try to answer in **CHAPTERS II** and **III**, as well as in **APPENDIX 3**, with a handout that has been applied to a particular reconstruction, but whose methodology can be generalised.

C.4.
Need for an approved e-documentation and standards

The primary importance of this issue is witnessed by the fact that, since the 1990s, there have been many calls for an approved e-documentation and validation process (Strothotte, Masuch, and Isenberg 1999; Kensek, Dodd, and Cipolla 2004) to apply to models addressed not only to scholars, but also to the mass.

International standards and guidelines have been developed, starting from the *Unesco* and *Icomos* documents and the *London Charter* (2006), establishing general principles that should be implemented by each specific community.

This has led, for example, in the archaeological field, to the publication of the *Seville Principles* (2011):

> «The application at a global level of the computer-aided visualisation in the field of archaeological heritage shows to date a panorama that could be qualified as of "lights and shadows" […] These projects were useful to demonstrate the extraordinary potential that the computer-aided visualisation en-

> closes in itself, but they also uncovered many weaknesses and inconsistencies. For that reason, starting a theoretical debate becomes unavoidable […] All in all, it is about establishing some basic principles that regulate the practices of this thriving discipline […] The London Charter (<http://www.londoncharter.org>) represents to date the international document that has made the most progress in this direction» (López-Menchero Bendicho and Grande 2011)[30].

Every reconstruction project needs at the same time more general and more particular guidelines, in a "tension between standardisation and customisation" (Gonzalez-Perez et al. 2012). Our intention is therefore to propose, rather than strict rules, a defined but flexible methodology that can be adjusted when necessary.

30 Translation by Irene Cazzaro. Original version: «La aplicación a nivel mundial de la visualización asistida por ordenador en el campo del patrimonio arqueológico presenta a día de hoy un panorama que podría ser calificado como de "luces y sombras" […] Estos proyectos han servido para demostrar el extraordinario potencial que la visualización asistida por ordenador encierra en si misma pero también han dejado al descubierto numerosas debilidades e incongruencias. Por ello se hace ineludible plantear un debate teórico […] En definitiva se trata de establecer unos principios básicos que regulen las prácticas de esta pujante disciplina […]La Carta de Londres (http://www.londoncharter.org) constituye hasta la fecha el documento internacional que más ha avanzado en esta dirección».

C.5.
Need for the dissemination of results

All these requisites, however, will not make sense if the research data remain ephemeral and the 3D reconstruction projects continue to fill the growing digital cemeteries.

Knowledge should not be lost, thus argumentation and reasons should be accessible through documentation environments such as *Sciedoc*[31], developed in 2017, or the already mentioned *DFG repository*, under development, to which we refer in our case study.

Publication in platforms or repositories makes the model interoperable and reusable, with metadata and paradata to reconstruct the process that led to its creation, so that all the choices that have been made remain transparent when shared within a network of academics and interested users.

In the following paragraphs of this introduction we will see how the above-mentioned problems are being tackled, especially through some actions:

(1) Defining standards starting from international guidelines such as the *London Charter* and the *Seville Principles*;
(2) Establishing a shared terminology as the basis for a shared methodology;
(3) Declaring the reconstruction process and its level of uncertainty (this topic will be explored more in depth in **CHAPTER II**);
(4) Documenting and publishing the model: this topic will be just briefly mentioned here, being it the focus of another PhD re-

31 <http://www.sciedoc.org/> accessed on 21/10/2024.

search at University of Bologna, being conducted by Igor Bajena, with whom the author has in large part cooperated.

D.
ATTEMPTS TO DEFINE INTERNATIONAL STANDARDS

We mentioned in **PARAGRAPH C4** the need for standards. In this context, many efforts have been made. Let's see them more in detail.

The *Nara Document* (1994)[32] was applied to physical cultural heritage and especially deals with concepts such as cultural diversity and authenticity. In particular, authenticity has a vital role in the scientific studies and in conservation and restoration operations. It is the essential qualifying factor for the available information sources. Conservation is justified by the value that we attribute to cultural heritage, whose perception depends on the credibility of the information sources, influencing our knowledge, understanding and interpretation.

This document is part of a genealogy of charters on preservation that starts with the *Athens charter* (1931) and the *Venice charter* (1964) and continues with the *Unesco Operational Guidelines for the Implementation of the 1972 World Heritage Convention*.

The *Unesco Charter for the preservation of digital heritage* (2003)[33] and the *London Charter for the computer-based visualisation of cultural heritage* (2006)[34] directly deal with digital cultural heritage. While the *Unesco Charter* generally warns against the risk of losing digital heritage and defines some strategies to select, preserve and protect these documents, the *London Charter* gives a series of (general) indications specifically related to computer-based visualisations.

As explained by the authors, in the *London Charter* general standards are established, dealing with rigour and transparency (Beacham, Denard,

32 <https://icomosjapan.org/static/homepage/charter/declaration1994.pdf> (accessed 29.10.2024).
33 <https://unesdoc.unesco.org/ark:/48223/pf0000179529> (accessed 29.10.2024).
34 <https://www.londoncharter.org/> (accessed 29.10.2024).

and Niccolucci 2006). In this regard, the collection not only of metadata (data about the reconstructed model), but also of paradata (data about the reconstruction process) is a fundamental step in documentation, which is one of the principles discussed there, together with intellectual integrity, reliability, sustainability and access.

The *Icomos Ename* (2008)[35] refers both to tangible and intangible cultural heritage sites, following the spirit of the previous *Icomos* and *Unesco charters*, and it focuses on the concept of interpretation and presentation.

In the *Archaeology Data Service* (2009)[36] the importance of preserving data, not only artefacts, paper and records is stated: this precludes costly re-digitisation in the future and ensures maximum accessibility and reusability of data, in this case obtained using the Dublin Core ontology.

Finally, in this chronology of international charters, the *Seville Principles*[37] follow on from the *London Charter*, of which they are a particular implementation: the concept of computer-based visualisation is in fact here applied to archaeological sites ('Principles of Seville' 2011; López-Menchero Bendicho and Grande 2011).

Although they don't constitute an actual standard (that is still missing and is not the purpose of this kind of document), the general principles stated in these charters have to be taken into account to arrive to the definition of guidelines and of a standard workflow for the source-based 3D digital models.

35 <https://www.icomos.org/images/DOCUMENTS/Charters/interpretation_e.pdf> (accessed 29.10.2024).
36 <https://guides.archaeologydataservice.ac.uk/g2gp/Main> (accessed 29.10.2024).
37 <http://sevilleprinciples.com/> (accessed 29.10.2024).

E.
TERMINOLOGY

The reason that guides the study presented in this chapter is that, to date, there is no uniformity in terminology in digital 3D reconstructions and this can be one of the limits in recognising the potentiality of this tool and its scientific value. We will see this, in particular, in the use of terms related to uncertainty.

As an example, it is sufficient to recall the considerations by Perlinska (Beacham, Denard, and Niccolucci 2006) regarding the words "uncertainty", "plausibility", "probability", "confidence": among these terms, which are often used in an interchangeable way without paying attention to their actual meaning, she would suggest "plausibility" as most suitable one in digital reconstructions, where the chance for the occurrence of an event is not calculated. However, at the end, she prefers using the word "probability" because it is more common in her field of interest.

Therefore, when we deal with establishing some standards, which should be, by definition, widely accepted in a community, the problems related to terminology acquire particular importance and cannot be ignored.

The development of standards depends, to a great extent, on the use of clear and shared terminology, thus an analysis of the occurrence of the most significant words related to digital reconstructions in recent papers becomes necessary.

The papers that have been analysed are written in five different languages (English, Italian, German, French, Spanish), thus an exact translation is possible only to some extent (Eco 2003).

The results of this study have been presented in the Amps Conference, Canterbury, June 2022 and in the UID conference, Genova, September 2022 (Cazzaro 2022, 2023)[38].

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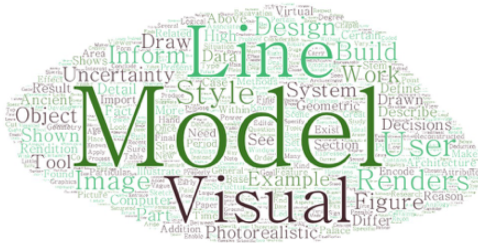
38 This paper was presented at UID (Unione Italiana del Disegno) conference in Genova in September 2022. The same topic was also presented at Amps conference in Canterbury in June 2022 and published in the proceedings in 2023.

Strothotte et al. 1999
Focus on visualisation of 3D models through different line types.

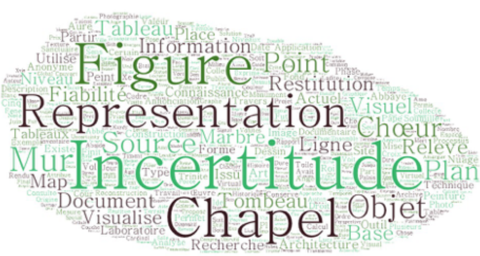


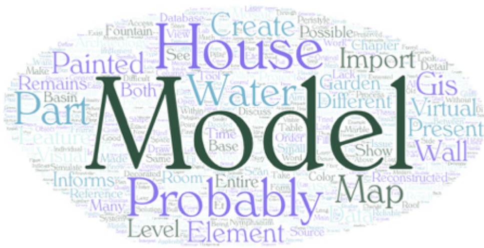
Kozan 2004
Focus on digital reconstructions in cultural heritage, data collection and uncertainty visualisation.

London Charter 2006
Focus on documentation and methods for the computer-based visualisation of cultural heritage.

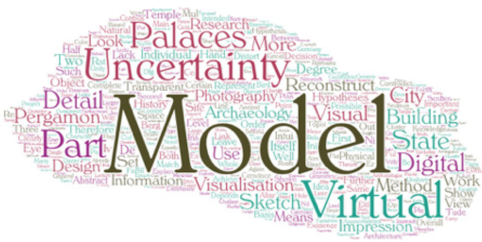
Seville Principles 2011
Focus on documentation, in the light of the *London Charter*, of computer-based visualisations applied to archaeology.

Favre-Brun 2013
Focus on the different solutions for the representation of uncertainty in digital models.





Perlinska 2014
Focus on virtual archaeological reconstructions, the application of a "probability map" and its integration in a geographic information system.



Lengyel and Toulouse 2015
Focus on visualisation of uncertainty applied to architectural structure (with a degree of abstraction), in opposition to realistic simulations.

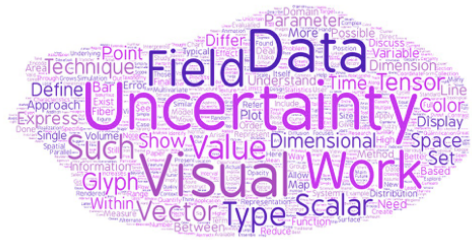
Lengyel and Toulouse 2016
Focus on conventions for the representation of uncertainty in virtual archaeological reconstructions.

Apollonio 2016
Focus on documentation of the process, uncertainty, evaluation of digital models.

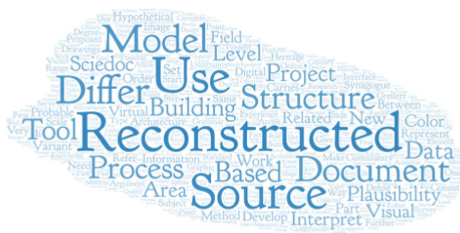
Grellert and Haas 2016
Focus on ways to give scientific relevance to complete models: documentation and uncertainty representation.

Rykl 2016
Focus on pictorial and then digital reconstructions in Bohemia.

Potter et al. 2017
Focus on quantifying and communicating uncertainty in different domains.

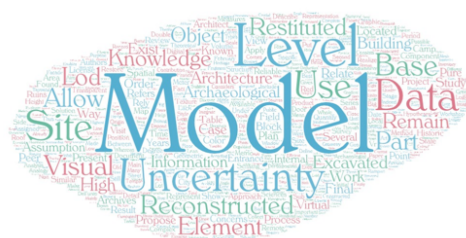


Grellert et al. 2019
Focus on the documentation of virtual reconstructions through the Reconstruction Argumentation Method and the platform "Sciedoc".



Heeb and Christen 2019
Focus on the representation of hypotheses (between fact and fiction) and on the different visualisation methods.

Landes et al. 2019
Focus on two different colour scales to represent uncertainty in two digital reconstructions of castles.



E.1.
Frequency of words

An analysis has been conducted on 27 papers related to the concept of hypothetical reconstruction, published in a period of 25 years.

For the most relevant among them, word clouds have been created on the basis of the most frequent words and, in a second step, the ones related to hypothetical reconstructions have been isolated and put in an Excel table (**TAB. 1**).

As a result, it has been found that "uncertainty" is the most used word followed by "knowledge", "science", "interpretation", "hypothesis". Other words such as "plausibility" and "reliability" are far less frequent, as we can see in more detail in the graph representing the frequency of terms expressing certainty about a reconstruction (**TAB. 2**). Only 13 papers appear in this graph because they were the most relevant for the use of the words mentioned above.

E.2.
Paths: evolution and relationships between words

If we broaden our research, we can try to relate these terms one to another to trace a short history (**FIG. 3**) of each group of words.

There are many paths that can be followed and they can be mainly grouped into these categories: virtual archaeology, visualisation, documentation, authenticity, uncertainty, cultural heritage (**FIG. 2**).

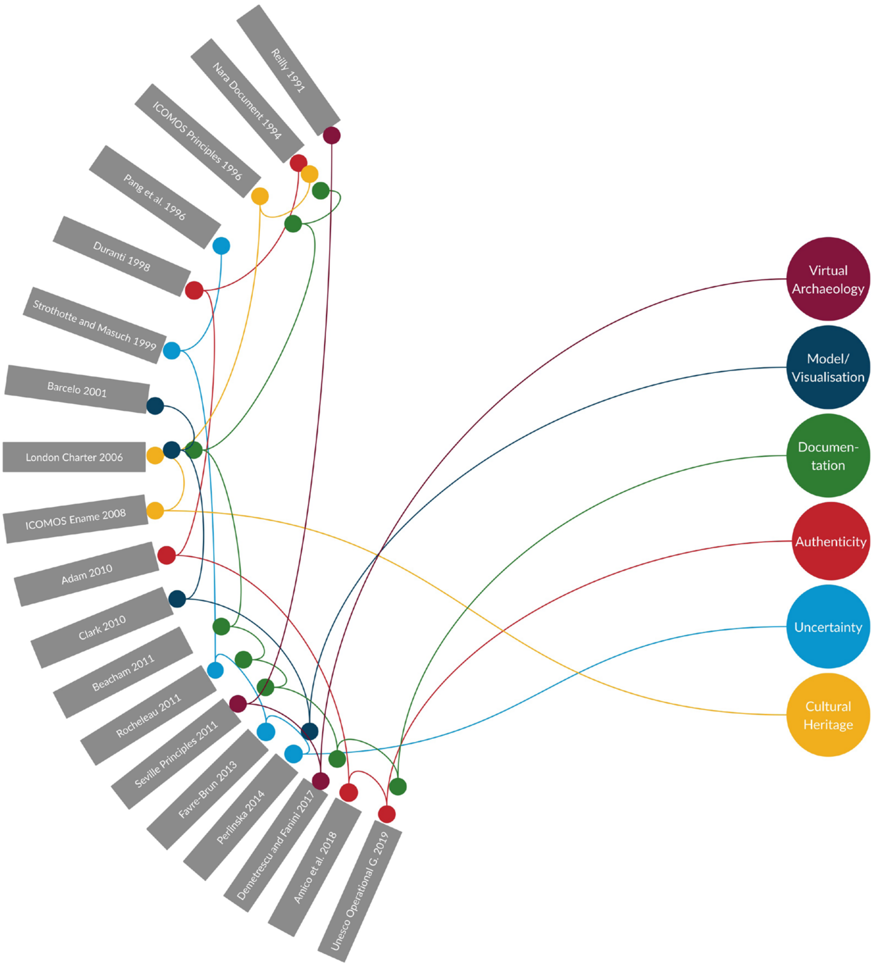
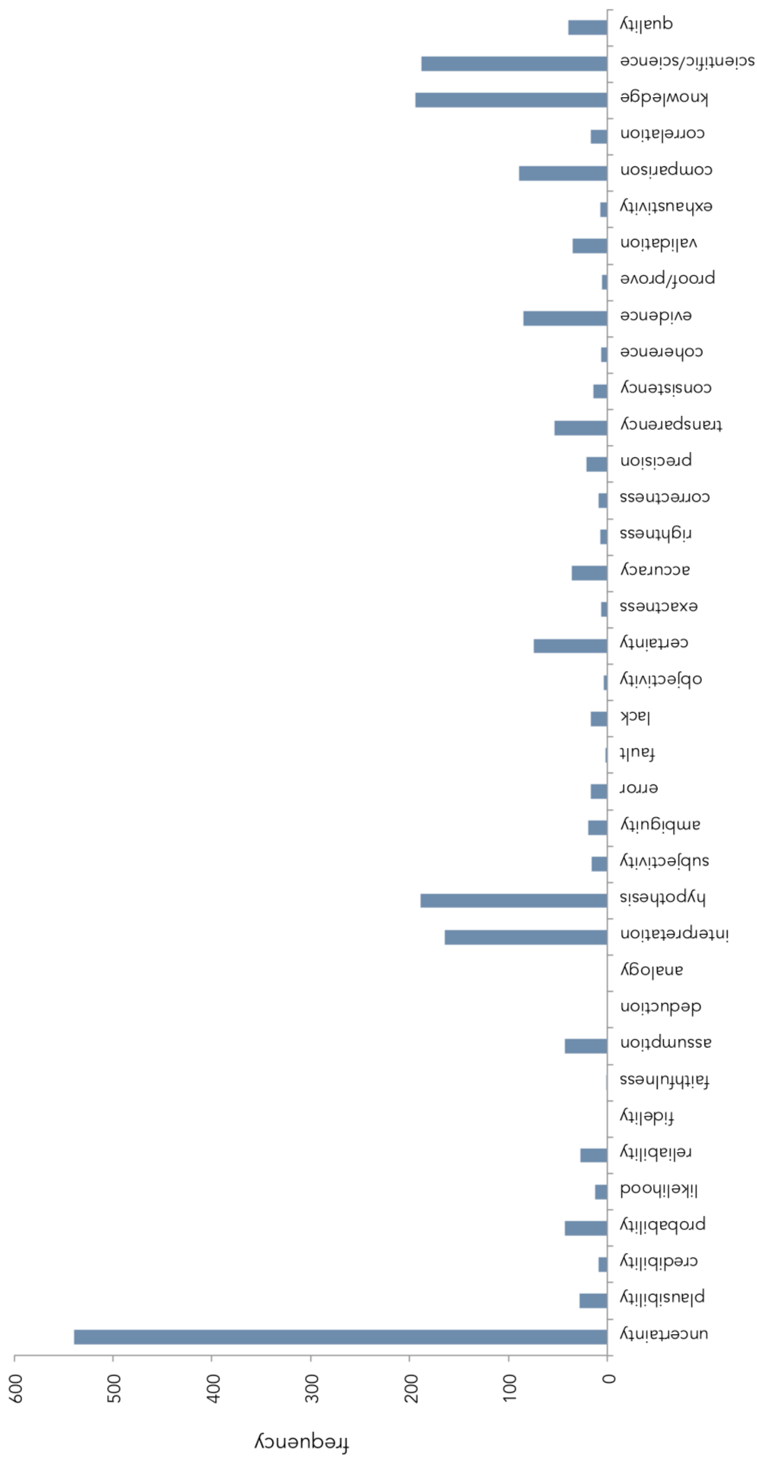
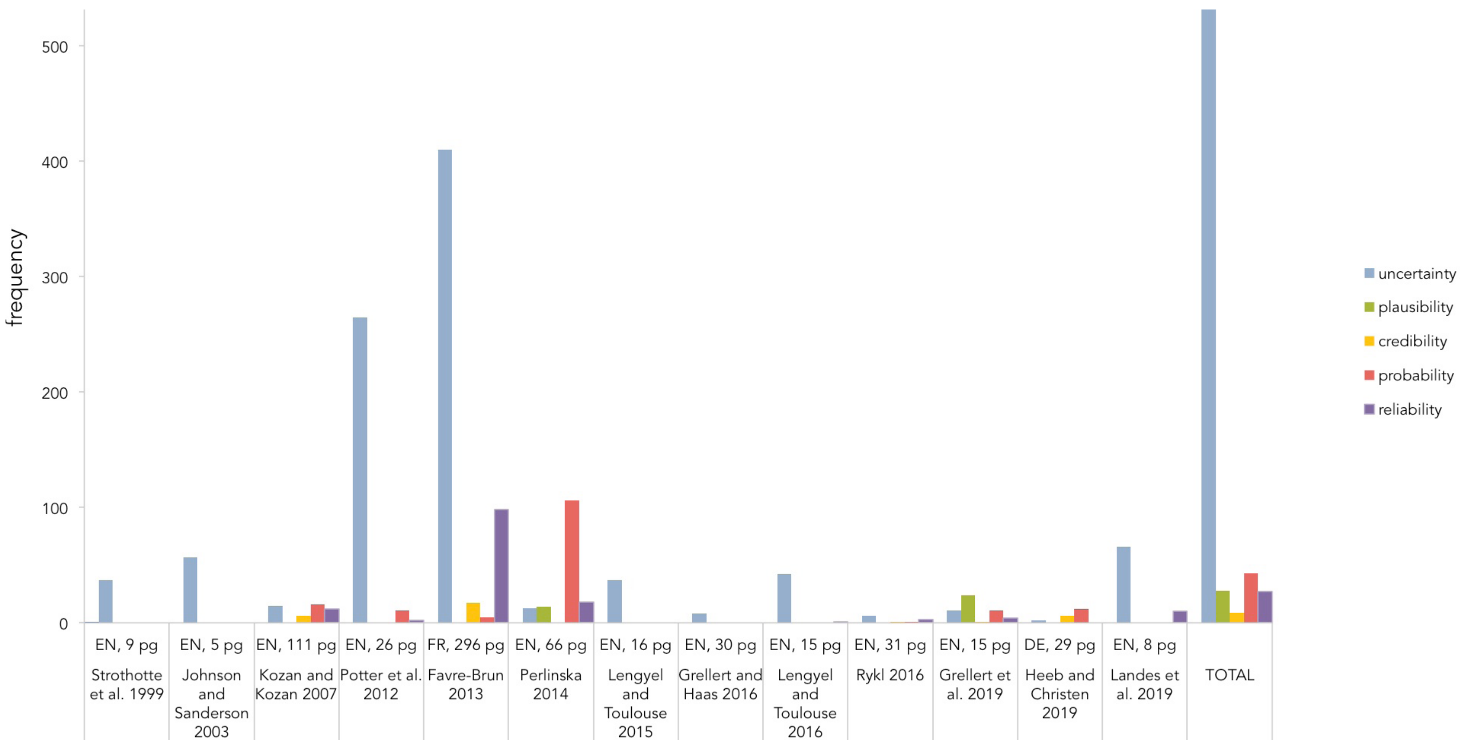


FIG. 2: Categories in which the terms related to a critique of source-based 3D digital models can be grouped. Author's visualisation.



TAB. 1: Frequency of use of words related to hypothetical reconstructions. Author's visualisation.



TAB. 2: Frequency of use of words indicating certainty in hypothetical reconstructions. Author's visualisation.

As an example, by following the cultural heritage path (**FIG. 4**) we can see how this concept is connected to information (or research) sources, conservation, transparency. In this context, the *Icomos* and *Unesco*[39] charters are relevant because they point the attention on the preservation of cultural heritage and they also give the definitions of specific terms, as we can see, for example, in the *Nara Document* (1994) – concerning physical heritage[40] rather than digital models – which defines "conservation" as «all efforts designed to understand cultural heritage» and «ensure its material safeguard» and «information sources» as a list of all the different types of sources that bring knowledge to cultural heritage.

The *Icomos Principles for the recording of monuments, groups of buildings and sites* (1996) give explanations for other related concepts, such as "recording", intended as the «capture of information which describes the physical configuration, condition and use of monuments, groups of buildings and sites», thus quoting again the definition of Cultural Heritage given in the *Nara Document* and, before, in the *World Heritage Convention* (1972), but this time including «tangible as well as intangible evidence». As a consequence, recording can contribute to «the understanding of the heritage and its related values» and is «an essential part of the conservation process».

This is also the scope of the *Unesco Charter for the Preservation of Digital Heritage* (2003), which includes any kind of «information created digitally, or converted into digital form from existing analogue re-

39 This genealogy of documents starts – before the digital era – from the *Athens Charter for the Restoration of Historic Monuments* published in 1931 by the International Museums Office, at the basis of the *International Council of Monuments and Sites* (Icomos), founded in 1965 as a result of the *Venice Charter* (1964).

40 The term Cultural Heritage, in the *Nara Document*, is defined according to article 1 of the *Unesco World Heritage Convention* (1972), thus including: "monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science; groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science; sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view".

sources» which are «frequently ephemeral» despite having «lasting value and significance», constituting «a heritage that should be protected and preserved for current and future generations». Thus, the purpose of the charter is:

> «preserving the digital heritage is to ensure that it remains accessible to the public. Accordingly, access to digital heritage materials, especially those in the public domain, should be free of unreasonable restrictions. At the same time, sensitive and personal information should be protected from any form of intrusion. Member States may wish to cooperate with relevant organizations and institutions in encouraging a legal and practical environment which will maximize accessibility of the digital heritage».

The concept of "research sources" emerging from the *London Charter* (2006)[41] can somehow be related to the one of "information sources" in the *Nara Document*, even though the aim of the former is its application to computer-based visualisations and, in defining "research sources" as «all information, digital and non-digital, considered during, or directly influencing» the creation of a model, it doesn't provide a list of sources, but rather focuses on the effect that can be generated.

In a similar way, "Intellectual transparency" is referred to information that should «allow users to understand the nature and scope of "knowledge claim"» and even "cultural heritage", in the *London Charter*, is defined as «all domains of human activity which are concerned with the understanding of communication of material and intellectual culture», but then some of the domains are listed (museums, art galleries, heritage sites, etc.). This can also be linked to the concept of "cultural heritage site" contained in the *Icomos Ename* (2008)[42] that derives from the previous *Icomos* documents and concerns historically and culturally significant places, localities, natural landscapes, settlement areas, architectural complexes, archaeological sites and standing structures.

41 In relation to the *London Charter*, see also (2018).

42 In relation to the *Icomos Ename*, see also (Beacham, Denard, and Niccolucci 2006; Denard 2012; Georgiou and Hermon 2011; Hermon, Sugimoto, and Mara 2007).

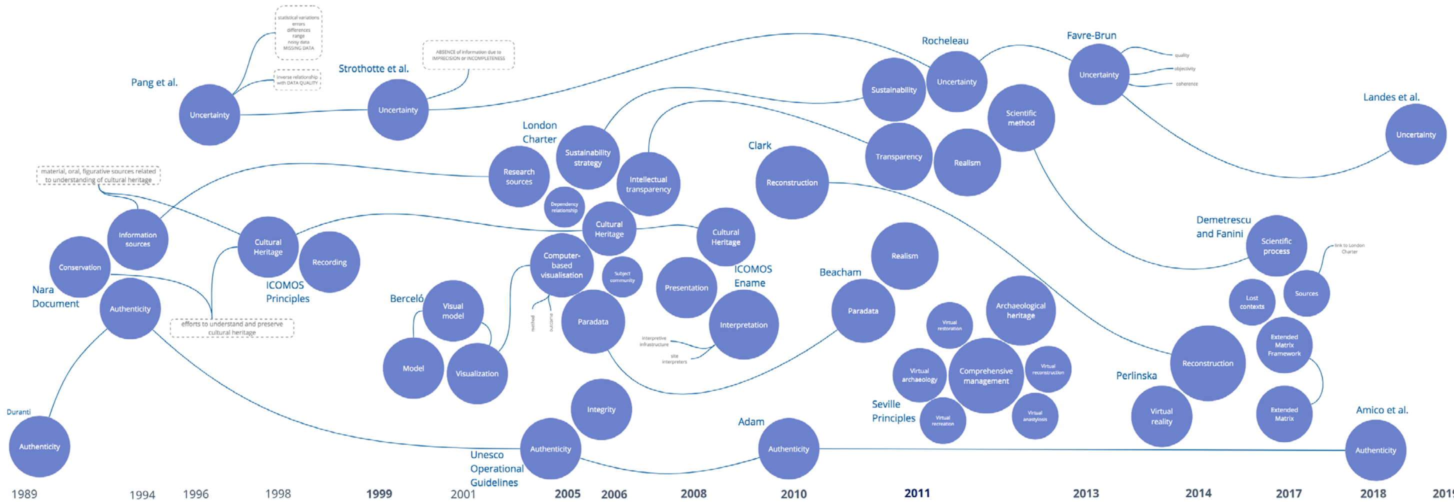


FIG. 3: Connections between terms related to a critique of source-based 3D digital models from 1994 to 2019. Author's visualisation.

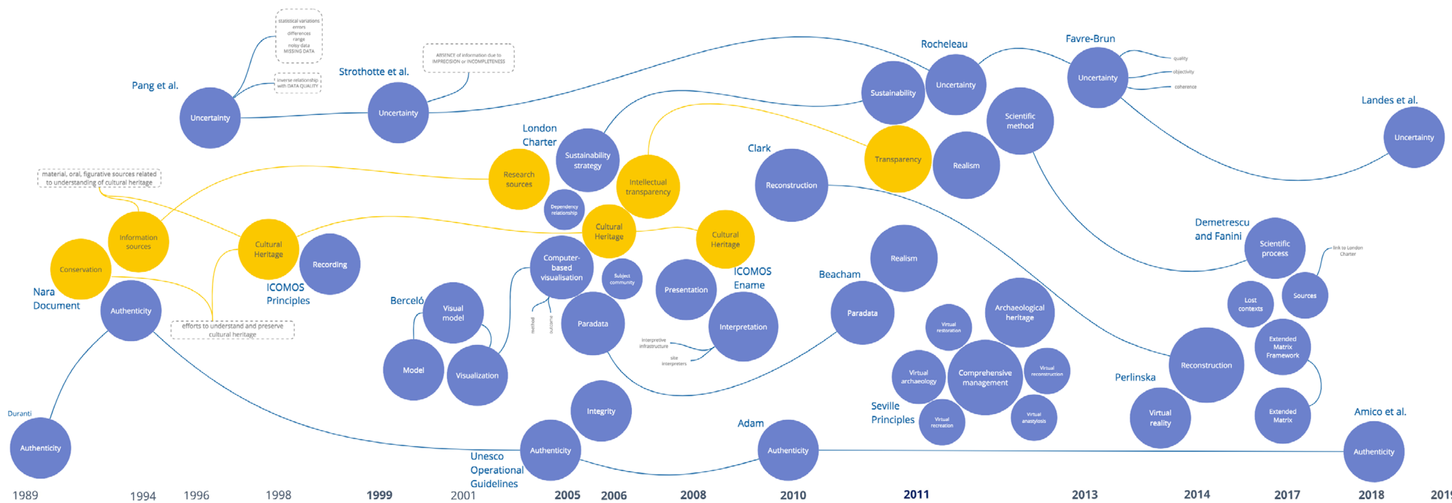


FIG. 4: Evolution in the definitions of terms related to the concept of „cultural heritage“. Author’s visualisation.

Rocheleau (2011) gives another definition of "transparency", after the one given by the *London Charter*: «the capability to consult the sources of every type of work in order to better understand the reasoning of an author and assess its rigour»[43].

The *Seville Principles* (2011)[44] apply to archaeology the guidelines established by the London Charter, therefore, instead of generally speaking of "cultural heritage", they focus on "archaeological heritage": «the set of tangible assets, both movable and immovable, irrespective of whether they have been extracted or not [...] which together with their context [...] serve as a historical source of knowledge on the history of humankind».

The term "authenticity" (**FIG. 5**) mainly appears in *Unesco* and *Icomos* documents[45], according to which it can be assessed based on the «degree to which information sources may be understood as credible or truthful» (Nara document, 1994); this definition is also part of the *Unesco Operational Guidelines for the Implementation of the World Heritage Convention* from the 2005 version[46].

There are more specific definitions of authenticity applied to archival documents and distinguishing legal, diplomatic and historical authenticity (2014).

However, Amico et al. (Duranti 1989; Adam 2010) suggest the use of the word "faithful" instead of "authentic" in relation to digital objects or physical replicas, which are never original and unique, but always copies that can be replicable and modifiable (Benjamin [1935] 2014).

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43 Original version: «la capacité de pouvoir consulter les sources de tout type de travail pour mieux comprendre le raisonnement d'un auteur et attester de sa rigueur».

44 See also the draft at the origin of the *Seville Principles* (Silberman 2003).

45 In the *Charter of Venice* (1964) authenticity is referred to restoration, as in Article 9: "The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents". In the introduction, another concept then included – to some extent – in the *Nara document* is stated: "It is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions".

46 The first version of the *Unesco Operational Guidelines for the Implementation of the World Heritage Convention* dates back to 1972.

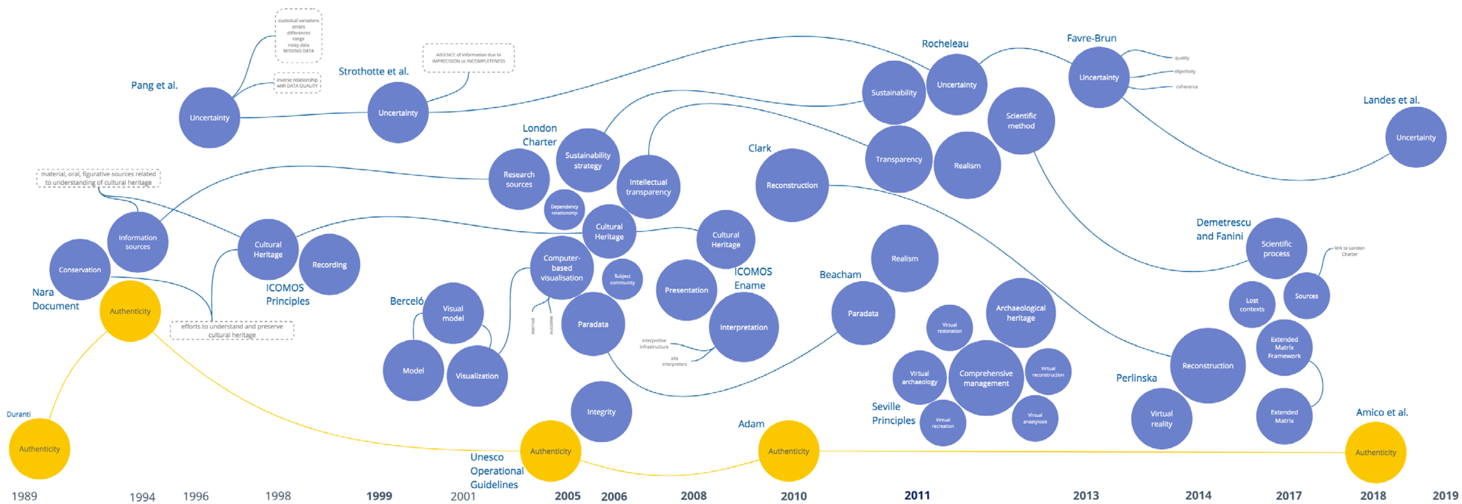


FIG. 5: Evolution in the definitions of the term "authenticity". Author's visualisation.

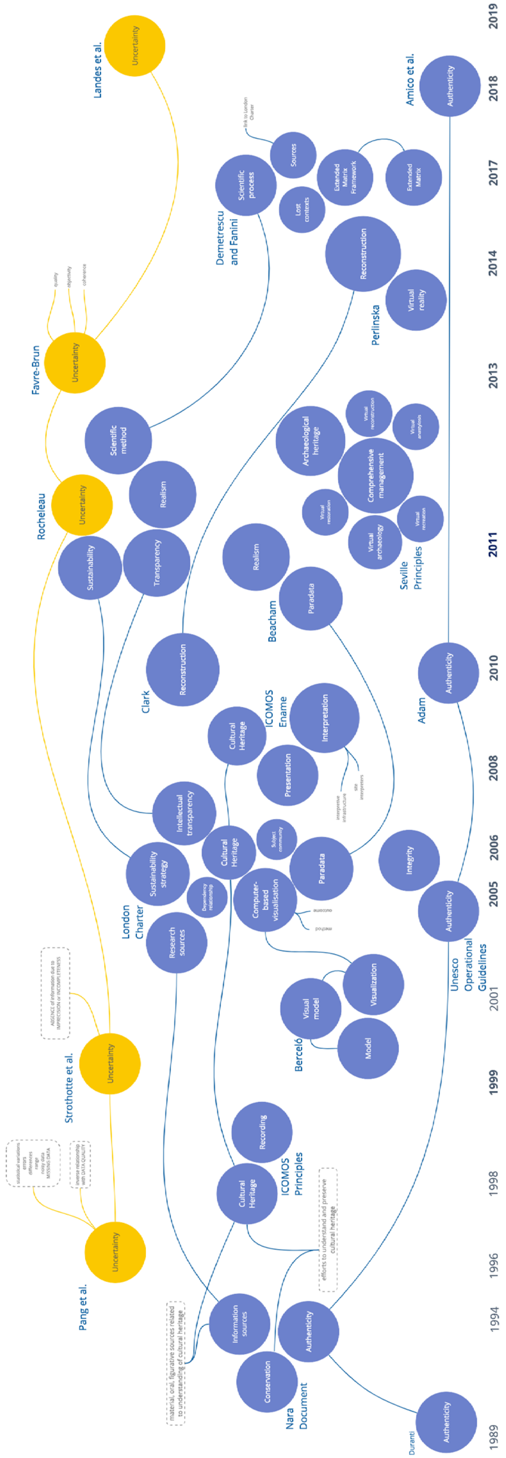


FIG. 6: Evolution in the definitions of the term “uncertainty”. Author’s visualisation.

The path corresponding to the definitions of uncertainty (**FIG. 6**) starts with the papers by Taylor and Kuyatt (1994) and Pang et al. (1996), who give a mathematical definition of it and continues with Gershon (1998), for whom uncertainty is part of the wider concept of imperfection and, as opposed to incompleteness, it represents results that may also be right, but it is not known.

On the other hand, according to Strothotte et al. (1999), imprecision and incompleteness are both part of uncertainty, defined as the absence of information.

Kensek et al. (2004) refer to "ambiguity, evidence and alternatives" for ancient, historic and no-longer-existing environments, thus highlighting the fact that there is no uniformity in terminology. They mention visual tools to indicate "uncertainty levels", but also a console for the users to visualise four "types of reliability".

The absence of uncertainty is listed, according to Blaise and Dudek (2006), among the limits of credibility together with the lack of connection to documentary sources and of dynamic updates when new information elements are collected.

A correspondence with similar terms is also established by Rocheleau (2011), who links transparency and intellectual honesty to uncertainty, the latter being one of the five rules proposed in order to obtain scientific digital reconstructions.

Uncertainty has also been classified in different ways, for example Potter et al. (2012) distinguish "epistemic uncertainty" due to limited data that could, in principle, be known, and "aleatoric uncertainty", which cannot be eliminated and consists, for example, in getting slightly different results each time an experiment is conducted.

Even in digital reconstructions different types of uncertainty can be recognised: Favre-Brun (2013) identifies three main categories related to the quality of information, its coherence and its objectivity.

Anyway, the use of these terms is still questioned and, according to Perlinska (2014), "plausibility" would be the most suitable word, since it «states the possibility of an event to occur, but the chance for it is not calculated» as it is for "probability". "Uncertainty" is, in her opinion, a «misleading word: an uncertainty map shows the level of our certitude, or incertitude» and "confidence" means having «faith in something».

However, at the end she decides to use the word "probability" because it is the most used in her field.

As far as this research is concerned, anyway, we have seen in the previous tables that "uncertainty" seems the most used word related to this context, thus we will focus on that. In more recent works, expressions such as "uncertainty" and "uncertain knowledge" are taken into account to refer to that state «between knowledge on one hand and lack of knowledge on the other hand» (Lengyel and Toulouse 2015), or to the result of missing data in visions of the past (Chandler and Polkinghorne 2016) where it cannot be «defined, quantified and expressed with the help of statistical measures» (Landes et al. 2019).

E.3.
DH/DHS relationships

The relationship between Digital Humanities (DH) and Digital Heritage Studies (DHS) is often discussed (Münster et al. 2019).

By "Digital Heritage", we mean the digital activities connected to the cultural heritage objects, from preservation and research to education (Unesco 2003).

"Digital Humanities" refers to digital technologies for humanities (Gibbs 2011), involving disciplines such as linguistics, codicology, art history, museology, archaeology. It was formerly known as "Humanities computing" and supported by many organisations, among which *Icomos*, besides the main organisation of the area (*ADHO – Alliance of digital humanities organisations*).

The main questions that arise from these two domains are: what are the objects, topics and methodologies; which applications in heritage are related to digital humanities; which are the shared problems and challenges. These definitions are sometimes blurred and, while text-oriented disciplines have defined digital methods, the images and visual objects are not tackled in the same way.

Digital heritage has evolved in a specific field; however, some shared characteristics can still be traced and analysed:

(1) The practical applications with a cross-disciplinary cooperation;
(2) Cultural heritage;
(3) Spatiotemporality.

Here, starting from a list of 60 words[47] – 30 related to DH and 30 to DHS – the connections between them have been studied. It has emerged that it is a dense network of relationships (**FIG. 7**) where the used words are in some cases the same, in some other similar (with a slight difference in the meaning) or referring to the same field.

47 Provided by Fabrizio Apollonio, who collected them based on their use in seminars and conferences.

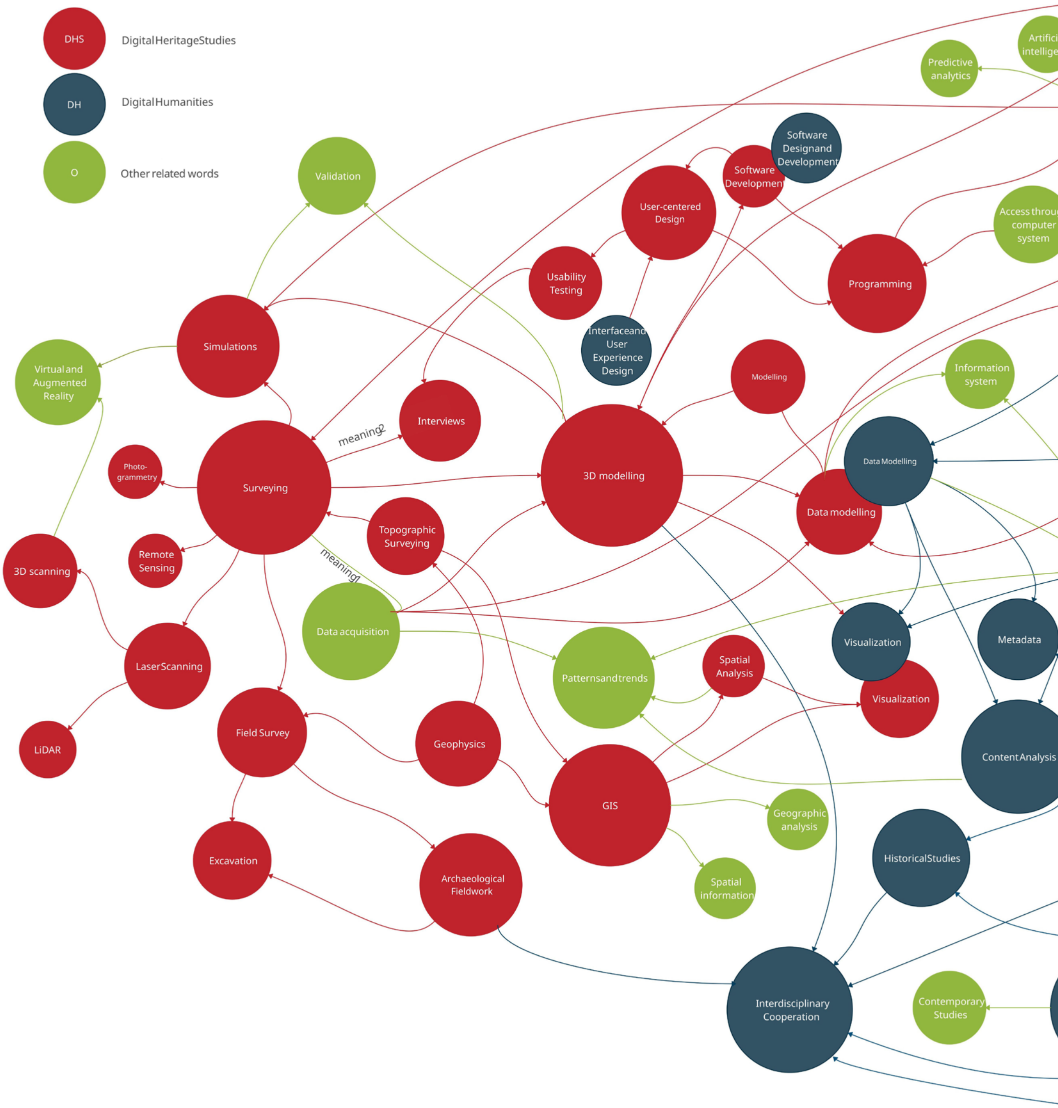
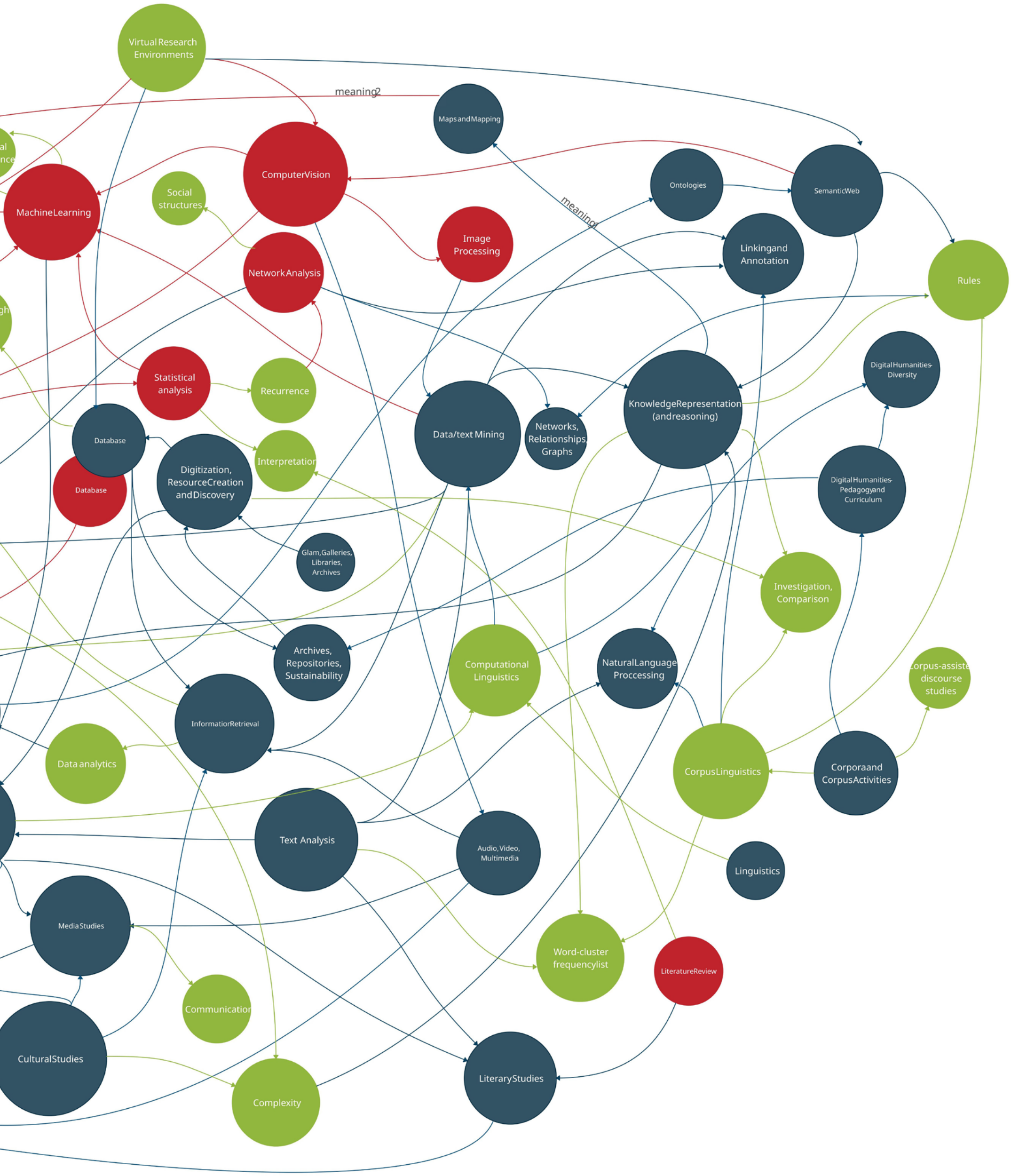


FIG. 7: Connections between terms related to Digital Heritage Studies (red) and Digital Humanities (blue). Other words (green) have been added later to the list in order to complete and strengthen some connections. Author's visualisation.



Virtual Research Environments
meaning2
Maps and Mapping
Computer Vision
Machine Learning
Social structures
Ontologies
Semantic Web
Image Processing
meaning
Network Analysis
Linking and Annotation
Rules
Statistical analysis
Recurrence
Data/text Mining
Networks, Relationships, Graphs
Knowledge Representation (and reasoning)
Digital Humanities Diversity
Database
Database
Digitization, Resource Creation and Discovery
Interpretation
Digital Humanities Pedagogy and Curriculum
Glam, Galleries, Libraries, Archives
Investigation, Comparison
Archives, Repositories, Sustainability
Computational Linguistics
Natural Language Proccessing
Information Retrieval
Data analytics
Corpus Linguistics
Corpora and Corpus Activities
Text Analysis
Audio, Video, Multimedia
Linguistics
Media Studies
Word-cluster frequency list
Literature Review
Communication
Cultural Studies
Complexity
Literary Studies

TAB.3: Relationships identified between terms related to Digital Heritage Studies (left) and Digital Humanities (right)

#	Digital Heritage Studies		Digital Humanities
1	3D modelling	7, 8, 11, 16, 19, 25, 27	Text Analysis
2	Photogrammetry	1, 16	Historical Studies
3	GIS	1, 7, 11, 19, 25, 27	Data /Text Mining
4	Laser Scanning	1, 11, 16, 19	Archives, Repositories, Sustainability […]
5	Interviews	16	Literary Studies
6	Usability Testing	1, 2, 3, 7, 8, 9, 10, 12, 14, 15, 17, 22, 27	Visualization
7	Statistical analysis	7, 11, 19, 27	Corpora and Corpus Activities
8	Computer Vision	1, 11, 15, 19, 23, 28, 30	Interdisciplinary Cooperation
9	Surveying	1, 2, 3, 4, 8, 9, 10, 11 12, 13, 14, 17, 27	Digitization, Resource Creation and Discovery
10	3D Scanning	7, 8, 11, 16, 19, 25	Content Analysis
11	Machine Learning	16, 19	Cultural Studies
12	LiDAR	1, 2, 3, 4, 8, 10, 12, 14, 15, 17, 18, 22	Knowledge Representation
13	Remote Sensing	7, 11	Natural Language Processing
14	Simulations	8, 11, 19, 27	Linking and Annotation
15	Image Processing	1, 5, 6, 20, 23, 24	Interface and User Experience Design
16	Literature review	7, 11, 16	Linguistics
17	Spatial Analysis	8, 11, 19, 25, 27	Networks, Relationships, Graphs
18	Field Survey	1, 19, 27	Metadata
19	Database	1, 7, 11, 19, 25, 27	Databases
20	Software Development	5, 6, 20, 23, 24	Software Design and Development
21	Excavation	8, 11, 25, 27	Digital Humanities - Pedagogy and Curriculum
22	Modelling	8, 11, 25, 27	Digital Humanities – Diversity
23	Programming	1, 3, 8, 14	Audio, Video, Multimedia
24	User-centered design	8, 11, 19, 25, 27	Maps and Mapping
25	Network Analysis	19	Glam, Galleries, Libraries, Archives
26	Topographic surveying	8, 14	Media Studies
27	Data Modelling	7, 11, 16, 19, 25, 27	Information Retrieval
28	archaeological fieldwork	1, 7, 11, 15, 19, 22, 25, 27	Data Modeling […]
29	Visualization	1, 8, 19, 27	Semantic Web
30	Geophysics	1, 8, 19, 27	Ontologies

The most relevant connections between these terms appear to be the following (the colours used in **TAB. 3** have been kept for clarity's sake):

First of all, there are four terms that appear in both columns: "database"/"databases", "software development"/"software design and development", "data modeling"="data modeling", "visualization"="visualization". There is also a close relationship between "network analysis" (which is the discipline) and "networks, relationships, graphs" (which are the tools).

3D modelling, as we know, can be connected to almost every field listed in "digital humanities". The closest ones are: "visualization", "knowledge representation", "metadata", but also "software design and development", "audio, video and multimedia", "data/text mining", "database", "interdisciplinary cooperation", "digitization, resource creation and discovery", "cultural studies".

Photogrammetry (that is connected to many other words in the same column related to survey/field survey such as "3D scanning", "remote sensing", "LiDAR", "spatial analysis") has been connected, in the field of DHS, to "digitization, resource creation, discovery", "visualization", "knowledge representation", "audio, video and multimedia". Maybe it is also close to "interface and UX design" and "software design", but these terms have been primarily considered for their role in the process of creation and visualization of the 3D model (for example in virtual research environment) and the subsequent possibility of information retrieval.

Excavation and topographic surveying are closer to the terms related to survey (listed above) than to terms of the other column.

GIS has <u>not</u> been connected to "maps and mapping" because, in Digital Humanities, is probably referred rather to conceptual maps than physical ones. Maybe it is closer to words from the same column such as "geophysics".

Interviews are connected, in the DHS column, to statistical analysis (that can also refer to the methods of machine learning – maybe this meaning is more important) and they can be important in the creation of widespread software, thus it has been related, in the DH column, to "Interface and UX design" and "software design and development", but also, in the DHS column, to "software development" and "user-centered design".

Usability testing also refers to terms related to software development.

Statistical analysis, in DH, is applied to databases and it has been connected to text analysis, content analysis, data/text mining, visualization, corpora and corpus activities, linguistics and natural language processing, information retrieval and data modeling. Statistical methods can also be used to analyse interviews for software development.

Computer vision and machine learning are applicable to almost all the terms in DH, especially "visualization", "digitization, resource creation and discovery", "text analysis", "content analysis", "linking and annotation", "networks, relationships, graphs", "maps and mapping", "semantic web", "ontology", but it is also close, for example, in DHS, to "3D modeling", "data modeling", "network analysis", "statistical analysis", "machine learning" and "image processing".

Simulations are linked to "digitization", "knowledge representation", "visualization", "audio, video, multimedia", "media studies", but also to "3D models".

Image processing, close to computer vision and machine learning, is connected to "visualization", "knowledge representation" and "data modeling".

Literature review mainly concerns text analysis, content analysis, but it also leads to literary studies, historical studies and cultural studies. It also has something in common with "linguistics", but maybe the latter is used here for the analogy with machine learning procedures.

Databases are what we need for cultural studies, content analysis, text analysis, information retrieval, they are often represented by archives and repositories and they are important in the creation of ontologies and in the semantic web.

A cluster of words is represented by interface and UX design, software development, software design and development, programming, user-centered design, usability testing, visualization, visualization.

Modeling includes "3D modeling" and "data modeling". It can also be related to visualization and knowledge representation.

Network analysis leads to information retrieval, it is applied to databases, thus it leads to data modeling (networks, maps, relationships…), especially through text analysis and content analysis.

Interdisciplinary cooperation is implicit both in "digital humanities" and "digital heritage studies", which combine information technology with history, archaeology, architecture, literature… As an example, we can connect to this term "3D modeling", "archaeological field", "programming"…

TAB.4: Relationships identified between terms related to Digital Humanities (left) and Digital Heritage Studies (right)

#	Digital Humanities		Digital Heritage Studies
1	Text Analysis	1, 2, 3, 4, 6, 8, 9, 12, 15, 18, 19, 23, 28, 29, 30	3D modelling
2	Historical Studies	6, 9, 12	Photogrammetry
3	Data /Text Mining	6, 9, 12, 23	GIS
4	Archives, Repositories, Sustainability […]	9, 12	Laser Scanning
5	Literary Studies	15, 20	Interviews
6	Visualization	15, 20	Usability Testing
7	Corpora and Corpus Activities	1, 3, 6, 7, 10, 13, 16, 19, 27, 28	Statistical analysis
8	Interdisciplinary Cooperation	1, 6, 9, 10, 12, 14, 17, 21, 22, 23, 24, 26, 29, 30	Computer Vision
9	Digitization, Resource Creation and Discovery	6, 9	Surveying
10	Content Analysis	6, 9, 12	3D Scanning
11	Cultural Studies	1, 3, 4, 7, 8, 9, 10, 13, 14, 16, 17, 19, 21, 22, 24, 27, 28	Machine Learning
12	Knowledge Representation	6, 9, 12	LiDAR
13	Natural Language Processing	9	Remote Sensing
14	Linking and Annotation	6, 9, 12, 23, 26	Simulations
15	Interface and User Experience Design	6, 8, 12, 28	Image Processing
16	Linguistics	1, 2, 4, 5, 10, 11, 16, 27	Literature review
17	Networks, Relationships, Graphs	6, 9, 12	Spatial Analysis
18	Metadata	12	Field Survey
19	Databases	1, 3, 4, 7, 8, 10, 11, 14, 17, 18, 19, 24, 25, 27, 28, 29, 30	Database
20	Software Design and Development	15, 20	Software Development
21	Digital Humanities - Pedagogy and Curriculum		Excavation
22	Digital Humanities – Diversity	6, 12, 28	Modelling
23	Audio, Video, Multimedia	8, 15, 20	Programming
24	Maps and Mapping	15, 20	User-centered design
25	Glam, Galleries, Libraries, Archives	3, 10, 17, 19, 21, 22, 24, 27, 28	Network Analysis
26	Media Studies		Topographic surveying
27	Information Retrieval	1, 3, 6, 7, 8, 9, 14, 17, 18, 19, 21, 22, 24, 27, 28, 29, 30	Data Modelling
28	Data Modeling […]		archaeological fieldwork
29	Semantic Web		Visualization
30	Ontologies	8	Geophysics

In **TAB. 4** the relationships have been identified starting from the words pertaining to the Digital Humanities field (the opposite as what had been done in **TAB. 3**; anyway, the information in the two tables corresponds, they have just been reversed).

In **FIG. 7** other connections were discovered, making it necessary to add a number of words that were not part of the initial list. These words, identified by green circles, establish further bridges between concepts, for instance:

(1) "Natural language processing", "corpora/corpus activities" and "knowledge representation" are connected to the added terms "investigations" and "corpus linguistics";
(2) "Information systems" is used to connect "information retrieval" and "data modelling";
(3) "Patterns and trends" has been added to link "spatial analysis", "content analysis" and "data/text mining".

The complete definitions of these terms and the chronology of all the collected definitions can be found in Appendix 1: Chronology of definitions.

F.
METHODOLOGY

A common terminology is the first step to define, subsequently, a common methodology.

This is needed for source-based 3D digital reconstructions if we want to use them as a scientific research tool.

A number of workflows have been proposed (without reaching, by now, a standard), among which:

A. The virtual reconstruction information management modelling (Apollonio 2015), composed of the following phases:

(1) Data collection;
(2) Data acquisition and semantic structuring of the artefact;
(3) Data analysis starting from the documentary sources;
(4) Data interpretation and extrapolation of information about the consistency of the artefact;
(5) Data representation by means of 3D modelling.

The final steps of this process are the semantic enrichment of the 3D model and the validation of the reconstructive hypothesis obtained during the data enrichment stage.

B. The reconstruction pipeline (Demetrescu 2018): it is a workflow for both reality- and source-based models with the aim of obtaining scientific reconstructions, where all information can be stored and traced and where the model is not closed in itself: the presence of incongruities can give rise to new research and adjustments in the model.

The process starts with the collection on the field through survey and/or excavation; then other available archival sources (ancient drawings, photos, information from similar context) are collected; subsequently, all information is organised in the *dossier comparatif*; then *eidotipi*, in the form of sketches and drawings to fix hypotheses, are created before starting modelling; after this step, the 3D model is created.

This seems to be the last phase, but the process is always open to new adjustments. Therefore, the model also works as a simulation to test the quality of research and validate the process (**FIG. 8**).

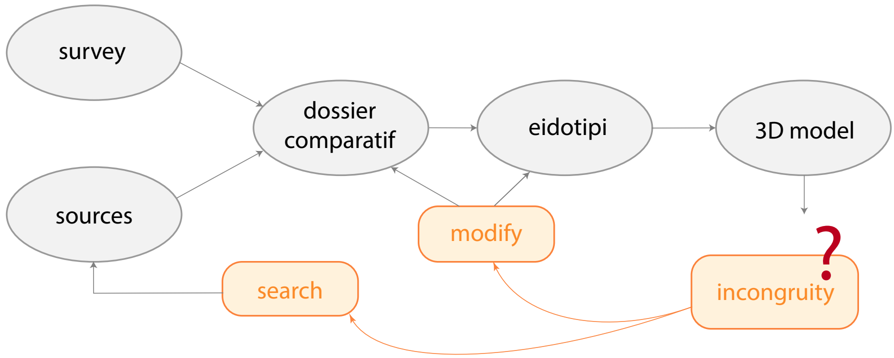


FIG. 8: Workflow for reality- and source-based 3D digital models (author's visualisation based on Demetrescu 2018) composed of the following phases: collection on the field; collection of other available (archival) sources; organisation of the dossier comparatif; creation of the eidotipi; creation of the 3D model, which can continue to influence the previous steps.

The collection of metadata about the reconstructed object and paradata about the reconstructive process, as defined in the *London Charter*, involves a series of actions: the analysis and interpretation of the sources, the documentation of the artefacts, the definition of a methodology (that should be transdisciplinary and, at least, adapt to describe architectural, archaeological and artistic heritage) and the long-term availability of information, in a transparent and comprehensible way (Apollonio 2019a).

These considerations have led to further methodological developments, recently witnessed by two studies that are somehow interrelated:

A. The Critical digital model (Apollonio, Fallavollita, and Foschi 2021) that should have defined qualities concerning:

(1) Constructive aspects: the geometric accuracy of the model;
(2) Traceability: the indication of the used documentation and its relationships with the quality of the model;
(3) Accessibility and interoperability: obtained sharing the models in platforms or repositories and using standard exchange formats;
(4) Visualisation: the way of graphically communicating the scientific content of these models.

B. The Scientific reference model (Kuroczyński, Bajena, Cazzaro, 2023[48]). This will be explained later, as it concerns the case study presented in **CHAPTER III.**

The two studies are considered together in a paper by Kuroczyński, Apollonio, Bajena and Cazzaro (Kuroczyński et al. 2023).

G.
METADATA AND PARADATA IN THE LIGHT OF THE SEMANTIC WEB

The work here presented – focused on terminology and uncertainty documentation and visualisation – is part of a wider research area that involves all the processes that lead to scientific 3D digital models in the cultural heritage domain. In this framework, documentation of the model and of the process leading to its creation is of primary importance.

All these data should then be published online together with the models and should be both human- and machine-readable. Here we refer therefore to the data model behind the digital (iconic) 3D model.

This will eventually avoid the creation of digital cemeteries.

We have created a huge number of 3D models, but many of them are not retrievable because they haven't been uploaded online; among those that have been uploaded online, some of them are in hardly reachable websites rather than in specific platforms; among these platforms, we should choose the ones that better document the reconstructions for cultural heritage purposes, thus complying with particular principles ensuring their scientific documentation. There is not a common standard, but some guidelines and attempts, as we saw before. Thus, we should start from them in order to define a valid methodology.

At the basis of this methodology there is certainly the development of a procedure for 3D documentation of cultural heritage assets. This

48 To be published; presented at CHNT conference in Vienna, November 2022.

should contain the description of all the steps: 3D data acquisition, post-processing, digital recording, documentation, preservation. The structure of the data should be given according to a "standard structure", for instance a metadata schema with project information, cultural heritage asset, digital resource provenance, activity.

Through metadata description, the process can be annotated. While in reality-based models the steps have closed outputs and are not intended to be modified, in source-based models there is an open output that can be re-discovered. From the beginning of the 2000s, tools have been developed to track and manage information especially connected to reality-based model creation, such as CIDOC CRM, CHARM and other metadata schemas for interoperability and dissemination.

Some solutions can be derived from these, but they mainly track the digital life of the model, not their interpretation. There are no standards to annotate the sources used and describe the process. Two approaches can be recognised and should be considered when dealing with metadata annotation: the description and management of the life cycle of the digital resources and the creation of the reconstructive record mentioning the potential events happened in the past (Demetrescu 2018).

Many examples of similar methodologies can be found, for example data can be stored in repositories such as *STARC*, which is connected to *Europeana* (Athanasiou et al. 2013). It helps preserve the digital assets while allowing interoperability.

The definition of accepted standards in documentation is the first step to produce outputs that can be understood by people (considering both an expert and a non-expert audience) all over the world, but data can also be, to some extent, interpreted by machines, thus allowing the creation of a web of interconnected raw data, according to the definition of the semantic web, firstly theorised by Tim Berners-Lee, James Hendler and Ora Lassila in their paper published in the *Scientific American* (Berners-Lee, Hendler, and Lassila 2001).

This innovation is proposed as a step forward in the technological evolution started with the connection of a series of computers through a telephone network. At the beginning, network protocols had to be known, but then, with the Internet and the HTTP protocol, all computers could be connected. With the World Wide Web, the connection began to be considered not between computers but between documents. Linked Open Data are the following step: the connection, in this case, is not between documents, but between raw data. It is an extension of the web, which becomes machine-readable and –understandable: «semantic web gives structure to the contents of the web pages where software agents will be able to read data in a sophisticated way and return information» (Berners-Lee, Hendler, and Lassila 2001).

Five years after this paper, Tim Berners-Lee, Wendy Hall and Nigel Shadbolt investigate the progress made by this technology already used in bots that undertake tasks on behalf of humans, even though they are usually handcrafted only for particular tasks (shopping, auctions…). Anyway, they conclude that semantic web has not failed: "agents can only flourish when standards are well established and […] the Web standards for expressing shared meaning have progressed steadily over the past five years", pointing the attention to the fact that "an incubator community with a pressing technology need is an essential prerequisite for success" (Berners-Lee, Hendler, and Lassila 2001).

The global adoption of a shared semantics and a web of data would be possible through the integration of heterogeneous data sets originated by distinct communities, leading to semantic interoperability, i.e. «the ability to process information from external or secondary sources without losing the actual meaning of information in the development of the process»[49].

The role of incubator communities is then vital to reach a «viral uptake» (Berners-Lee, Shadbolt, and Hall 2006) once automated processes, concept definitions and relationships have been defined, allowing at the same time the continuous adjustment and development of ontologies, which are considered living structures.

Linked data (that remove technological barriers) together with open data (that remove conceptual barriers) lead to the passage from the web of documents (identified by a URL – Uniform Resource Locator) to the web of data (identified by a URI – Uniform Resource Identifier).

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49 Guidelines for the semantic interoperability through LOD, 2013: <https://www.agid.gov.it/sites/default/files/repository_files/documentazione_trasparenza/semanticinteroperabilitylod_en_3.pdf> (accessed 12.08.2024).

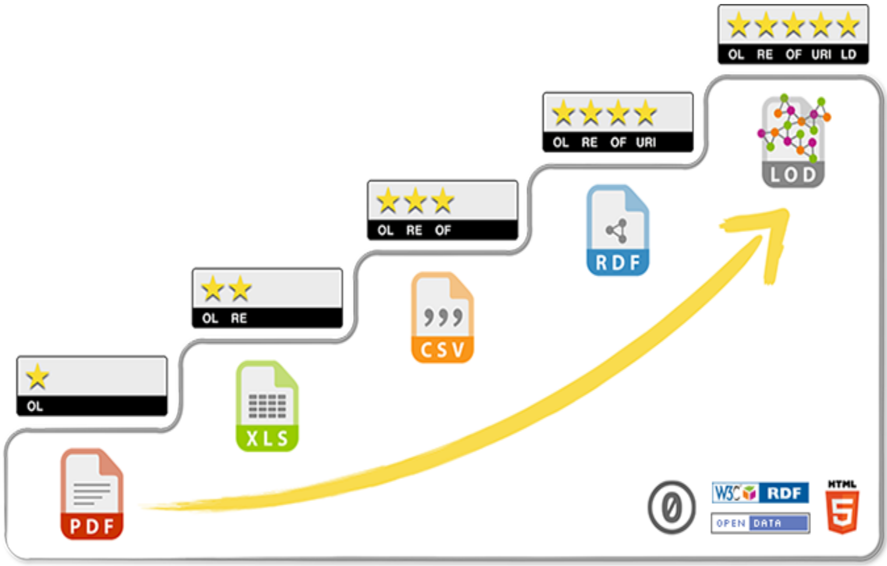

FIG. 9: The five-star model according to Berners-Lee et al. (2006). <https://commons.wikimedia.org/wiki/File:5-star_deployment_scheme_for_Open_Data.png> (Wikimedia Commons, PD).

In order to explain the passage to linked open data, simplifying the access and reuse of information, the "five-star model" (**FIG. 9**) has been conceived (Berners-Lee, Shadbolt, and Hall 2006).

The levels, represented by an increasing number of stars, are explained in this way:

(*) Documents are interpreted by humans through formats such as PDF (Portable Document Format) and are under open licence, ensuring transparency;

(**) Documents are presented in the form of structured data in XLS (Excel Binary File) format, still requiring human intervention; the use of open licence again ensures transparency;

(***) The CSV (Comma-separated values) format, besides the features of the previous level, makes data readable also by machines, even though not interpretable. This leads to open data;

(****) RDF (Resource Description Framework) allows the description of data using ontologies based on statements composed of the triple subject-predicate-object. The process can be interpreted by machines, almost without human intervention; raw data are identified by a URI;

(*****)The "web of data" is generated by the interconnection of data with a semantic description in the form of URIs and readable by computers: this finally leads to LOD (Linked Open Data).

In this framework, the main ontologies and metadata schema used in the Cultural Heritage field are the following ones:

CIDOC CRM[50] – Conceptual Reference Model of the International committee for documentation, developed in the light of a shared understanding of cultural heritage information. It provides a common and extensible semantic framework for evidence-based cultural heritage information;

LIDO[51] – Lightweight Information Describing Objects with an XML harvesting schema, designed to describe museum or collection objects. It is a specific application of CIDOC CRM;

CHML[52] – Cultural Heritage Markup Language, also based on CIDOC CRM;

EDM[53] – Europeana Data Model, an interoperable framework allowing the collection, connection and enrichment of cultural heritage metadata;

Dublin Core[54] – also known as Dublin Core Metadata Element Set (DCMES), consisting of fifteen "core" metadata elements;

X3D[55] - Extensible 3D Graphics, an open standard for publishing, viewing, printing and archiving interactive 3D models on the Web.

CHARM[56] – Cultural Heritage Abstract Reference Model, an alternative to CRM expressed in ConML, a well-defined conceptual modelling language. It is a more abstract model that needs to be extended to fit specific needs (Castano et al. 2021).

We said that, among the shared standards for the documentation of reconstructions, there are some approaches based on CIDOC CRM and

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50 <https://www.cidoc-crm.org/> (accessed 21.10.2024)
51 <https://cidoc.mini.icom.museum/working-groups/lido/lido-overview/> (accessed 21.10.2024)
52 <https://github.com/chml-3d/chml-ontology> (accessed 21.10.2024)
53 <https://pro.europeana.eu/page/edm-documentation> (accessed 21.10.2024)
54 <https://www.dublincore.org/> (accessed 21.10.2024)
55 <https://www.web3d.org/x3d/content/semantics/semantics.html> (accessed 21.10.2024)
56 <http://www.charminfo.org/> (accessed 21.10.2024)

CHML (Cultural Heritage Markup Language), even though they primarily describe physical objects and not the abstract (hypothetical) ones that would as well be useful for virtual reconstructions.

There are studies related to the use of these ontologies to document the data model behind a digital 3D reconstruction (Gonzalez-Perez et al. 2012; Apollonio and Giovannini 2015; Sikos 2015; Kuroczyński, Hauck, and Dworak 2016; Kuroczyński 2017).

Anyway, an extension of the CIDOC CRM would be desirable for the documentation of hypothetical parts of the reconstructions (some examples will be specified in **CHAPTER II**. CRMinf[57], for argumentation and inference making, goes somehow in this direction.

As far as structured terminology for cultural heritage is concerned, we mention, first of all, the *Getty vocabularies*[58], used in the semantic segmentation of the synagogue in **CHAPTER III**.

The integration of data about the Speyer synagogue in *Wikidata* and *Wikipedia* (that is, the generation of a URL and URI accepted by an already established community) can be found in **CHAPTER III** as well.

The aim of these activities is arriving to the transparent publication of the results, improving the «scientific qualities» of research and enabling the «possibility of re-using the raw reconstructive record in outputs such as virtual museums and digital libraries» (Demetrescu 2018).

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57 <https://www.cidoc-crm.org/crminf/home-4> (accessed 21.10.2024)
58 <https://www.getty.edu/research/tools/vocabularies/> (accessed 21.10.2024)

H.
ACCESSIBILITY: PROJECTS AND ONLINE PLATFORMS

Open science and citizen science are increasingly spreading, together with concepts such as open government and open data, which are based on transparency, participation, cooperation.

By “data” we mean the elementary description of information, the elaboration of which leads to knowledge.

Open data are thus data that can be used and redistributed by everybody, quoting the source and keeping a licence of the same type. In order to be “open”, they should be complete, not proprietary, free, rapid, reusable, accessible, researchable, readable by machines, permanent, not biased (Hafer and Kirkpatrick 2009; Suber 2012).

Open licences are increasingly spreading: they protect the author of the data, which cannot be subject to transformations without his approval, but they also give rights to users, who can distribute and manipulate the data to create derived works.

One of the most used and well-known open licences is Creative Commons, which is articulated in six subcategories based on the recognised rights. The conditions for use are indicated by pairs of letters: CC BY, CC BY-SA, CC BY-NC, CC BY-ND, CC BY-NC-SA, CC BY-NC-ND. (Berners-Lee, Shadbolt, and Hall 2006).

CC BY is the most open license, allowing the redistribution, creation of derivatives and publication for commercial activities, provided the credit to the author (BY) and indication of possible adjustments.

CC BY-SA is an open license as well, where the letters SA (share alike) mean that the adjusted work has to be shared under the same reuse rights.

NC (non-commercial use) and ND (no derivative works) are additional conditions for more restrictive CC licenses.

Free access to archives, databases, information about public subjects makes open government a sustainable model also in administrations.

The directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 directly concerns open data and the re-use of public sector information[59] and is based on the previous one (2013/37/UE, 26 June 2013)[60].

Open Data dell'Emilia Romagna[61] and *dati.camera.it*[62] are examples of data collected by Italian institutions and accessible to every user. Open data have been largely collected during Covid-19 pandemic[63] as well.

In our field, accessibility is enabled in projects such as *Archéogrid*[64] (Vergnieux 2005), a collaborative tool developed in France to manage the documentation of digital humanities projects integrating 3D data: annotation, indexing, preservation, safeguard, dissemination. It also includes a national 3D data repository.

Other platforms, such as the ones we will see in **CHAPTER II**, as well as the *DFG repository* that we will use, are conceived to comply with the purposes of open data and open science.

In this context, we just define some useful words in this field:

A "data set" is a collection of data ready to be reused;

An "aggregator" or "catalogue" is a series of data sets;

"Open data" are non-proprietary data to be presented for the reuse in a structured format, accompanied by an "open" licence, which must declare and guarantee the reuse of data without restrictions after their release;

"Interoperability" is the ability of different systems to work together, that is the ability to combine databases. This is at the basis of communication, and it is allowed by open data.

Interoperability, in a wider sense, is the ability of different users to work together on the same data without losing information, which will be the focus of the final part of **CHAPTER III**.

59 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L1024> (accessed 19.10.2024).
60 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013L0037> (accessed 19.10.2024).
61 <https://dati.emilia-romagna.it/> (accessed 18.10.2024).
62 <https://dati.camera.it/> (accessed 17.10.2024).
63 < https:// www.arcgis.com/apps/dashboards/b0c68bce2cce478eaac82fe38d4138b1> (accessed 17.10.2024).
64 <https://www.archeogrid.fr/> (accessed 18.10.2024).