Digital 3D reconstruction as a research environment in art and architecture history

Uncertainty classification and visualisation

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SPECIALISED INFORMATION SERVICE ART · PHOTOGRAPHY · DESIGN

Digital 3D reconstruction as a research environment in art and architecture history

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A model is a simplification and an idealization,
and consequently a falsification.

ALAN TURING
The chemical basis of the morphogenesis (1952)

contents

preface

The dissertation addresses the still not solved challenges concerned with the source-based 3D reconstruction, visualisation and documentation in the domain of archaeology, art and architecture history.

The emerging BIM methodology and the exchange data format IFC are changing the way of collaboration, visualisation and documentation in the planning, construction and facility management process. The introduction and development of the Semantic Web (Web 3.0), spreading the idea of structured, formalised and linked data, offers semantically enriched human- and machine-readable data.

In contrast to civil engineering (BIM/IFC) and cultural heritage (CIDOC CRM), academic object-oriented disciplines, like archaeology, art and architecture history, are acting as outside spectators. Since the 1990s, however, it has been argued that a 3D model is not likely to be considered a scientific reconstruction unless it is grounded on accurate documentation and visualisation (Strothotte, Masuch, and Isenberg 1999; Kensek, Dodd, and Cipolla 2004).

Thus, there have been many calls for an approved e-documentation related to 3D reconstruction projects and addressed to the mass, but these standards are still missing and the validation of the outcomes is not fulfilled. Meanwhile, the digital research data remain ephemeral and the 3D reconstruction projects continue to fill the growing digital cemeteries.

This study focuses, therefore, on the evaluation of the source-based 3D digital reconstructions and, especially, on uncertainty assessment in the case of hypothetical reconstructions of destroyed or never built artefacts according to scientific principles, making the models shareable and reusable by a potentially wide audience.

In particular, the main questions that are here analysed are:

(1) How can we express the scale and levels of uncertainty in the visualisation of the (human- and machine-readable) data model?
(2) What kinds of tools do we have to make uncertainty data shareable and interoperable?

These are interrelated questions that lead, first of all, to the exploration of the attempts to define a series of standards for 3D models, from the *Nara document* (1994) to the *London Charter* (2006) and the *Principles of Seville for archaeological 3D reconstructions* (2011). To achieve this result, on the basis of these documents, some rules (or good practices that have been or should be applied) have already been defined and they mainly concern authenticity, transparency, uncertainty representation, sustainability ('The London Charter' 2006; Rocheleau 2011).

Authenticity is often confused with photorealism, and thus the abundance of detail; conversely, it should refer to historical accuracy and data fidelity, based on physical, written or iconographic sources. As a result, a model of a destroyed or never built artefact remains, in some respects, an interpretation: this means that, instead of being considered a final representation, it should retain the possibility of being adjusted by other users. Consequently, the transparency of a model becomes a significant issue: the sources and the methodology adopted in the reconstruction should be accessible, in the form of "metadata" associated with the model, ensuring that the decisions that led to it can be reconstructed and the scientific validity can be assessed.

The comparison of a certain number of documents may sometimes result in the formulation of different reconstruction hypotheses and, thereby, in the introduction of a method to visualise these alternatives by attributing to each one of them a level of uncertainty, in other words, a measure to indicate certainty about a reconstruction.

However, there is still a lack of uniformity, for instance, in the terminology and in the scale of values used to visualise this "uncertainty", which is also (less frequently) defined with the words "plausibility", "reliability" or even "probability".

Many different strategies have been adopted to identify the levels of uncertainty (Kensek 2007; Apollonio 2016), for example acting upon the different curvature, sharpness or detail of lines (Strothotte, Masuch, and

Isenberg 1999; Potter, Rosen, and Johnson 2012), applying optical transparency (De Luca et al. 2010), wireframe (Kensek, Dodd, and Cipolla 2004), the superimposition of a schematic rendering on a photorealistic one (Zuk, Carpendale, and Glanzman 2005), different colour scales (Dell'Unto et al. 2013; Grellert et al. 2019; Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018; Landes et al. 2019). These different strategies will be discussed and validated.

Furthermore, the application of these three principles (authenticity, transparency, uncertainty) will only make sense if our models, instead of filling digital cemeteries, are shared among people according to the principle of sustainability. In this framework, virtual research environments are becoming increasingly important because they allow users to upload their models (with metadata and paradata) online, where they can be visualised, shared, adjusted by other users, with a view to promoting not only open access and citizen science, but also the use of Linked Open Data, which should be readable by humans and machines through systems of data sharing such as BIM/IFC and according to the concept of Semantic Web (Berners-Lee, Hendler, and Lassila 2001).

The proposed work will initially focus on terminology and on the definition of a workflow especially related to the categorisation and visualisation of uncertainty in hypothetical 3D digital reconstructions. The workflow will then be applied to specific cases of 3D models uploaded in the DFG repository that is being developed by AI Mainz. In this way, the available methods of documenting, visualising and communicating uncertainty will be analysed.

In the end, this process, which is being discussed in international networks, will lead to a validation or a correction of the workflow and the initial assumptions, but also (dealing with different hypotheses) to a better definition of the levels of uncertainty.

This study will be conducted keeping in mind that a model is "a simplification and an idealization, and consequently a falsification" (Turing 1952); anyway, as the statistician George Box wrote, "all models are wrong, but some are useful" (Box 1976).

November 2024

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.

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

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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

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-

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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.

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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].

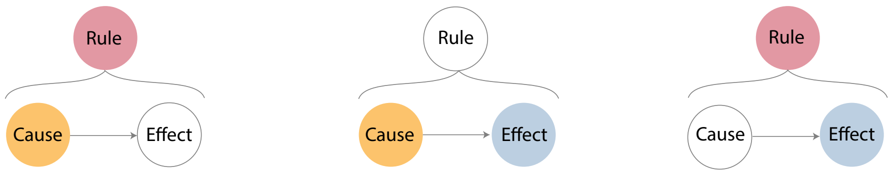

FIG. 1: Deduction: given the rule and the cause, deduce the effect; induction: given a cause and an effect, induce a rule; abduction: given a rule and an effect, abduce a cause. Author's elaboration based on <https://math.stackexchange.com/questions/619311/abductive-vs-inductive-reasoning> (accessed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

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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-

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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,

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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 re-usability 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.

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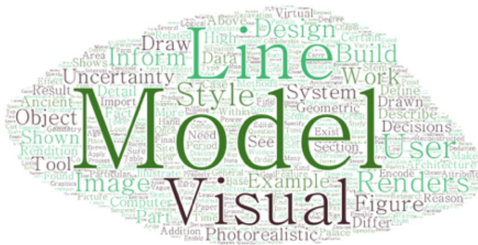
38 This paper was presented at UID (Unione Italiana del Disegno) conference in Genova in September 2022. The same topic was also presented at Amps conference in Canterbury in June 2022 and published in the proceedings in 2023.

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

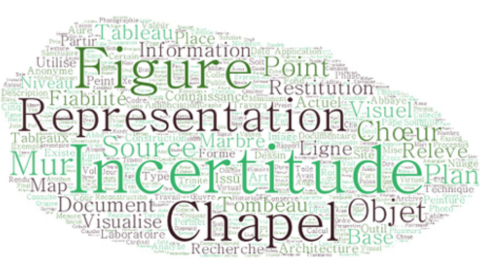


Kozan 2004
Focus on digital reconstructions in cultural heritage, data collection and uncertainty visualisation.

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

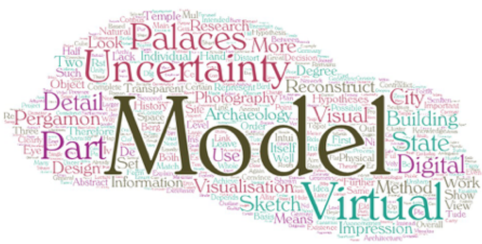
Seville Principles 2011
Focus on documentation, in the light of the *London Charter*, of computer-based visualisations applied to archaeology.

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.



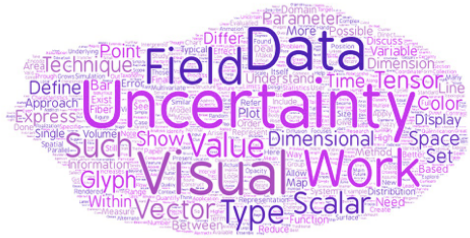
Lengyel and Toulouse 2016
Focus on conventions for the representation of uncertainty in virtual archaeological reconstructions.

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

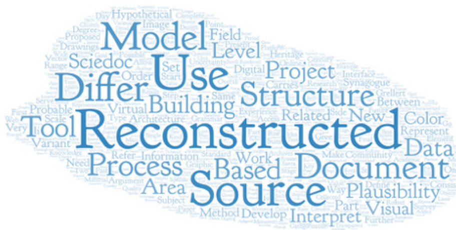
Grellert and Haas 2016
Focus on ways to give scientific relevance to complete models: documentation and uncertainty representation.

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**).

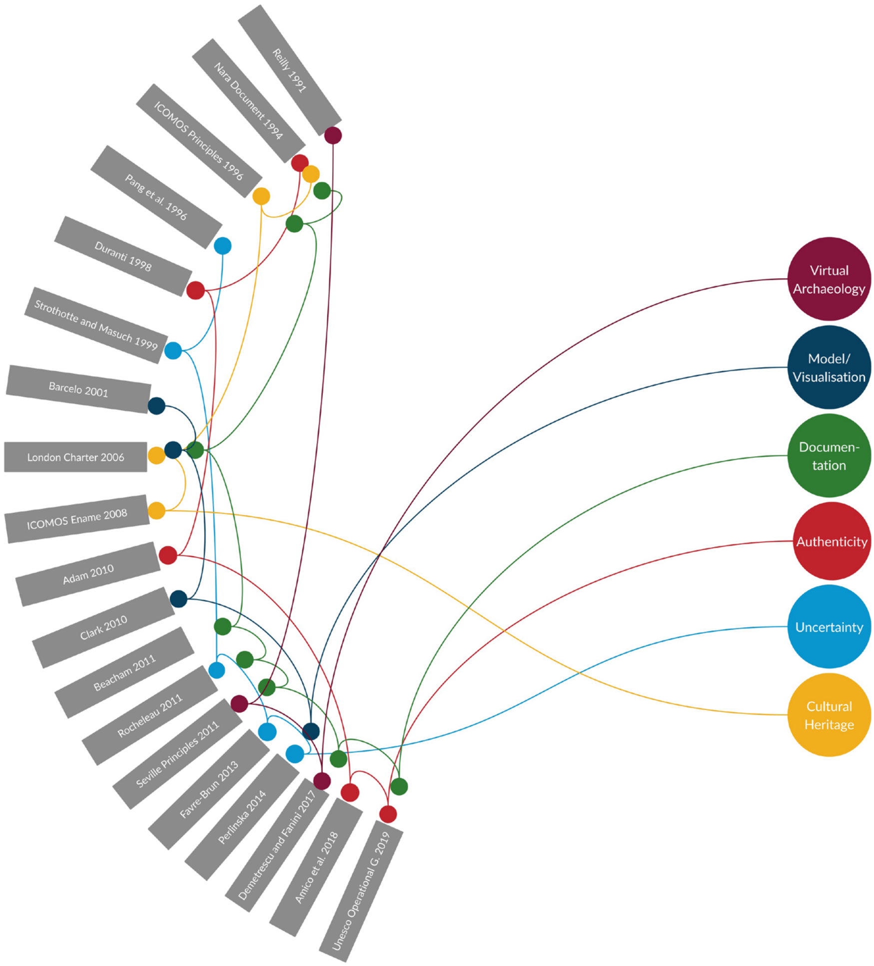
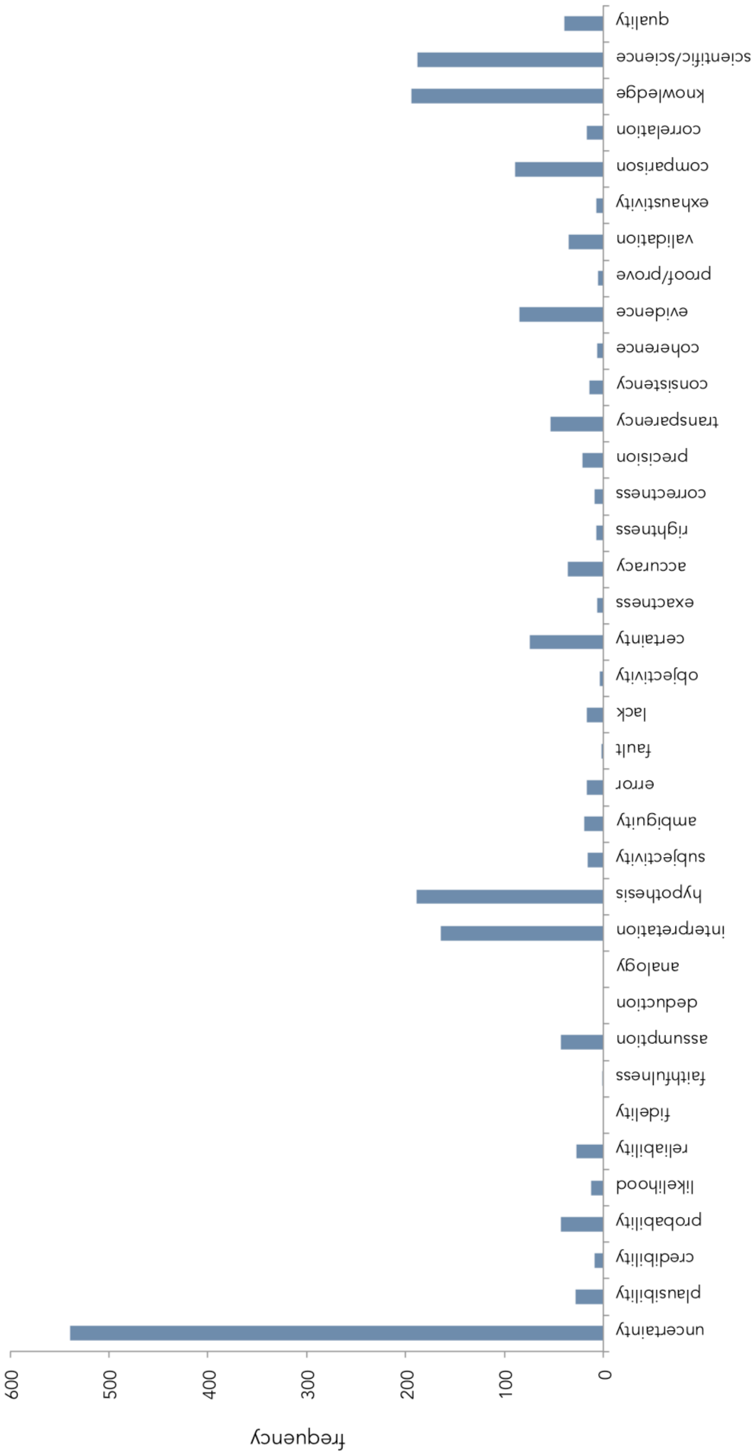
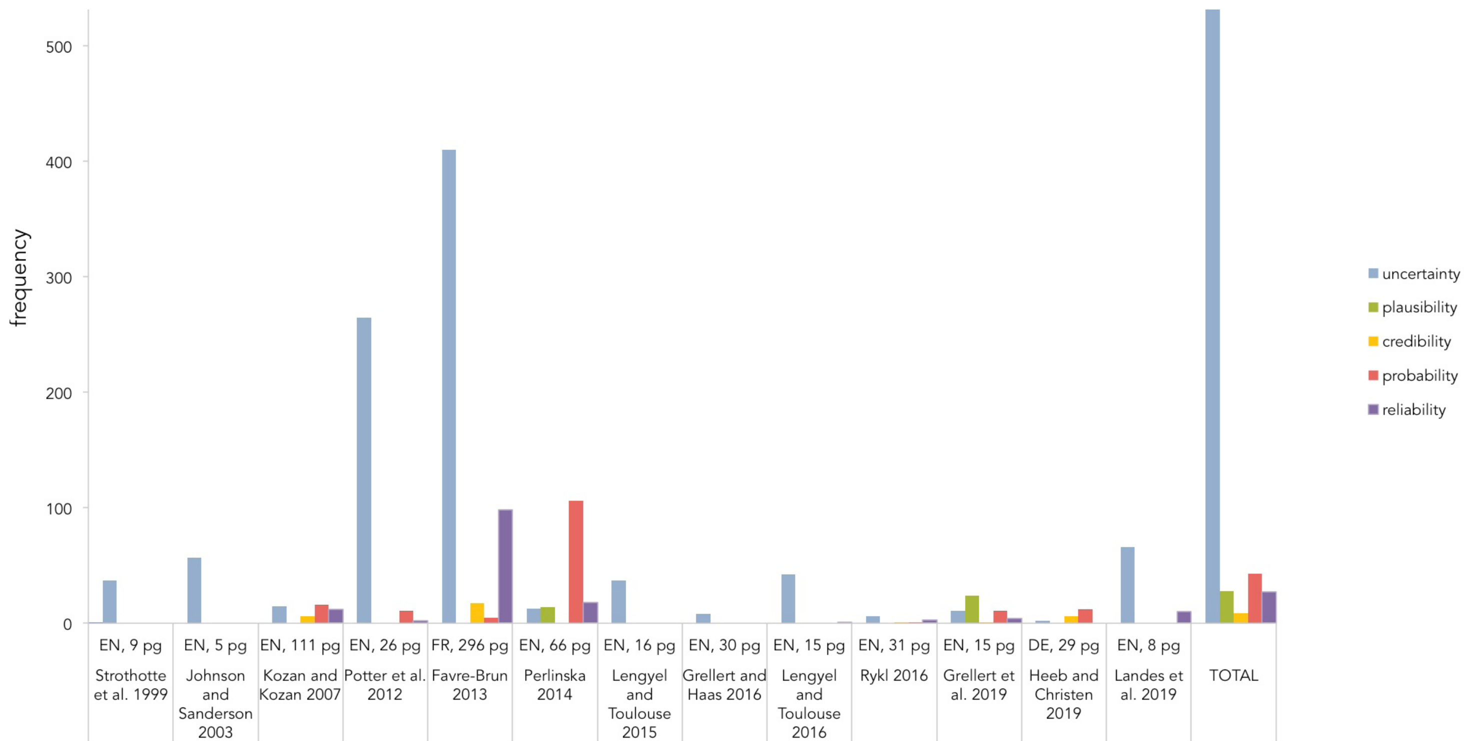


FIG. 2: Categories in which the terms related to a critique of source-based 3D digital models can be grouped. Author's visualisation.



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-

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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).

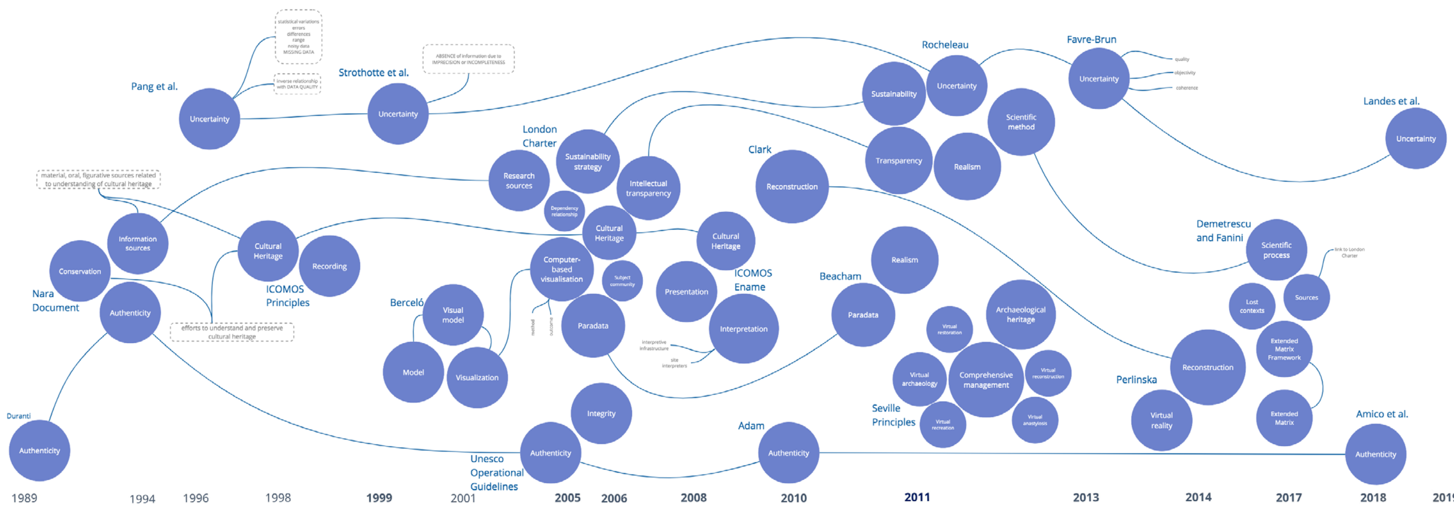

FIG. 3: Connections between terms related to a critique of source-based 3D digital models from 1994 to 2019. Author's visualisation.

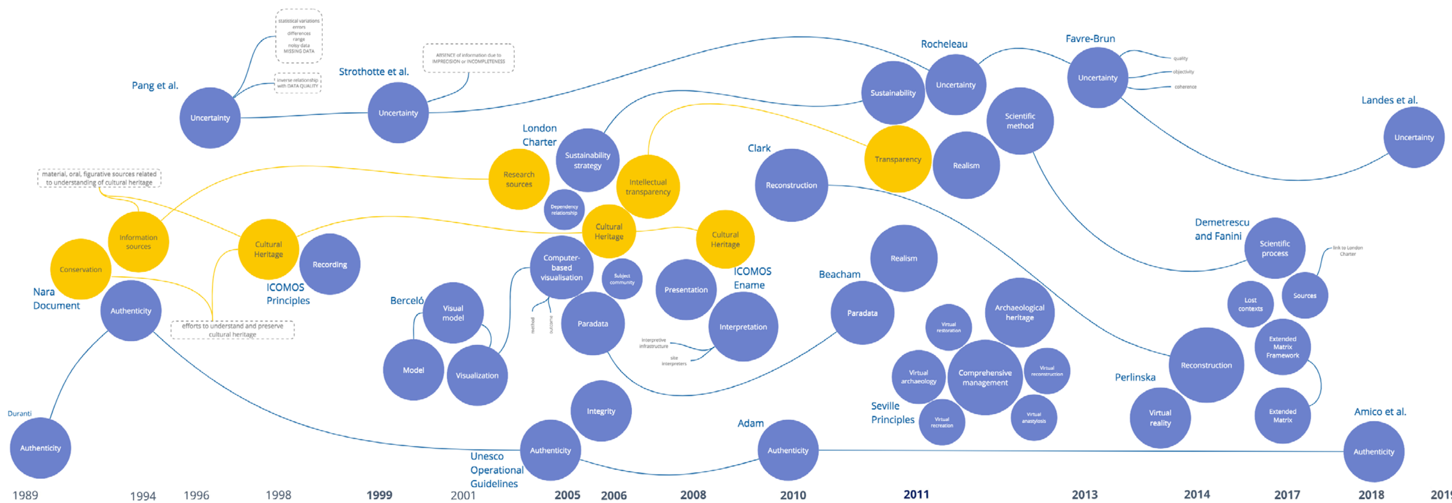

FIG. 4: Evolution in the definitions of terms related to the concept of „cultural heritage“. Author’s visualisation.

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.

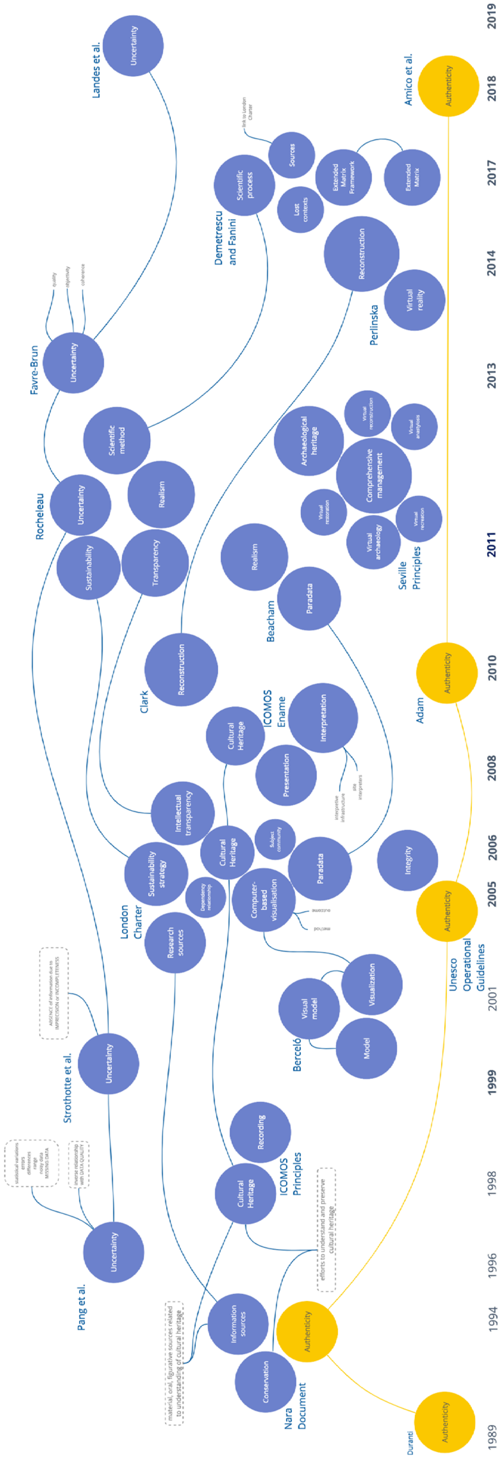


FIG. 5: Evolution in the definitions of the term "authenticity". Author's visualisation.

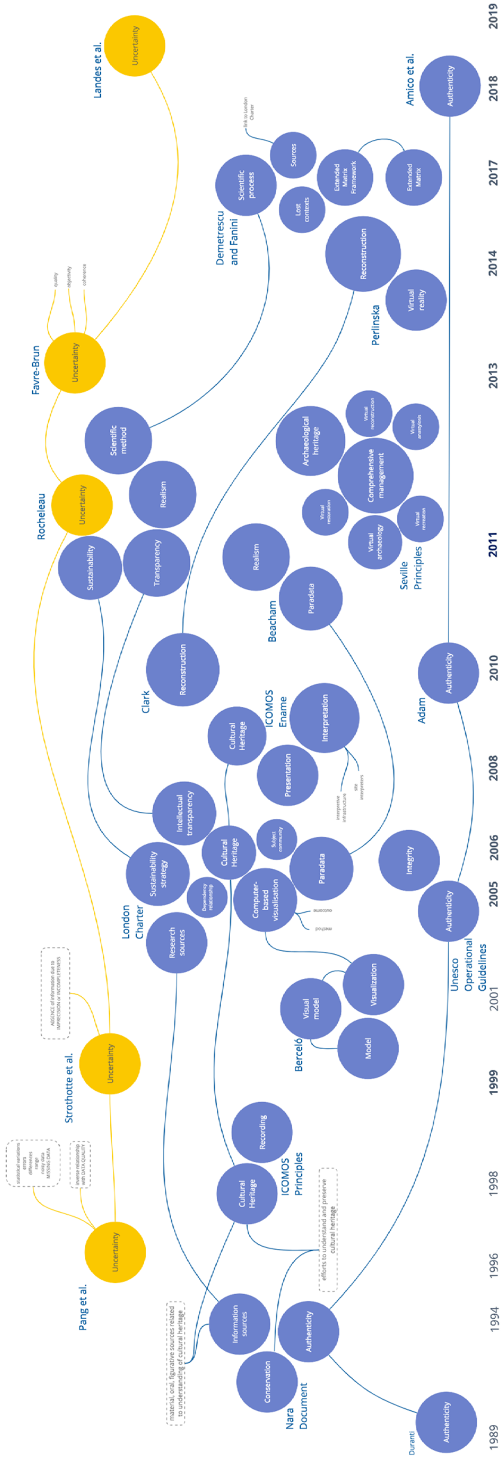


FIG. 6: Evolution in the definitions of the term “uncertainty”. Author’s visualisation.

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.

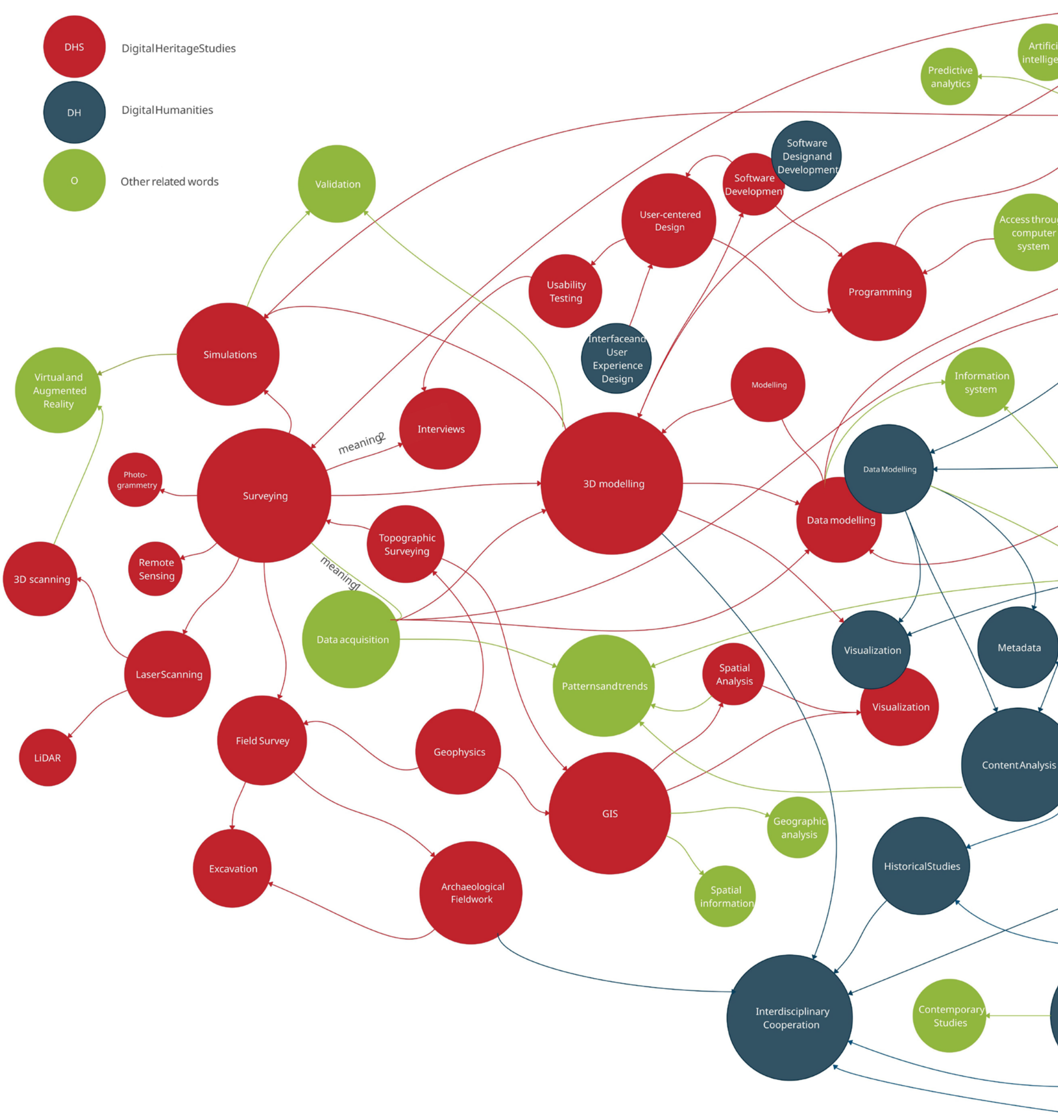
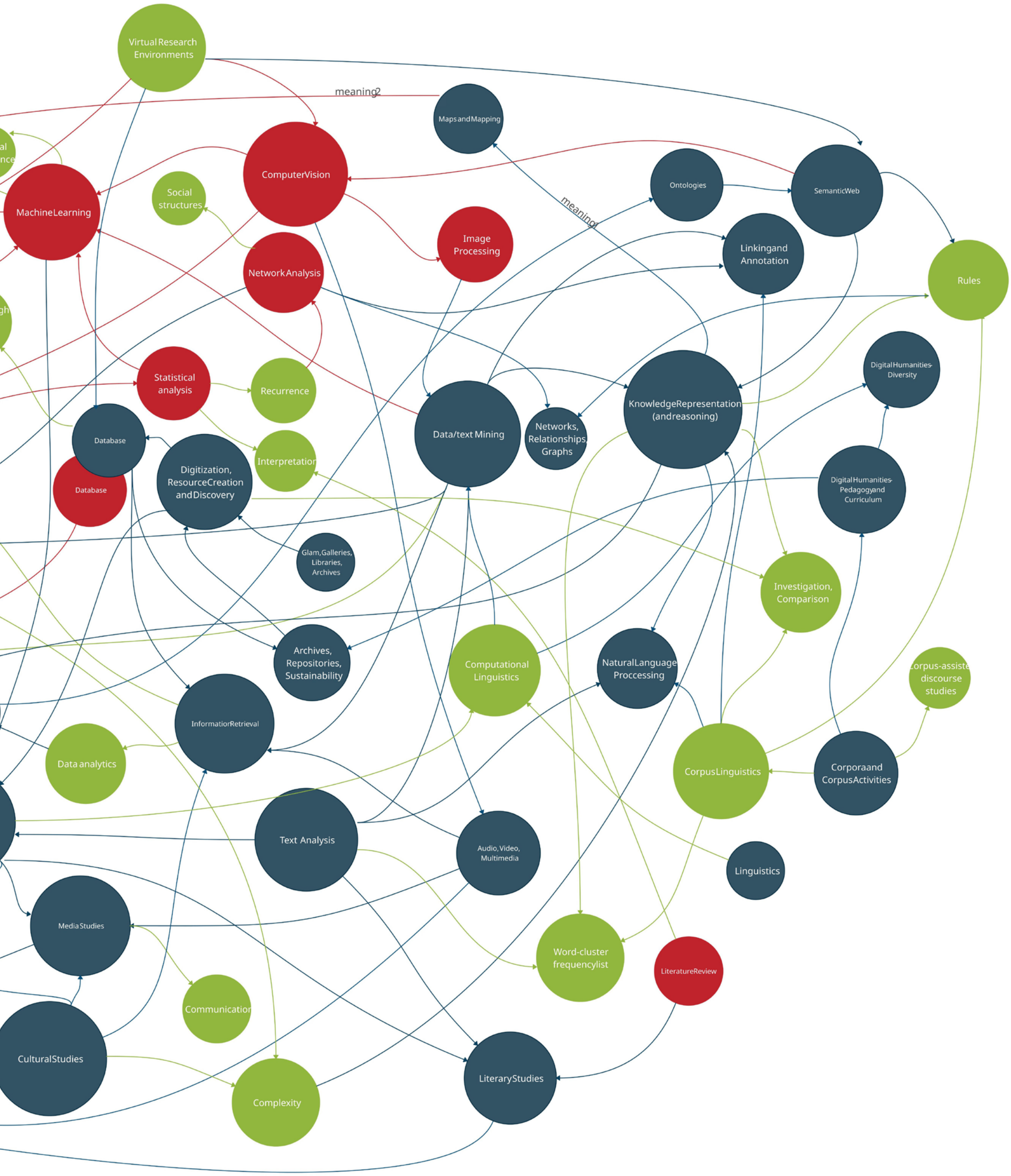


FIG. 7: Connections between terms related to Digital Heritage Studies (red) and Digital Humanities (blue). Other words (green) have been added later to the list in order to complete and strengthen some connections. Author's visualisation.



Virtual Research Environments
meaning?
Maps and Mapping
meaning?
Computer Vision
Machine Learning
Social structures
Image Processing
Ontologies
Semantic Web
Network Analysis
Linking and Annotation
Rules
Statistical analysis
Recurrence
Digital Humanities-Diversity
Data/text Mining
Networks, Relationships, Graphs
Knowledge Representation (and reasoning)
Database
Interpretation
Database
Digitization, Resource Creation and Discovery
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**).

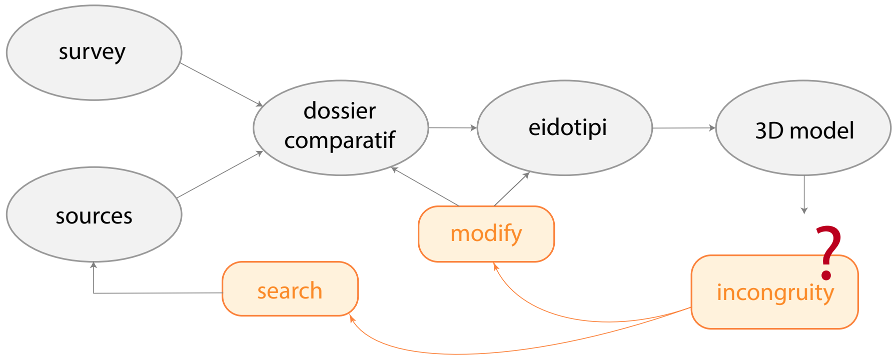


FIG. 8: Workflow for reality- and source-based 3D digital models (author's visualisation based on Demetrescu 2018) composed of the following phases: collection on the field; collection of other available (archival) sources; organisation of the dossier comparatif; creation of the eidotipi; creation of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

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).

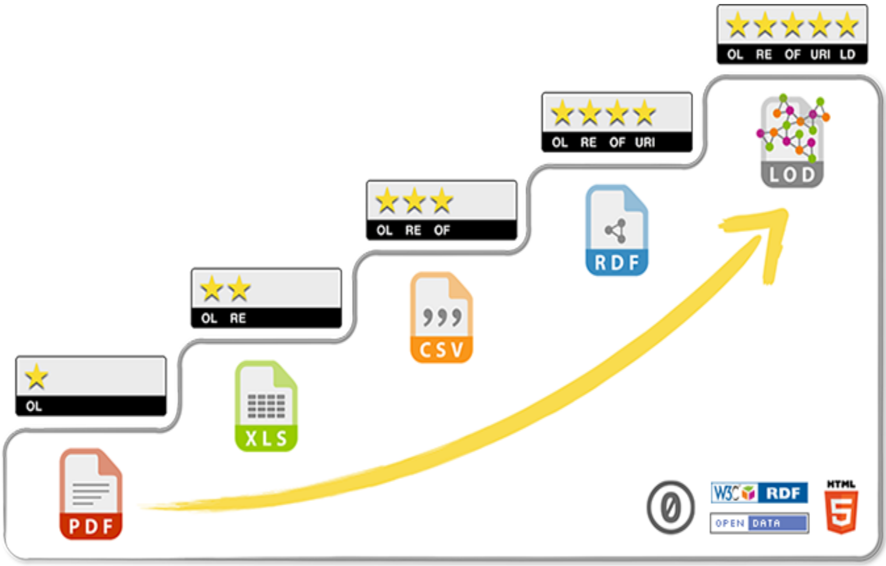


FIG. 9: The five-star model according to Berners-Lee et al. (2006). <https://commons.wikimedia.org/wiki/File:5-star_deployment_scheme_for_Open_Data.png> (Wikimedia Commons, PD).

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).

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**.

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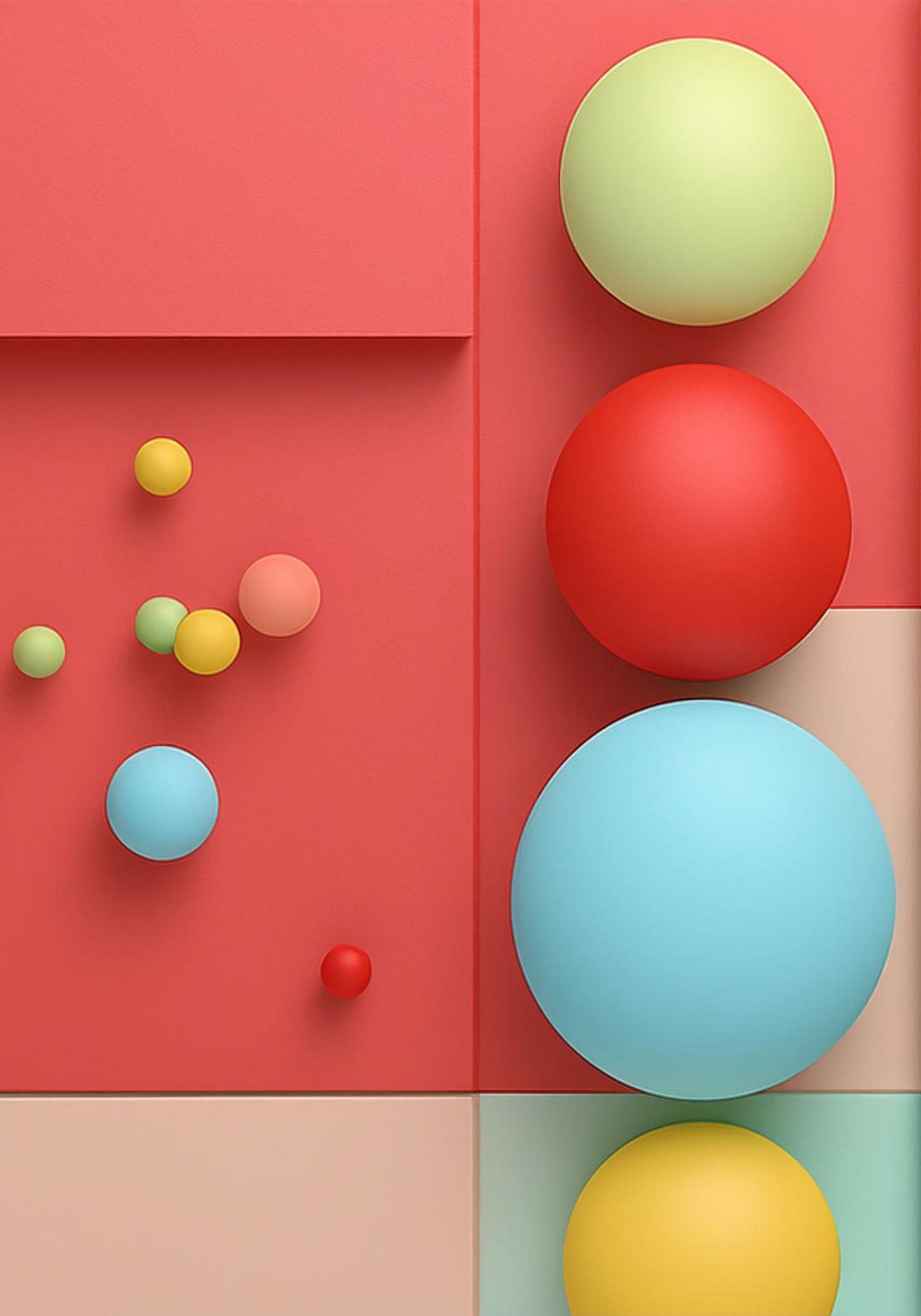
59 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L1024> (accessed 19.10.2024).
60 <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013L0037> (accessed 19.10.2024).
61 <https://dati.emilia-romagna.it/> (accessed 18.10.2024).
62 <https://dati.camera.it/> (accessed 17.10.2024).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



II uncertainty

Assessing and visualising uncertainty in reconstructions has been challenging since the 1990s and various methods have been proposed to address this issue in different ways, according to audiences and levels of expertise. Many of the proposed methods assign uncertainty levels to the different reconstructed elements, also incorporating information visually. Non-photorealistic renderings, in this framework, are often used for the communication of uncertainty through visual styles.
The use of false colours and colour scales is a common approach to assessing uncertainty, although standardisation across disciplines remains a challenge.
While there's no universal colour code, understanding colour palettes is crucial. The discussion navigates between physiological and cultural analyses of colour perception, considering linguistic influences on colour cognition and classification.

‘Communication is too often taken for granted when it should be taken to pieces.’

John Fiske, *Introduction To Communication Studies*, London, New York: Routledge, 1990.

II

uncertainty

classification and visualisation

The work on terminology (**CHAPTER I**) introduces the following study related to uncertainty: even if we agree upon the term "uncertainty" and we choose it instead of alternative words such as "reliability", "plausibility", etc., which seem to be less used, there are many ways of dealing with "uncertainty" at a level of both classification and visualisation.

This is exactly the focus of the present work: classifying and visualising uncertainty in order to assess source-based 3D reconstructions for cultural heritage, in particular in the domain of archaeology, art and architecture history. The application of an uncertainty scale to these models is in fact of vital importance in order to declare to which extent the collected documents allow an accurate reconstruction: being this a hypothetical reconstruction process to be applied to lost artefacts in the field of cultural heritage, it is necessary to elaborate solutions useful to declare the extent of missing parts and inconsistencies.

The digital 3D models that are produced are too often taken into account as «objective truth» in public representations, far from scientific criticism, as they seem to focus more on the «optimization of technological aspects» (Niccolucci and Hermon 2004).

In this framework, some considerations about the accuracy of the model and its relationships with the used sources become vital in order to limit, as far as possible, subjective interpretations (which are nevertheless unavoidable), excluding the wrong ones and declaring on which kind of evidence the proposed ones are based.

Therefore, the definition of the level of uncertainty should be listed among the good practices to adopt in the context of the development of a scientific methodology for hypothetical digital 3D reconstructions.

It is important to develop a process for acquiring knowledge from the analysis and interpretation of the collected data, making the reconstruction understandable and, finally, leading to the validation of the entire process. We need to develop the ability to «assess the proper level of knowledge related to the hypothetical reconstructive process, with its flaws and lacunae, and to carry out comparative operations on the set of data and information held» (Apollonio 2016).

This has been stated also in other occasions, in relation to the large amount of data that we can capture nowadays: « […] the wish to summarize all the sources of data (including the knowledge of the specialists) into one 3D model is a big challenge. In order to guarantee the reliability of the proposed reconstructed 3D model, it is of crucial importance to integrate the level of uncertainty assigned to it» (Landes et al. 2019).

The methods to assess the created model vary from more mathematical ones such as fuzzy logic (Niccolucci and Hermon 2004) to others referred to specific fields such as the extended matrix (Demetrescu 2018), an extension of the Harris matrix used in archaeology to incorporate information about things that no longer exist or variants of the same objects.

In addition, we have more widespread methods that are not strictly connected to a discipline or a group of experts, since many examples of them have been found in different fields and will be analysed: they are non-photorealistic renderings based on variations on colours, line types, transparency (Strothotte, Masuch, and Isenberg 1999; Kensek 2007; Apollonio 2016). In many cases, information about uncertainty is incorporated into a photograph, even though the integration into the model itself is being studied: an application will be presented in **CHAPTER III**.

There have been several proposals concerning uncertainty scales, based not only on different visualisation techniques (Kensek 2007), but also on different parameters, such as quality, coherence, type of source (Favre-Brun 2013; Grellert et al. 2019; Apollonio, Fallavollita, and Foschi 2021).

Here we propose a study on the existing uncertainty documentation techniques and elaborate a simple uncertainty scale (with some more complex variations) that will then be applied to a group of models uploaded in an online repository, always keeping in mind that the problem of uncertainty classification and visualisation cannot be universally solved (Landes et al. 2019).

A brief introduction to classification and visualisation of uncertainty, analysing the existing methods to assess it, is thus necessary before focusing on the inclusion of data related to uncertainty in source-based (hypothetical) 3D reconstructions.

This study has been carried out inside the research group of prof. Fabrizio Apollonio (with prof. Federico Fallavollita and research fellow Riccardo Foschi), who especially studies uncertainty classification and visualisation in 3D digital models for cultural heritage since 2013 and has published several papers on the subject, which are the primary references of this work.

These topics have been widely discussed during the meetings of the DFG and CoVHer international projects in which the author has had the pleasure of taking part.

A.
METHODS TO ASSESS UNCERTAINTY

Assessing and especially visualising uncertainty has been a challenge since the 1990s. Pang et al. (1996) have highlighted the «inherent difficulty in defining, characterizing, and controlling the uncertainty in the visualization process» that too often leads to the separation of the presentation of uncertainty from data, while they should be presented together in a holistic way.

A number of solutions have been proposed in order to declare to which extent we can be certain of a reconstruction. The main ones are collected in the following paragraphs. We start with two specific methods (and tools) to assess it and then we will mention other more general ways of dealing with this issue.

A.1.
Fuzzy logic

Fuzzy logic is a probabilistic way of analysing data in many different domains, such as economy, anthropology, natural and social sciences.

It has been initially developed in 1960s (Zadeh 1965; Zimmermann 2010)[1] considering a continuum of states between 0 and 1 and not only the two extreme values as happens in Boolean logic. It is based on the concept that a true/false logic is not usually applicable to reality, where categories have blurred boundaries. Thus, it is a way of defining "how much" an object belongs to a category, rather than "to which" category an object belongs.

It is also used to assess archaeological reconstruction models, where a value between 0 and 1, based on «verifiable elements», is given to their

1 Fuzzy logic – initially fuzzy set theory – was first proposed in 1965 by Lotfi Zadeh in his paper Fuzzy sets (Zadeh 1965) as an extension of Boolean logic. In 1973 he began to actually speak of "fuzzy logic" (Zadeh 1973). Hans-Jürgen Zimmermann, then, collected the studies on fuzzy sets, logic, analysis, data, together with some applications of these concepts (Zimmermann 1985).

components (Niccolucci and Hermon 2003; 2004). The interval (0,1) derives from probability; however, unlike probability, in fuzzy logic the sum of the values assigned to all the alternatives isn't necessarily 1: this is because we are not making random experiments to predict the future, but we are making non-verifiable statements about the past, as happens in archaeology (Niccolucci and Hermon 2017).

In these studies, three elements that should be evaluated for a «critical analysis» are identified: the accuracy of the reconstruction, the reliability of the used sources and the relationship between archaeological and virtual reality.

Ambiguity has to be preserved and communicated, expressing the subjective (and not arbitrary) component of the reasoning (De Finetti 1970; Savage 1972). This means that the values are assigned based on the experience and ability of the researcher, who has to motivate his choices by reconstructing the process of facts and deductions that guided his activity with numerical (and not only textual) values.

Sorin Hermon and Franco Niccolucci (2003) developed some tables with examples to show how fuzzy logic can be applied: each object is given a series of values to indicate how much it belongs to the corresponding series of categories.

The calculation of the fuzzy coefficients (what we would call "uncertainty") has been performed on a simple example (Niccolucci and Hermon 2004): a bell tower that is virtually reconstructed starting from its remains. The process is divided in four steps that correspond to the subsequent virtual additions of the missing parts: the completion of the existing part of the tower, the bell cell, the cornice and the roof. For each step, the fuzzy value is calculated. In particular, the roof opens to several interpretations, thus also variants of the model. Usually the fuzzy function has a trapezoidal shape that has a value of 1 in the central segment, but decreases towards 0 at the extremes: this means that there is an area in which we are sure that an element belongs to a given category, but also two fuzzy areas towards the extremes in which we are not sure about the nature of that element (**FIG. 10**).

Some techniques for visualising uncertainty are also proposed, for example an interface that shows only the elements that pass a reliability threshold, or other methods that have been applied to GIS concerning the variation of hue, saturation and transparency. In these cases, a slider is proposed to regulate the desired level of reliability.

However, the concept of "fuzziness" is still too close to probability and too formalised at a mathematical level: maybe this is the reason why it is not widely used in the field of cultural heritage, where more "humanistic" terms such as plausibility, reliability or uncertainty (Perlinska 2014) are preferred, since we do not know, for each considered element, the totality of possibilities of which the assigned value would be a fraction between 0 and 1. The totality of variants, however, can reach numbers higher than 1, thus the fact that we do not deal with a closed system is taken in consideration.

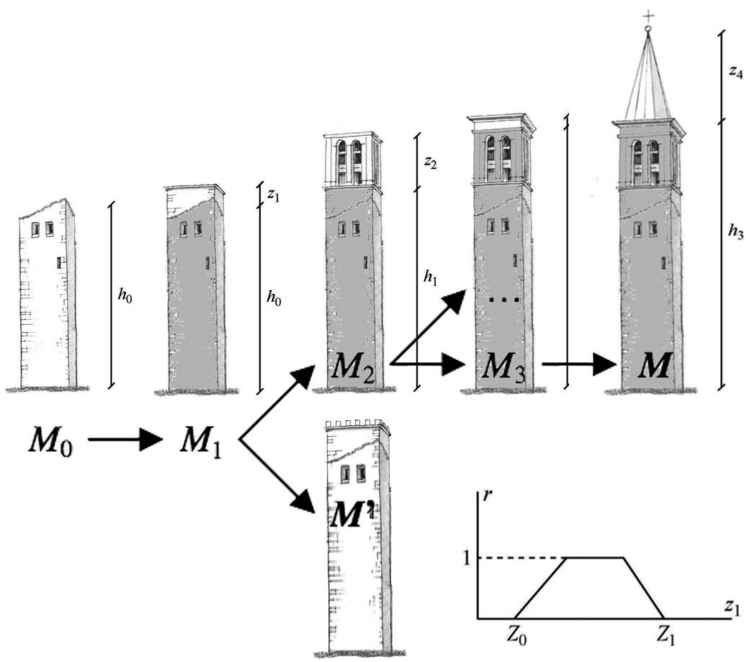


FIG. 10: An example of "uncertainty" evaluation based on fuzzy logic (Niccolucci and Hermon 2004). For each element in which the model is segmented, a calculation of fuzziness is performed by means of coefficients according to fuzziness diagrams such as the one shown here in the bottom right. For some elements, the creation of more variants may be necessary.

A.2. Extended matrix

The extended matrix, introduced by Emanuel Demetrescu, is grounded on the Harris Matrix[2], widely used in archaeology, filling its gaps by adding to it the paradata about the reconstruction of missing parts (Demetrescu and Fanini 2017; Demetrescu 2018). It is a formal language that allows a scientific reconstruction, trying to solve two problems: the "black box effect" and the "palimpsest effect".

The "black box effect" concerns the gap in the communication of the reconstruction process, making the process behind the reconstruction unreadable. 3D models are often considered a tool to synthesise the results of a reconstruction, but, if we refer to archaeology or to buildings that do not completely exist at present, the reconstructed elements usually have different reliability according to the availability of direct or indirect sources.

Therefore, if this is not documented, we cannot distinguish what is real from what is invented: an element, for instance, can be considered sure, hypothetical or just evocative.

The "palimpsest effect" is the phenomenon according to which every context shows the stratification of modifications through time: there is not a single building; conversely, there are remains of different buildings of different periods. Thus, in a reconstruction of a specific historical period, we should ideally remove all the non-coeval elements. The same process should also be adopted for 3D reality-based models.

The extended matrix is a human- and machine-readable set of data designed in order not to lead to the loss of information from these points of view.

It is similar to the ConML language (**CHAPTER I**), but it organises the data along a timeline, with a metadata approach and including the granularity of the stratigraphic record.

The 3D archaeological records are thus organised at different levels

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2 The Harris matrix was developed by Edward C. Harris in 1973 as an abstract system to describe the different elements and temporal phases of an archaeological site.

(standardised workflow, visual tools for analysis and synthesis, data visualisation, publication) so that the modelling steps are «smoother, transparent and scientifically complete» (Demetrescu 2018). All the sources are integrated into the model, maintaining the same level of documentation used during the excavation and interpretation of sources. The extended matrix, from this point of view, is a specific reference that connects the "proxy model" (the model of data) and the "representational model", storing the stratigraphic relationships and providing "data-driven representations" of them through computer graphics (**FIG. 11**).

The metadata are stored in GraphML, a format compliant to XML, with graphical representations that facilitate human reading.

The model is segmented based on the typology and the "supposed degree of certainty" of the sources, a feature that is usually represented through a colour scale. Anyway, complexity is part of this process and is the greatest challenge: segmentation is often done according to a single source typology (evidence, analogy…) even though it is based on different sources blended together; besides this, there are various specific properties that can be validated: position, shape, dimension…

All these aspects are present in the extended matrix, which provides the details of the sources and corresponding properties for each stratigraphic unit – both existent and virtual. A dataset can include more temporal phases, each of which has its own report with a written text to explain the reasoning. For every activity, the correspondent portion of the extended matrix graph is represented, together with the proxy and representational models. In this way, both the black box effect and the palimpsest effect are solved. Moreover, the connection between information becomes tighter and the visualisation of data through graphs is easily readable by humans (Tufte 1990).

In this way, the connections between elements can be studied. There is no fixed schema, just a common structure in which the heterogeneous reconstructed objects are fitted according to incompleteness of historical record. The descriptive elements (nodes) are the modular grammar to compose the final description of the reconstruction process. One or more qualities can be described (there are no fixed numbers) and each one of them can be validated using one or more sources. In this way, paradata are included in the stratigraphic reading. Different virtual reconstructions can be stored into this data structure that is embedded in the Blender[3] model.

This seems to be a very effective and thorough method to keep track of the reconstruction process in the field of archaeology, even though it doesn't seem so adapt to – and used by – a wider public: the author himself declares that it is «intended to be used by archaeologists and heritage specialists to document in a robust way their scientific hypotheses» (Demetrescu 2018).

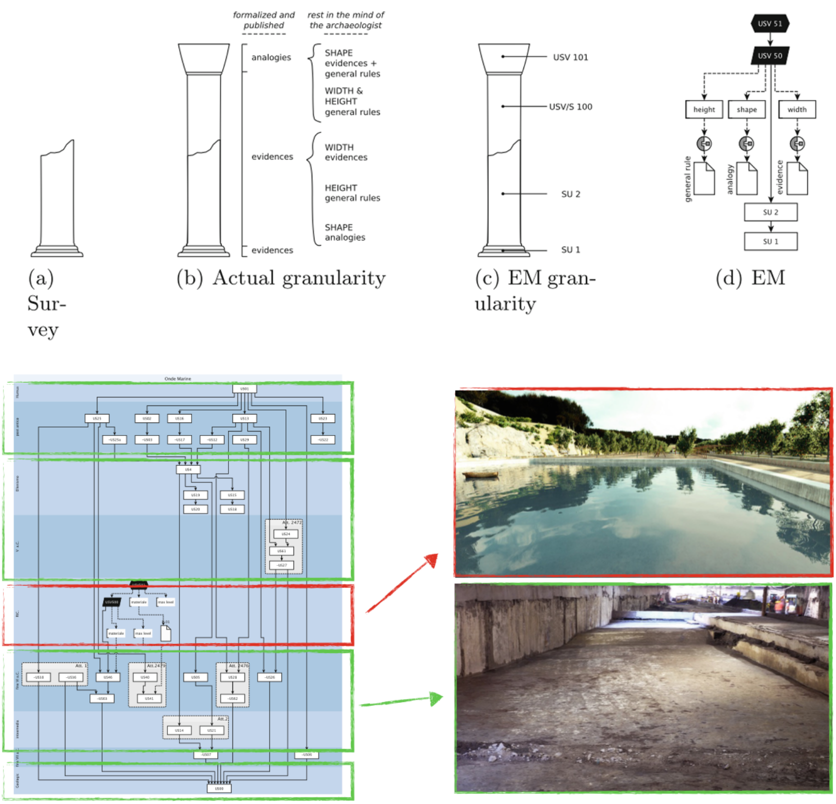

FIG. 11: An example of extended matrix in which, to the stratigraphic units found on site, some virtual stratigraphic units are added according to deductions and analogies. In the diagrams, they correspond to the cells with black background (Demetrescu 2018).

3 See the website <http://osiris.itabc.cnr.it/extendedmatrix/> accessed 30.10.2024

A.3. Metres and matrices

A gradient scale or a table indicating the level of uncertainty of a reconstruction and/or of its elements can be simply attached to the model, stating that some evaluations have been performed: it is a «symbology able to allow the traceability of uncertainty that characterises each element based on a subjective but controlled understanding and interpretation of data objects[4]» (Apollonio 2015).

Graphic techniques that meet these requirements include error bars, scatter plots, histograms. The most used ones in digital 3D reconstructions seem to be bars with variations in colour.

Several different scales, in this context, have been created especially in the last twenty years.

John Pollini and Nicholas Cipolla from the University of Southern California elaborated, between 2002 and 2008, a tool[5] for studying and testing interpretations of historical buildings through visual means.

It has been applied to the digital reconstruction of the Mausoleum of Augustus in Rome with the aim of decreasing the gap between physical evidence and virtual world: the visualisation can be explored with techniques for making ambiguity explicit and distinguish fragmentary physical evidence from interpretive reconstruction.

ICT methods and visualisation tools for data annotation and presentation include visualisation from different angles and from the spectator's point of view, scrollable text commentaries and a "reliability metre", in the form of a table below the picture of the reconstruction, providing graphic assessment of evidence and suggesting a degree of "likelihood", that they also call "reliability", based on for parameters: overall, archaeological, comparative and documentary likelihood.

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4 This especially refers to the use of a gradient colour scale that may also correspond to coloured elements on the model. The examples here listed don't necessarily include uncertainty data directly inside the model.

5 The project is here presented: <http://3dvisa.cch.kcl.ac.uk/project6.html> (accessed 29.10.2024).

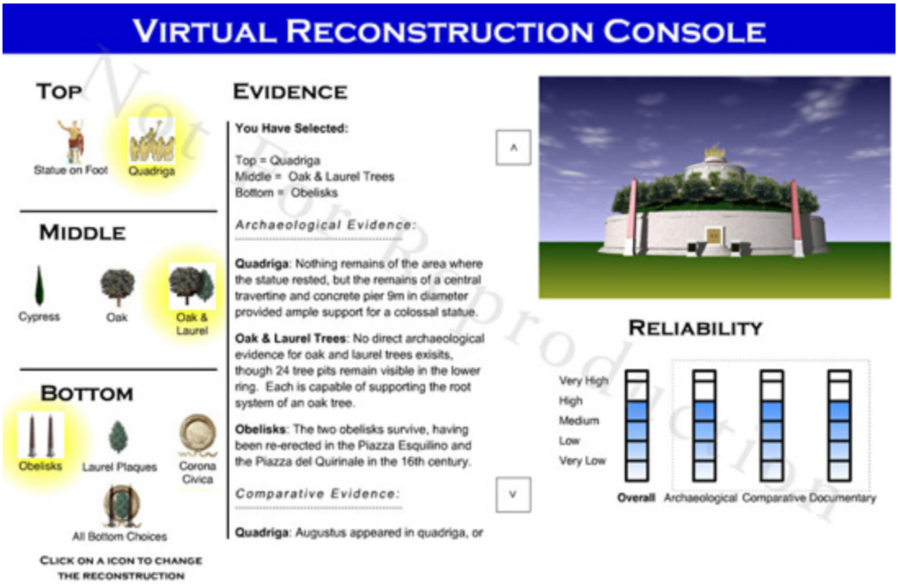

FIG. 12: Digital tools to assess the reliability of a hypothetical digital 3D reconstruction (retrieved from <http://3dvisa.cch.kcl.ac.uk/project6.html>, accessed 20.10.2024).

The levels are five and vary from "very high" (blue) to "very low" (white), according to a lightness gradient[6].

The *ScieDoc*[7] webtool for the scientific documentation of decisions, developed at TU Darmstadt by Marc Grellert and Mieke Pfarr-Harfst, also includes a numerical evaluation of uncertainty as part of the reconstruction-argumentation method (Grellert and Pfarr-Harfst 2019), which, similarly to visual comparisons in art history and archaeology, is based on the connection between:

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6 The description of the reconstruction and of the uncertainty scale that was applied are described in the website: <http://3dvisa.cch.kcl.ac.uk/project6.html> (accessed 30.10.2024).

7 <http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=home> (accessed 30.10.2024).

(1) A screenshot (or rendering) of the model or a part of it;
(2) The sources that were used to reconstruct it;
(3) A textual argument that explains the process followed to arrive to a particular result.

For each part in which the model is segmented, any number of variants can be documented.

The evaluation of the variants takes place according to four levels that in 2019 were: 1-*gesichert* (substantiated), 2-*wahrscheinlich* (likely), 3-*möglich* (possible) and 4-*hypothetisch* (hypothetical). As we can see in the last models uploaded (**FIG. 13**), the scale has recently evolved into: 0-nicht bewertet (not evaluated); 1-gesichert (substantiated); 2-*sehr wahrscheinlich* (very probable); 3-*wahrscheinlich* (probable); 4-*möglich* (possible). The evolution of these scales takes place in large part during the meetings of the scientific community working on these topics, in this case the DFG Network "Digitale Rekonstruktion", during which there were several proposals especially from the research group by Fabrizio Apollonio, who mainly deals with visualisation and presentation issues broadly connected to uncertainty documentation and, in this context, had proposed similar scales with an extra level grouping the elements for which uncertainty is not evaluated.

Such colour scales can validate different features of the model. Consequently, a more complete analysis may be done by integrating the different degrees of certainty corresponding to all the identified features, among which:

(1) Shape;
(2) Colours;
(3) Material used (texture);
(4) Location;
(5) Time.

This leads to the classification problems that we will encounter in **PARAGRAPH D** (where we will also discuss the fact that the application of a particular scale often depends on the disciplinary area to which the creators of the model are affiliated) and to the combination of more scales in the form of matrices (**PARAGRAPH D5**).

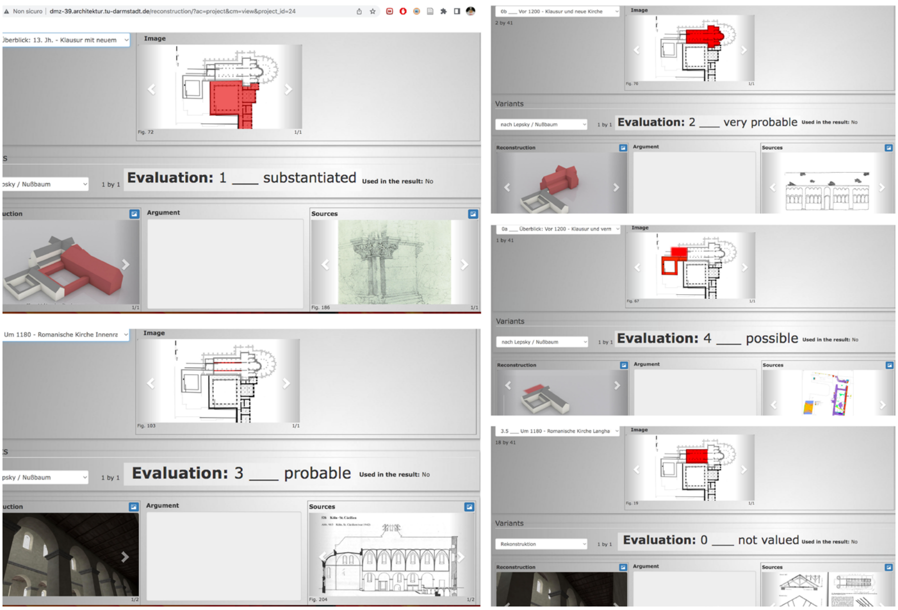

FIG. 13: Documentation related to five different parts of the Kloster Altenberg, the last edited model in ScieDoc: <http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=24> (accessed 16.10.2024). The "evaluation" field has been enlarged here for a better legibility.

A.4. *Glyphs and icons*

It is a simple way to incorporate information in a visualisation (**FIG. 14**) and it is largely employed in infographics and cartography (Bertin 1967; Tufte 1990), even though «the process is sometimes counter-intuitive. For example, while a glyph may appear appropriate by itself, the user's perception of the glyph may be different when a group of them is presented in various scales and locations» (Pang, Wittenbrink, and Lodha 1996).

Moreover, it is difficult to effectively integrate this technique into a 3D model in an interactive representation, without affecting legibility. Due to these difficulties, it isn't largely used in hypothetical digital 3D models.

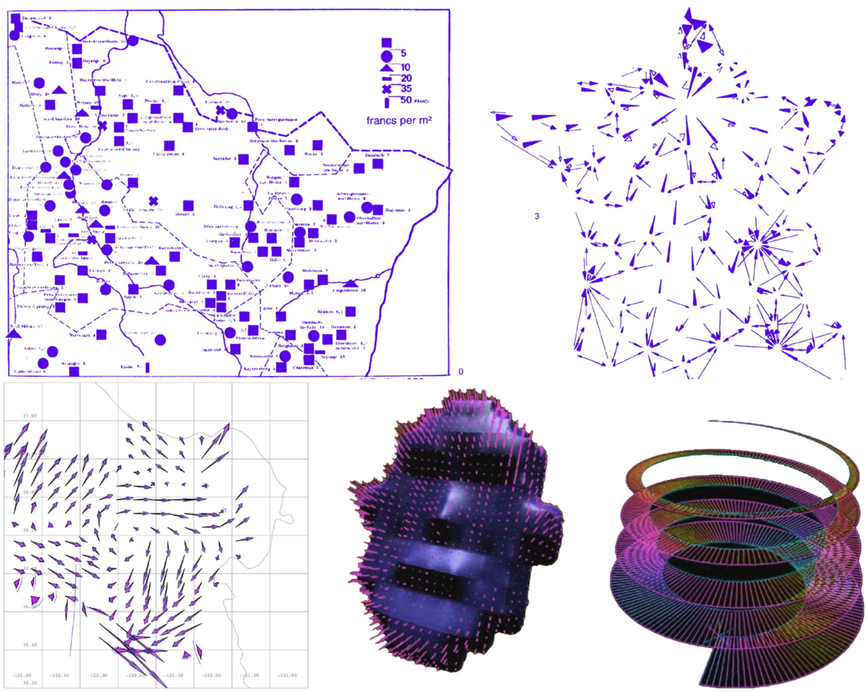

FIG. 14: The approach that consists in visualising information through glyphs and icons especially derives from cartography (above), where it is particularly used to express quantity or flux (Bertin 1967). Below, we can see examples of glyphs specifically used to represent uncertainty (Pang, Wittenbrink, and Lodha 1996) regarding (from left to right): vector fields of winds and currents, line glyphs showing the gaps between two differently interpolated surfaces, line glyphs connecting particle positions along two streamlines calculated using different methods. Author's elaboration.

A.5. Non-photorealistic renderings

In order to visualise data in our 3D digital models, we can choose between photorealistic and non-photorealistic renderings.

Many studies have proved that photorealistic renderings have «greater chance of adding subjective conjectures» (Apollonio, Fallavollita, and Foschi 2021), even though they are crucial and largely employed in the entertainment field: in this case, scientific documentation and accuracy are often secondary; still, these models can be useful to an expert audience if the sources and levels of uncertainty are declared.

Besides this, non-photorealistic renderings (**FIG. 15**) seem to be a valid alternative to graphically communicate lacks and inconsistencies, but we should be careful, since they can be tricky: as an example, it has been observed (Heeb and Christen 2019; Apollonio, Fallavollita, and Foschi 2021) that the use of a single white or grey material when we don't know the actual materials of a building might induce the user to think that it was entirely covered with plaster, similarly to the neoclassical misconception according to which the ancient temples were believed to be white, evocating different atmospheres with respect to the one wanted by the original author(s).

To avoid the generation of these unintended conjectures, when drawings are used as the primary source, a "diplomatic" model (Apollonio, Fallavollita, and Foschi 2021) has been proposed by extracting the texture, with different projection and mapping techniques, from the original drawings themselves (**FIG. 16**), in order not to lose the information initially conveyed by them[8].

This can be possible when we have enough (and not too different) high-quality sources; otherwise, different digital tools (see **PARAGRAPH B**) have to be used.

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8 In previous publications, a number of buildings by Claude-Nicolas Ledoux were reconstructed and presented as monochromatic renderings, which could still be a solution, since they refer to an "ideal" drawn architecture and not to the reconstruction of destroyed (thus once materialised) buildings (Apollonio et al. 2017; Apollonio 2019b).

It can also be considered a variant in addition to a photorealistic one and/or to a non-photorealistic and more “abstract” one, intended to include other kinds of information, such as the level of uncertainty.

FIG. 15: A simple monochromatic rendering can be an alternative to photorealism when textures are not available. This model represents the Traianeum in Pergamon, 200 AD (author's elaboration based on Lengyel and Toulouse 2016).

Depending on the material, i.e. the textures used in a reconstruction, the atmosphere perceived by an observer can indeed radically change: many conjectures are based on these kinds of choices.

Thus, if not well documented, both photorealistic and non-photorealistic techniques can generate ambiguities. It is also true that, when there is not enough documentation available and a photorealistic rendering is not required, it is recommended to use non-photorealistic alternatives, such as the ones presented in the next paragraphs.

In non-photorealistic renderings, techniques such as the ones seen before (icons, glyphs, particular representation styles, colour scales) may be integrated into the model. Among the examples that have been presented, the first two approaches (fuzzy logic and extended matrix) are more technical and require an expert audience and sometimes particular tools, whereas the last three, which seem to be more flexible and adapt to a wider public, are not separate one from another: they are often com-

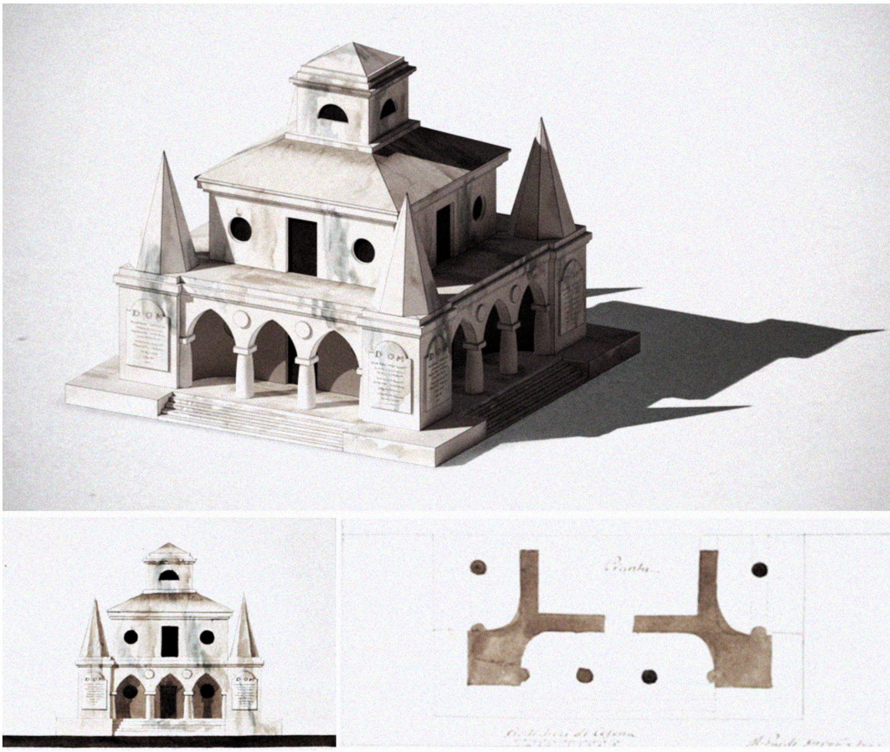

FIG. 16: "Diplomatic" visualisation method (author's elaboration based on Apollonio, Fallavollita, and Foschi 2021) according to which, rather than a photorealistic rendering or a neutral mono-material, the texture of the original drawing is used. Here on the top is a model of a square tomb developed starting from some drawings by Mauro Guidi (on the bottom) taken from Cesena Nuova, Atlante 41, Carta 48.

bined in the examples that we propose. In particular, the use of a model with false colours, complemented by a colour scale to make it easily understandable, is one of the simplest and most widespread methods to assess uncertainty: we will see here different examples from different disciplines and written in different languages. Since it is so widely used, we have focused on this technique. Of course, a "universal" solution would be utopic, but still we can study the bases on which these scales (that are sometimes hardly comparable) are grounded (**PARAGRAPH C**) and make a proposal (**CHAPTER III**) that aims to be clear, accepted and shareable through the *DFG repository*.

B.
UNCERTAINTY VISUALISATION TECHNIQUES

Showing uncertainty should become a standard for scholarly representations, but it is often difficult to decide upon the methods that are clearer and more instructive, also depending on the public to whom they are addressed. We always have to take into account (and keep trace of) all the phases and evaluations that may be clear for the reconstructor, but not for the final user. Several problems arise also because it is usually impossible (or not recommended) to equally solve the uncertainty problem at all levels: it is not sufficient to say that something is uncertain; conversely, it is important to declare "how uncertain" it is.

The visualisation techniques here listed refer to a typology of non-photorealistic renderings, which are the most widely used technique to visualise uncertainty in digital 3D models. It has been employed at least from 1999: we refer to the work by Strothotte et al., in which, together with the photorealistic rendering of the palace of Otto the Great in Magdeburg, a sketch was drawn (**FIG. 17**), with lines presenting different curvatures and lightness that corresponded to different levels of uncertainty (Strothotte, Masuch, and Isenberg 1999).

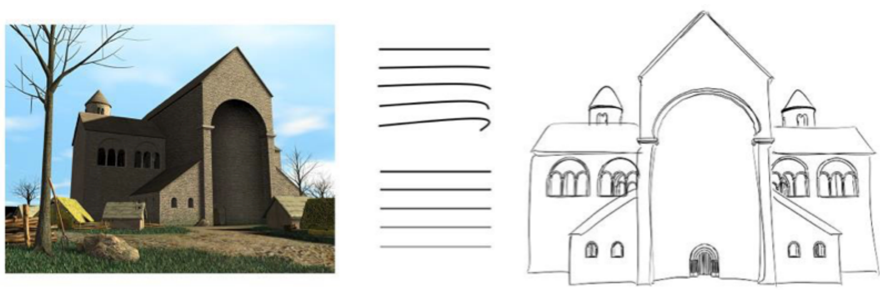

FIG. 17: Variations in the line type to visualise uncertainty (Strothotte, Masuch, and Isenberg 1999).

Prior to this, the studies on uncertainty visualisation didn't directly concern digital 3D models, but were generally carried out in the field of computer science.

The most used techniques, in this context, were the addition of glyphs, the addition or modification of geometry, the modification of attributes, sonification, animations and psycho-visual effects (Pang, Wittenbrink, and Lodha 1996).

It was also noted that «different kinds of renditions actually have a very different effect on viewers» and «non-photorealistic images actually do deserve their place in the repertoire of CAD systems» (Schumann et al. 1996).

The main techniques to visualise uncertainty specifically in digital 3D models have been collected more recently (Kensek 2007; Apollonio 2016)[9].

In the survey by the architect Karen Kensek from the University of Southern California, the existing methods to show missing data, document variants and indicate the level of uncertainty were analysed (Kensek 2007), emphasising the struggle of historians, archaeologists and curators «with the problems of reconstructing buildings and artefacts without having enough data to be certain of their results», saying that architects have learnt what archaeologists already knew: the fact that a reconstruction can be based on different operations, such as inference, guesses, plain speculation.

In physical reconstructions, historic preservationists decide how to reconstruct a building and which epoch they take into account, usually considering the 10-inch rule, which states that the difference from the original part should be visible, but only under the distance of 10 inches; globally, the building has to be perceived as a whole. By analogy, digital reconstructors should show most prominently the real material, then attempt to fix minor details, patch major areas and finally create missing parts while clearly documenting changes and assumptions.

This, however, is not so simple and it is bound to generate a range of different approaches.

A first and very simple classification of the possible techniques, in the case of missing data, according to Kensek is[10]:

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9 The work is being further developed by Fabrizio Apollonio's research group, especially in the context of the *DFG* Network *Digitale Rekonstruktion* and of the *CoVHer* project.

10 Here she refers to both physical and digital reconstructions.

(1) Leaving the gaps empty;
(2) Filling them with another material (or technique);
(3) Making them look like the rest.

Making the uncertain part look like the rest is what is done mostly in photorealistic rendering[11], where uncertainty is very often not declared; leaving the gaps empty is used to declare that those parts are uncertain without declaring "how much". The case of interest, for the present study, corresponds to the decision to fill the gaps with a technique that allows not only the differentiation of the gap from the rest, but also the differentiation of uncertainty degrees based on how we reconstruct that gap.

This is obtained, in many cases, by reducing the level of detail: by doing without details, decisions are simplified when we don't have enough documentation. The main elements become more prominent and recognisable, whereas information about less certain structures is strongly reduced. In this context, the strategies to visually distinguish the reconstructed parts according to their level of uncertainty can be generally classified as follows:

(1) Curvature, sharpness, type and detail of line (**FIG. 17**). Through line representation, the model is, in some cases, strongly reduced to the pure outline; in other cases, more complex representations are obtained with internal and hidden lines. Vagueness is expressed by varying them and by omitting details about structure, material or colour (Strothotte, Masuch, and Isenberg 1999; Potter, Rosen, and Johnson 2012). Scanline is a method to extract

11 Photorealistic renderings are very common and for this reason we mention them as the main example here; however, also the choice of more schematic representations – equal for all the elements – as well as the use of a monochromatic material for the entire model, are different ways of not declaring the uncertainty degree of the various elements. This is further discussed in this paragraph.

and process these lines with an algorithm, also used to obtain textures (**FIG. 19**);

(2) Wireframe: only lines corresponding to the edges of an object are visible, without any kind of texture. A combination of false colours and wireframe (**FIG. 18**) has been used in an interface proposed to evaluate models according to four different scales (Kensek, Dodd, and Cipolla 2004);

(3) Optical transparency (De Luca et al. 2010): it is used in a similar way to other techniques, making the reduction of contrast and detail a suitable means of marking up hypothetical structures (**FIG. 20**). However, it is difficult to perceive the space and to add details such as windows and doors: the overlays can become confusing. It has been also noticed that «transparent objects neither represent a spatial situation with nor without them. Instead of visualizing two options, transparency visualizes none of them, but informs about this uncertainty in a non-spatial, rather theoretic way» (Lengyel and Toulouse 2016);

(4) Rendering type, for instance a superimposition of schematic and photorealistic rendering (**FIG. 21**) or also the use of a cartoon effect (**FIG. 22**) to differentiate the rendering by which uncertainty data are conveyed (Freudenberg et al. 2001; Zuk and Carpendale 2006);

(5) X-ray representations, variations on translucency and/or alpha opacity: these techniques allow, to some extent, to see through the model and they can be used to indicate the uncertain parts (Apollonio, Fallavollita, and Foschi 2021);

(6) Simplified models or sketches (Heeb and Christen 2019): this implicates a reduction in the level of detail towards a higher degree of abstraction (**FIG. 23**), which can also involve the reduction of colour or the use of a greyscale, or even the decontestualisation of the model. Using a sketch can also be a solution, being it by definition a simplified drawing that sharpens the more important (in this case, certain) things and leaves other elements almost undefined (**FIG. 24**). The combination of different degrees of exe-

cution can therefore be perceived as a variation in the uncertainty degree;

(7) Flat shading: a model presented without any shadow (Apollonio, Fallavollita, and Foschi 2021), to keep the same colour independent from the orientation. This can be hard to read because our eye is used to shading and to perceive, to some extent, the same colour despite the variation of light. Moreover, the third dimension becomes hardly readable.

(8) Ambient occlusion: this enhances the perception of 3D details without defining the material and the light emitter (Apollonio, Fallavollita, and Foschi 2021).

(9) Patterns, hatches, materials. These kinds of «abstract coloured textures» might however «disturb the perception of the object shape and proportions» (Apollonio, Fallavollita, and Foschi 2021);

(10) Filtering techniques including fuzziness or blurriness (varying the number of effects) or changing the density of information being shown. Blur, as well as focus and perspective, can also be adopted to draw attention to particular parts, but the viewer cannot see the entire model (Heeb and Christen 2019);

Colour scales (Dell'Unto et al. 2013; Grellert et al. 2019; Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018; Landes et al. 2019) appear to be the most used technique: these can be coloration schemes relying on variations in the shades of colour, obtained by adjusting their hue, saturation or lightness, but also on a contrast between colour and greyscale or even just on greyscale. Greyscale images imitate a realistic situation of light and shadow, but with single, neutral colour, without providing much detail: colour information is limited to limit conjectures. This makes it clear that they are abstract representations; however, there is the risk that they can be perceived as uncoloured objects. Coloration is a common visual tool used for highlighting hypothetical areas of the reconstruction. However, if a colour covers a large area, it is difficult to display additional information, for instance the supposed material, whereas, if we include realistic colours, it is difficult to visualise the difference between finding and hypothesis. As a consequence, a false-colour model is usually employed as a visual "variant" of the model containing other information. Considered in this way, abstract solid colours avoid the problem of colours that are too similar to actual materials, which can be confusing (Apollonio, Gaiani, and Sun 2013).

Using false colours in shading allows nevertheless in an easy way to retrieve information about uncertainty, even before accessing the related sources: this is why it is largely employed and at the centre of the international debate. It should also be noted that, when greyscale is the only possibility to visualise the model, a simple desaturation of the colour scale is not recommended because a variation in hue doesn't directly correspond to a variation in brightness; moreover, even if we apply a new greyscale based on a variation in brightness, the lights and shadows can deceive the viewer.

An alternative would be converting the scale into graphical black and white pattern, even though it would be difficult to distinguish small elements (Apollonio, Fallavollita, and Foschi 2021).

We will see this also in **CHAPTER III**.

Mixing different rendering types leads to the visual differentiation of the uncertainty levels: the most uncertain part is the one represented with wireframe, whereas the more realistic one has a higher level of confidence.

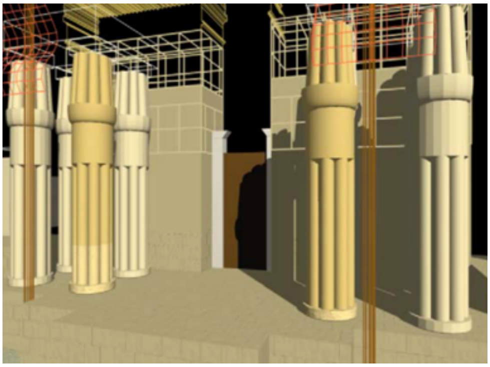

FIG. 18: Use of wireframe to visualise the most uncertain parts (Kensek, Dodd, and Cipolla 2004).

Through the "scanline" technique, the lines representing the edges of an object are extracted using an algorithm that generates then a texture in which the level of detail varies according to the uncertainty level. It is similar to the technique used by Strothotte et al. (1999) that generated line types with different sharpness and curvature. The process was tested by Potter et al. (2007) on a model of a Maya pyramid with different uncertainty levels, corresponding here to «sketchiness levels» (the upper part is more uncertain).

FIG. 19: Use of scanlines to obtain textures with different levels of detail (Potter et al. 2007).

The use of transparency and its variations can indicate different degrees of spatial uncertainty. This technique was applied by Chiara Stefani (2010) to two hypothetical reconstructions: the southern and eastern galleries that compose part of the cloister of the abbey in Saint-Guilhem-le-Désert and the Tropaeum Alpium in La Tourbie.

FIG. 20: Transparency variations: the more transparent, the more uncertain (Stefani 2010).

The superimposition of two renderings with very different characteristics, also adding a colour gradient, can also indicate different degrees of uncertainty.

FIG. 21: Superimposition of a schematic render to the photorealistic one, with variations on transparency (Strothotte et al. 1999).

The cartoon effect, with a lightness gradient from blue to white, can identify the non-photorealistic model used to visualise uncertainty (Freudenberg et al. 2001).

FIG. 22: Use of a cartoon effect to visualise uncertainty (Freudenberg et al. 2001).

Variations in the level of detail (Heeb and Christen 2019) can be obtained by showing the texture of a building when available and reconstructing just the shape of the rest.

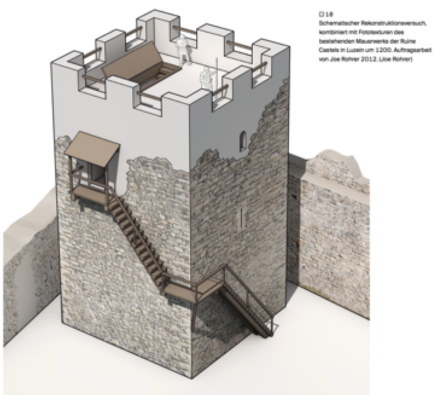

FIG. 23: Variations in the level of detail (Heeb and Christen 2019).

Sketches (Heeb and Christen 2019) allow to present in a clearer way the elements about which we have more information, while leaving other things just outlined.

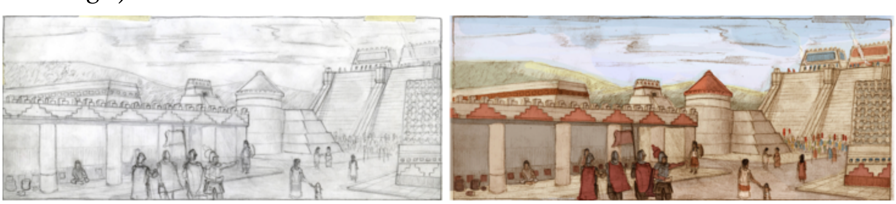

FIG. 24: Creation of sketches (Heeb and Christen 2019).

A colour scale that follows the visible spectrum of colours is used to indicate certainty in a numerical scale from 0 to 1, similar to a probability scale. In this quite continuous variation of colour, we can identify four main categories: assumption, indicated in red, analogy in yellow, deduction in green and model (that is, "still existing") in blue. The scale is quite similar to the one we will use in our case studies.

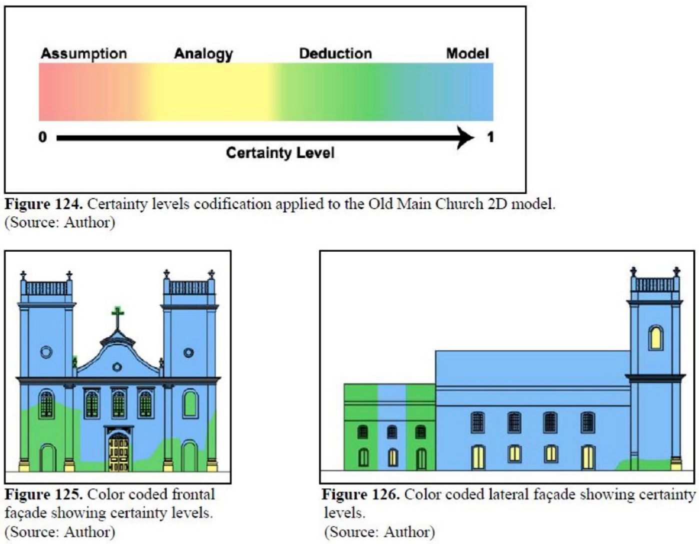

FIG. 25: Colour-coded uncertainty levels (Kozan 2004)

A simple colour scale has been proposed (Georgiou and Hermon 2011) based on the three main colour of the RGB colour codification.

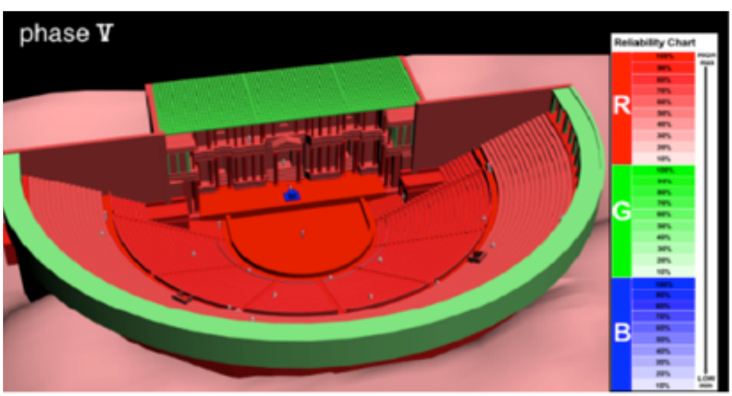

FIG. 26: RGB Colour mapping (Georgiou and Hermon 2011)

The project “Byzantium 1200”, founded by Tayfun Oner, introduced a colour scale following the spectrogram, but indicating with red the maximum certainty (still existing in original). This scale has also been the basis of the work done by the archaeologists Pablo Aparicio Resco and César Figueiredo.

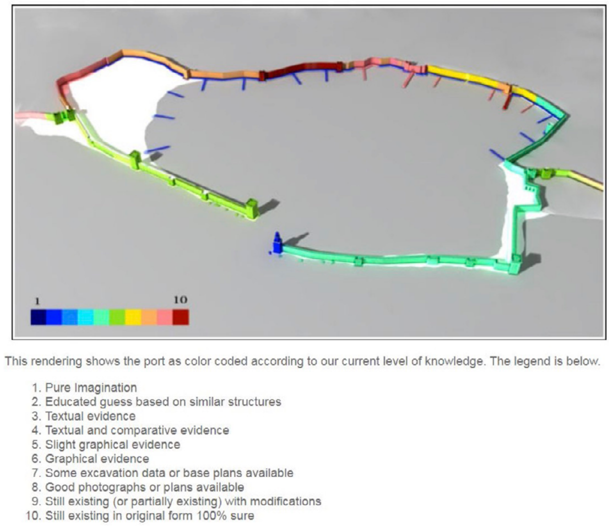

FIG. 27: The ten uncertainty levels in the project “Byzantium 1200”, 2011.

The colour scale here is based on the type of sources used to reconstruct the “Villa for a twin” by Andrea Palladio after RIBA XVII 15R (Apollonio et al. 2013).

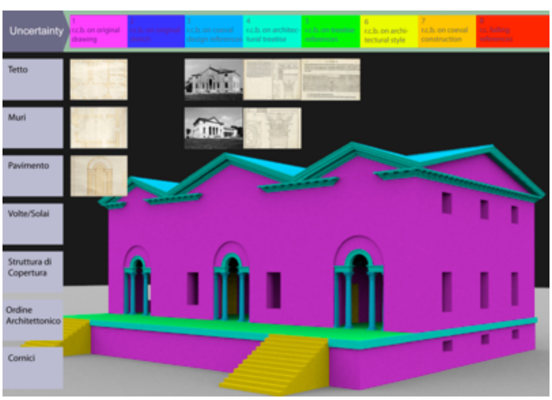

FIG. 28: Source-based colour scale applied to a drawing by Palladio (Apollonio, Gaiani, and Sun 2013).

The Swedish Pompeii project (Dell'Unto et al. 2013) deliberately uses a scale in which colours are not chosen according to a uniform gradient.

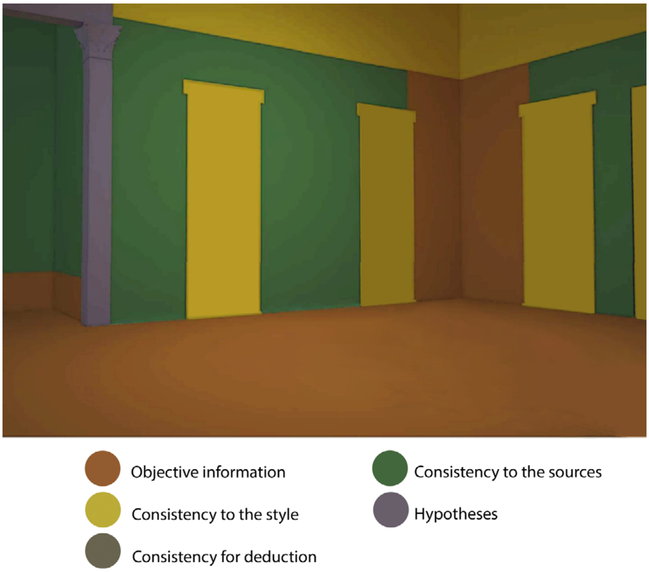

FIG. 29: The five-level uncertainty scale for The Swedish Pompeii project (author's elaboration based on Dell'Unto et al. 2013).

A simple scale with four colours (green, yellow, orange, red) has been used in this probability map visualised in 3DStudio Max and then imported in ArcGis (Perlinska 2013).

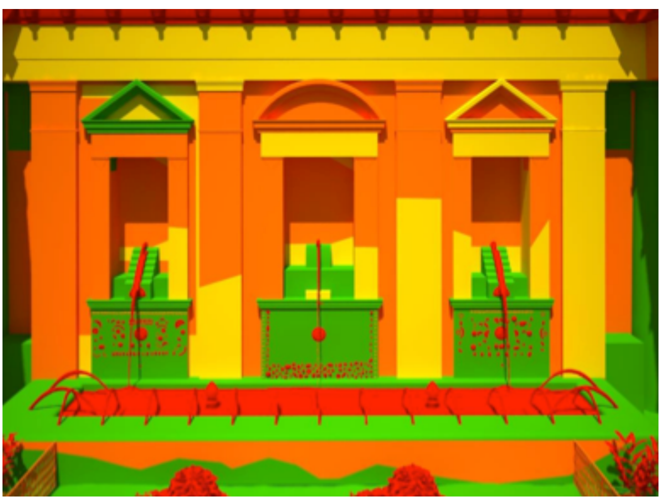

FIG. 30: Four-colour probability map (Perlinska 2014).

Resco and Figueiredo (2014) elaborated, on the basis of "Byzantium 1200", a scale ranging from red (existent) to purple (imagination). Recently (in 2022) the scale has been slightly changed removing purple that could be misleading, being it equally distant from blue and red. Consequently, now imagination is represented in blue (see FIG. 36).

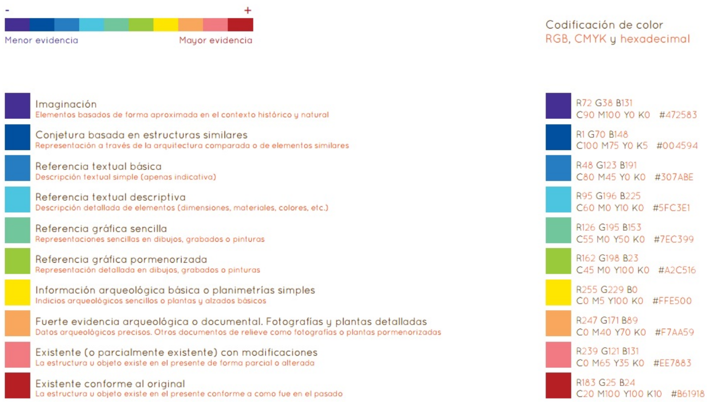

FIG. 31: Ten-level uncertainty scale (Resco and Figueiredo 2014).

Similarly to the approach by Dell'Unto et al. (2013), here a scale other than the spectrogram is adopted. On the left, the scale presented by Cordero et al. (2017) differentiates itself from the previous one proposed by Tayfun Oner for Byzantium 1200.

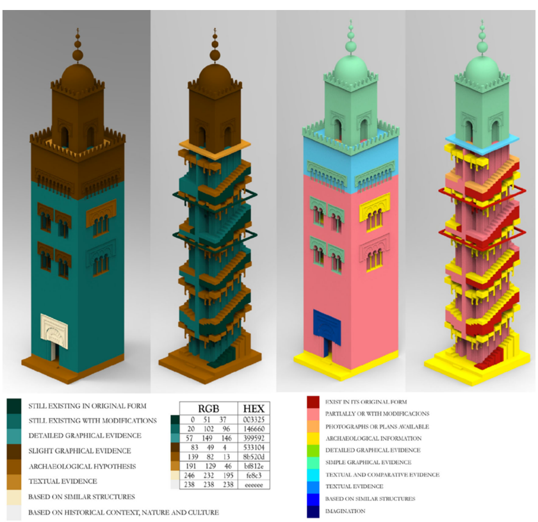

FIG. 32: Comparison between a spectral and a non-spectral scale (Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018).

Landes et al. (2019) use a scale from red (maximum uncertainty) to green (minimum uncertainty) corresponding to a qualitative assessment of the reconstruction process.

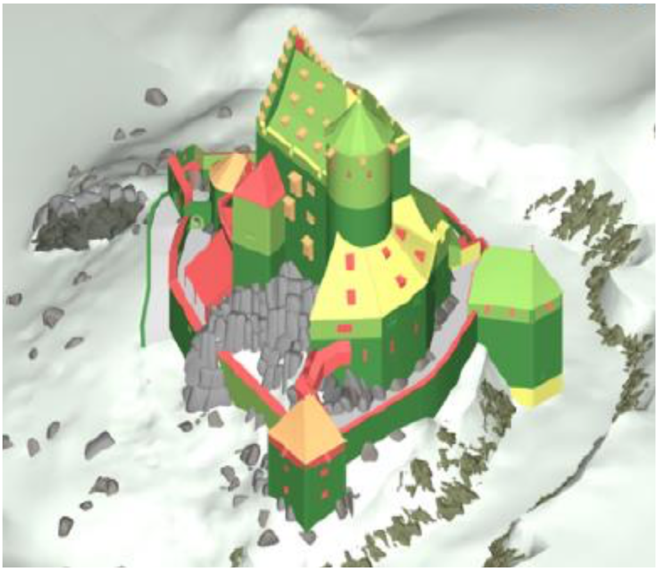

FIG. 33: Green-to-red qualitative uncertainty scale (Landes et al. 2019).

Apollonio in 2019 adopted these double visualisations (Grellert et a. 2019) according to two different scales: one representing the plausibility of the reconstruction (from blue to white, with variation in lightness) and one related to the type and clarity of the used sources.

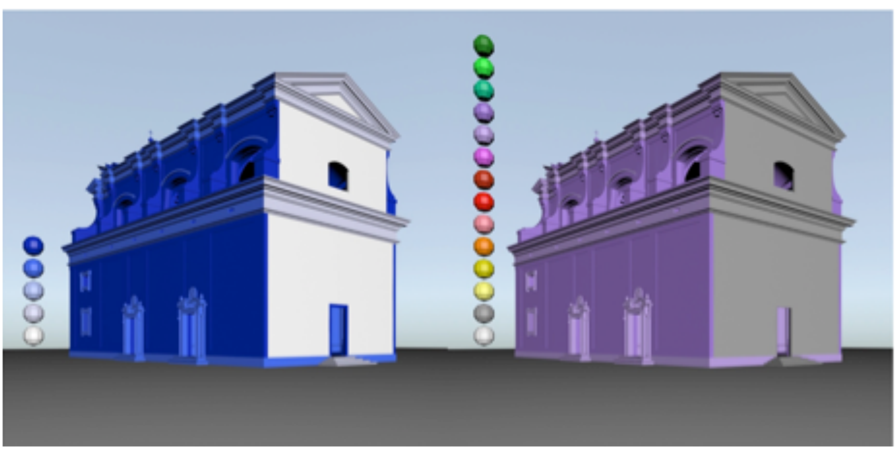

FIG. 34: Two different scales to visualise uncertainty (Grellert et al. 2019).

Apollonio et al. (2021) elaborated a colour scale that allows different granularity (actually, in this sense, the scales are three). The colours range from red (maximum uncertainty) to blue (minimum uncertainty) according to the spectrogram. The white level represents the elements still on site (100% certain), whereas the black level represents the things that are not taken into consideration in the uncertainty assessment.

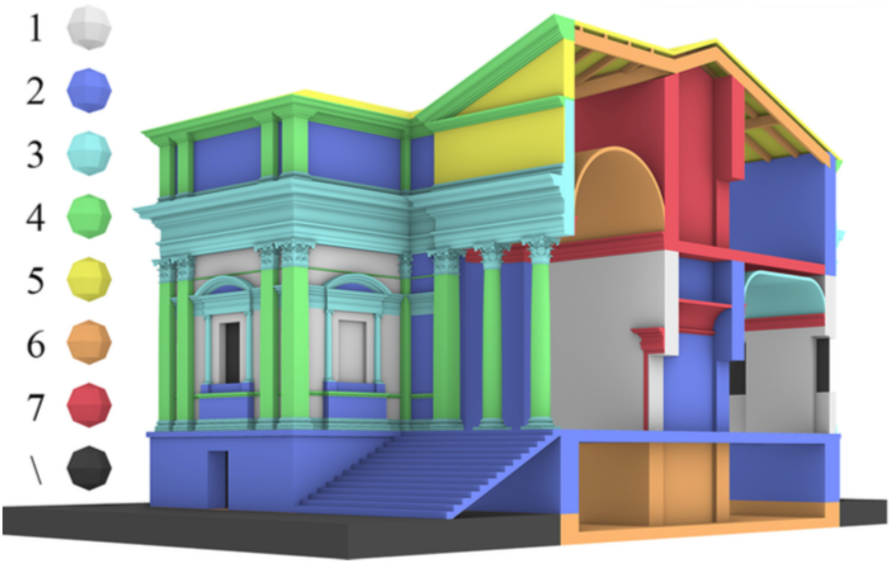

FIG. 35: Uncertainty scale allowing different granularity, here in the 7+1 variant, applied to the Villa Pisani in Bagnolo by Andrea Palladio (Apollonio, Fallavollita, and Foschi 2021).

FIG. 36: Reconstruction of an archaeological site and superimposition of an uncertainty scale by Pablo Aparicio Resco. It is possible to switch between the two images by means of a slider. The uncertainty scale has been updated with respect to the 2014 one: instead of purple (a misleading colour), grey has been chosen. <https://parpatrimonioytecnologia.wordpress.com/2022/06/06/hacia-una-nueva-version-de-la-escala-de-evidencia-historico-arqueologica/> (Accessed 31.10.2024).

Among the visual filter schemes several possibilities have been listed in addition (or complementary to) the ones analysed before:

(1) Application of effects such as twirl, ripple, emboss, solarise, grain, etc.;
(2) Different clarity of fuzziness, both to blur less confident areas and to indicate the variety of possibilities (this is used in physics to represent the possible locations of an electron);
(3) Variation in the levels of density of information (the most certain elements are in this case richer in information, that is more detailed);
(4) Size distortion schemes: bigger or smaller parts can rate the uncertainty of each element, even though they can be confusing, since they considerably alter our perception of space;
(5) Representation of a model partly in 3D (axonometry, perspective) and partly in 2D (plan view). The two-dimensional representation would correspond to the areas for which we don't have enough information;
(6) Animation, blinking, toggling between values;
(7) Translation into sound;
(8) Tactile experiences based on malleability, texture, temperature, to be applied to physical reproductions of the digital models.

Almost all the mentioned techniques are connected to the sense of sight, except the last two, which can therefore be useful in cases of sight deficiencies such as blindness, where tactile models are already employed to allow the exploration of space.

An uncertainty scale can also be based on a combination of these approaches, ensuring clarity and appropriateness. The goal of the reconstruction can help determine the best method to use.

Temporal uncertainty – the one related to the period that is reconstructed – has been visualised in the ArkVis interface through different visual techniques: transparency, colour variation, fog, vertical displacement (Zuk, Carpendale, and Glanzman 2005).

It is clear, indeed, that different goals require different communication strategies and that, in this process, designers have a decisive influence on the content that an image might convey, which can be related to facts, but also to hypotheses and speculations: incomplete knowledge can be concealed, but also presented in a transparent and readable manner.

In addition to these main design tools, Kensek (2007), Lengyel and Toulouse (2016) and Heeb and Christen (2019) enumerate other operations sometimes used in a wide range of different domains, where it is important to declare the process and the potential of error:

(1) Size distortion or dimensional characteristics such as the presence of both 2D and 3D elements, as well as comparative schemes with reconstructed parts as offsets (exploded) can also be used;

(2) Projections, holographs, animations, sound-based effects (silence for missing parts, change of volume or voice over for reconstructed parts: these can be used also on a digital image where sound can change according to the movements of the mouse);

(3) The non-reconstructed image can simply be put next to the reconstructed one or they can be superimposed as spatially concurrent images with rollover possibilities;

(4) Distance, through the choice of the point of view and framing (**FIG. 37**), is also useful to decide what we want to communicate. A wider angle corresponds to less detail shown in the model; the combination of wider and closer zoom can convey an overview and the detail of the most certain things, while hiding less documented areas;

(5) Decontextualisation: taking an object out of its context and inserting it in a neutral space indicates a clear demarcation with respect to a photorealistic model, in a way that is comparable to coloration, but the environment and the information about size is lost. This technique is used when there is little information about the environment and just some elements are reconstructed.

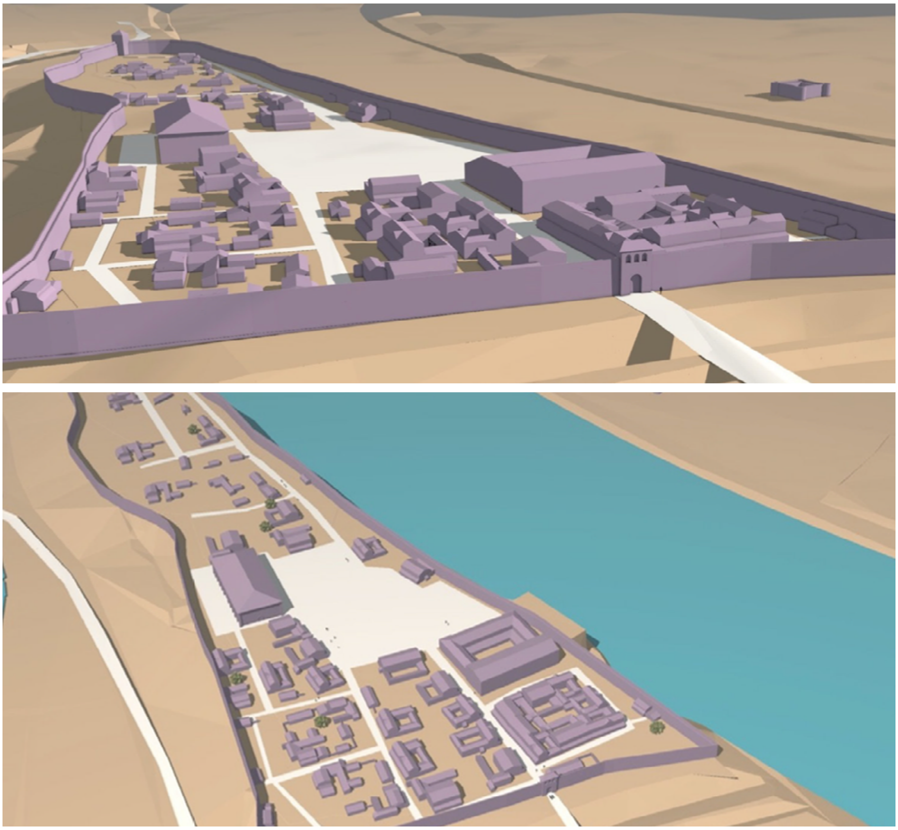

FIG. 37: Use of different points of view to highlight different features of the model (Heeb and Christen 2019).

More in general, among the different strategies for the visual communication of knowledge gaps, depending on the conceptual decisions that require the use of particular appropriate tools (Heeb and Christen 2019), we should also cite the representation of variants (**FIG. 39**).

More versions of an object sometimes have to be considered in order not to take a single interpretation for granted, as if it were indisputable.

Showing multiple reconstructions is an opportunity to portray many «lines of conjecture», signalling that any single reconstruction is not certain: they can be adjacent, concurrent, sequential as pop-ups appearing in a website, animations, virtual worlds (Kensek 2007).

Sometimes there is also the possibility to choose which specific reconstruction to exhibit from a set of possibilities by means of an interactive console (**FIG. 38**) that allows to pick subsets and combine them.

A virtual reconstruction console with a typology of columns, for instance, was created by Karen Kensek and her research group (Kensek 2007).

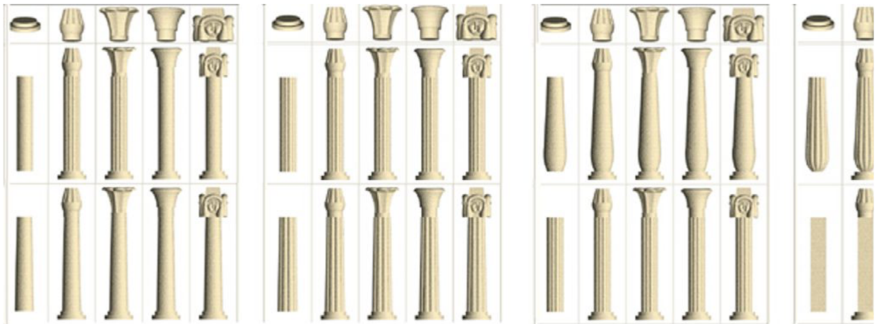

FIG. 38: Selection of variants of Egyptian columns through an interface that allows the combination of a base, eight shafts and four capitals (Kensek 2007).

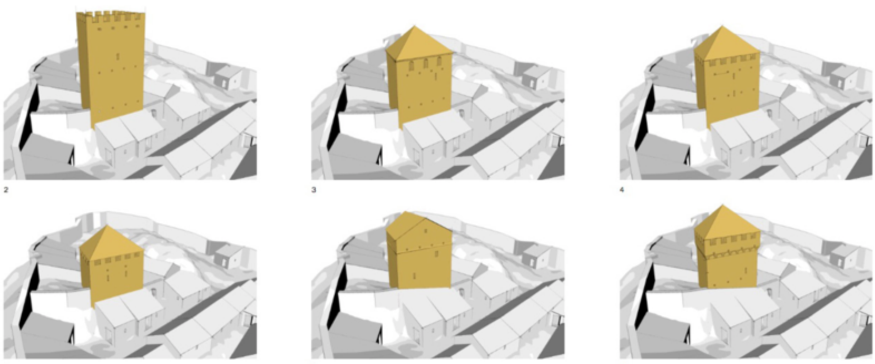

FIG. 39: Variants of the same tower according to different documentation (Heeb and Christen 2019).

Chandler and Polkinghorne have suggested as well, as a future direction of their work, the use of variants for the visualisation of the destroyed Royal Palace of Angkor, Cambodia (Chandler and Polkinghorne 2016):

> «What is required is a plural approach that communicates alternative possibilities […] multiple inter-

> pretations to imagine the layout of the Palace compound. Within the scope of contemporary computer and multi-media interfaces it is unproblematic to offer plural visions of the Palace open to manipulation. In a visualisation that uses graphic scripting parts of buildings or entire edifices can be repositioned, realigned and rescaled according to art historical, archaeological or architectural evidence […] An interactive visualisation (perhaps framed within a game engine) allows scholars and students to model the archaeological landscape directly».

The foundations of this kind of work date back again to the end of the 1990s.

The Ceren project (1998) carried out by Mark Gross, Jen Lewin, Payson Sheets and Mark Ehrhardt[12] showed that a model, initially conceived as an exercise in rendering, developed at a later stage into a «collaborative research effort to understand and interpret the source data».

The reconstruction of the agricultural village in Joya de Ceren, El Salvador allowed the creation of panoramic images and interactive walkthrough with hotspots on artefacts that linked to a database of archaeological specimens corresponding to the findings in that area. The reconstructors said that, while modelling, they «discovered various ambiguities and inconsistencies in the raw site data and drawings were provided». Thus, they resolved these problems with a re-interpretation of data, working in synergy with archaeologists.

Besides these visual strategies, we can also just rely on labels connecting missing or reconstructed data with a text and with image sources: the knowledge gaps and degrees of uncertainty can also be indicated with the design tools seen before, but the possibility of including diagnostic data connected to the model leaves the judgement to the viewer: this might be more adapt to expert users than to general ones.

Zwicky boxes[13], a sort of morphological thinking that helps divide a problem into categories represented by boxes (spaces in a digital document) can also help sort out the content.

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12 <http://mdgross.net/portfolio/virtual-archaeology-at-ceren/> (Accessed 10.10.2024).
13 <https://nesslabs.com/zwicky-box> (accessed 17.10.2024).

In the simplest cases, viewers can compare the reconstructed model with the original material, giving their own determination of accuracy or likelihood. However, the techniques here proposed are used exactly to make the viewer easily understand the reconstruction process and things that may not be seen otherwise. Other strategies that still allow these evaluations, without using visual representations directly on the model, are (Kensek 2007):

(1) Text-based systems used through labels such as "artist's rendering", "likely", "doubtful";
(2) Written material added as a footnote or endnote, or as pop-ups with hyperlinks to websites with evidence of the level of uncertainty;
(3) A percentage to evaluate alternatives, as happens for the weather forecast. The error range can also be indicated.

Graphic versions of 3D objects may also be connected to the written information about them. Before the use of the computer, a code number on the physical object (i.e. an archaeological find) constituted the link to a folder with archival documentation about it.

Digitally, this is entirely possible with CAD and especially with BIM, overcoming the problems that were still declared some years ago (Kensek 2007), when this process could be «difficult for high-end modelling and rendering software», even though there were already some applications in GIS (Forte and Siliotti 1996).

Many of the methods seen before can be translated into more visual depictions and vice versa.

This property becomes crucial when we have to communicate our assessments using standard exchange formats that may not keep the colour visualisation of the original model, but still can incorporate a number and a brief description for each uncertainty level (see **CHAPTER III**).

C.
COLOUR AND VISUALISATION OF INFORMATION

Among the methods seen in the previous paragraph, we will focus on the most documented and used one, which is the visualisation of uncertainty by means of colour schemes. The theoretical foundations of this design tool, as we will see here below, can be found in a genealogy of studies about colours starting from Newton and Goethe, until the books by Jacques Bertin and Edward Tufte on the use of colour (among other features such as shapes, textures...) especially related to cartography; other studies such as the one by Berlin and Kay (1960s) focus on the appearance of colour in various cultures: in the light of these approaches, we can see that, even though it is impossible to obtain a universal answer to this problem, it is quite reasonable to use the colours from red to blue in the proposed scale and follow the order of the spectrogram as already happens in other fields.

A colour gradient or scale, in the form of a spectrogram (**FIG. 40**), is indeed largely used in scientific disciplines for the analysis of parameters such as deformation, temperature, pressure (Apollonio, Fallavollita, and Foschi 2021), so it is important to understand how colour is used in scientific visualisations and see whether a comparison with the uncertainty scales used for CH can be done.

Another useful example is provided by heat maps (**FIG. 41**), data visualisation techniques in which colour represents the variation in the magnitude of a phenomenon. They have been (and are) applied in a variety of fields from science to economics. It is curious to notice how the history of these maps, starting from the end of the 19th century, is similar to the (more recent) one of uncertainty scales for 3D models.

At the beginning, there was no uniformity in the graphical way of visualising the values: greyscale, different symbols, etc. (Wilkinson and Friendly 2009). Greyscale was obviously the most used techniques because the graphs were done by hand; now, heat maps use a colour scale that generally ranges from red to blue (**FIG. 42**).

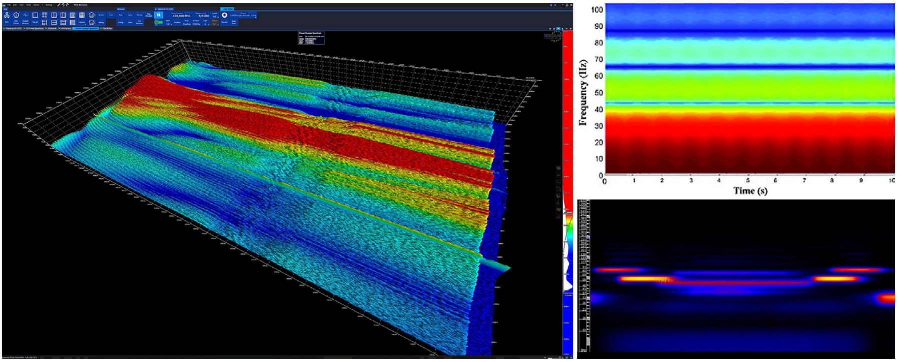

FIG. 40: Three examples among the many spectrograms used in scientific disciplines. On the left: the RF (radio frequency) spectrum of a battery charger over time; top right: spectrogram of an arterial blood pressure; bottom right: melodic range visualiser. <https://commons.wikimedia.org/wiki/File:3D_battery_charger_RF_spectrum_over_time.jpg>; <https://www.researchgate.net/publication/301644768_Detecting_heart_rate_while_jogging_blind_source_separation_of_gait_and_heartbeat>; <https://commons.wikimedia.org/wiki/File:Sonic_visualiser_melodic_range_spectrogram_example.jpg>; (accessed 10.10.2024).

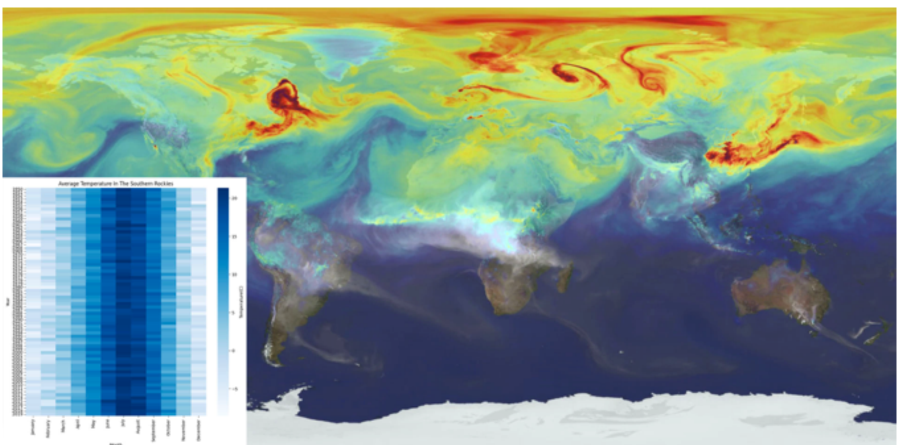

FIG. 41: Two heat maps visualising temperature variations. The larger one, using a scale from blue (cold) to red (hot), represents the different temperatures around the world; the smaller one, on bottom left, uses a lightness gradient to visualise on a matrix the different temperatures over a year in the same place. The months are given on the x-axis, the days on the y-axis.
<https://commons.wikimedia.org/wiki/File:Average_Temperature_In_The_Southern_Rockies.png>; <https://commons.wikimedia.org/wiki/File:World_heat_map.png> (accessed 10.10.2024).

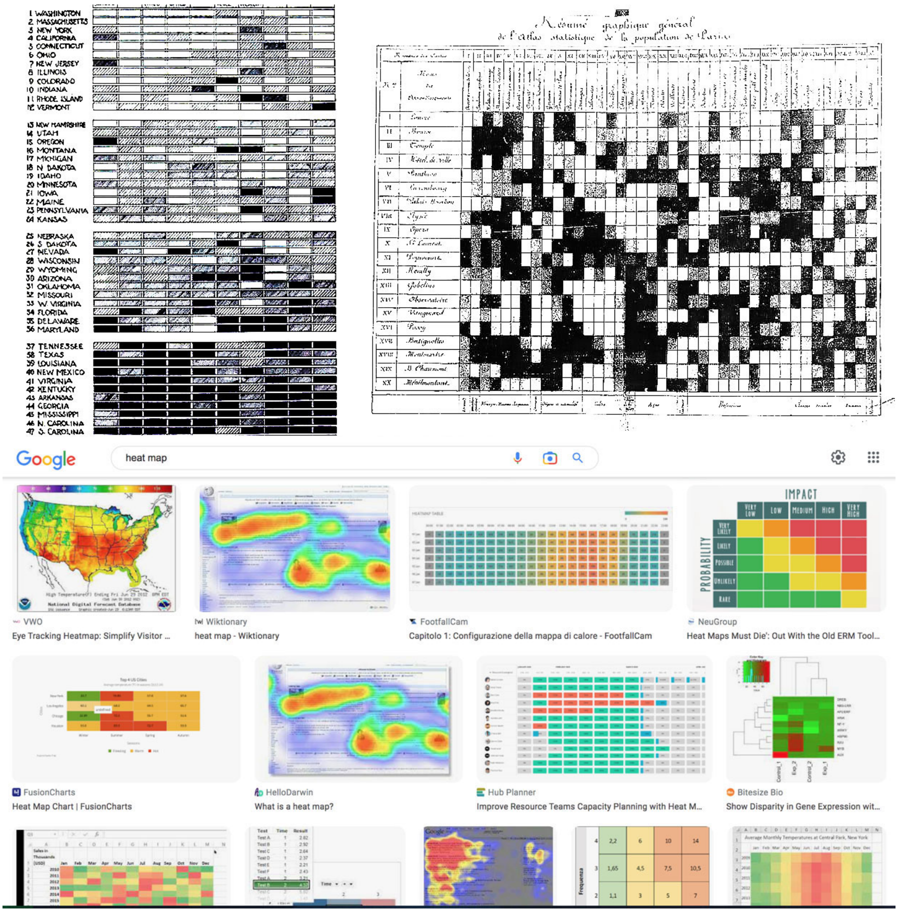

FIG. 42: Historical heat maps in greyscale drawn by hand (Wilkinson and Friendly 2009) and the first results on Google Images (accessed 10.01.2023) when typing "heat map". We can see that now they usually follow the colours of the spectrogram or a reduced green-red scale. Author's elaboration.

This is a curious event that leads us to investigate the bases of visualisation.

Visualisation is of primary importance to have an idea of a model stored in binary language in our computers, thus 3D modelling and 3D visualisation are entangled concepts[14].

In the field of digital 3D reconstructions, visualisation is sometimes

14 The importance of visualisation in these terms is stressed in the draft book of the DFG project.

identified with computer visualisation and therefore considered a recent field (AA.VV. 2005).

The National Science Foundation's Visualization in Scientific Computing Workshop report, for instance, explained (McCormick, DeFanti, and Brown 1987):

> «Visualization is a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method for seeing the unseen. It enriches the process of scientific discovery and fosters profound and unexpected insights. In many fields it is already revolutionizing the way scientists do science… The goal of visualization is to leverage existing scientific methods by providing new scientific insight through visual methods».

However, it is clear that this concept is far more ancient and it starts with our eyes and our way of processing information, even before computers performed similar tasks.

Since visualisation can be considered the creation of a "geometric representation of the regularity present in a data set", the first tool we use to produce visual models is our brain (Mouromtsev and D'Aquin 2016):

> «Our brain produces visual models to understand reality. When we see any object, we are not seeing that object, but our senses capture sensorial information (luminance contrasts), which is then transformed into a high-level representation of the shape of the object, in the form of a set of surfaces, that is in terms of observable geometric properties».

Brain is the place where sensorial information is transformed into visual models after the observation phase that includes perception, recognition and description. Images are data, thus formal description of something that really exists. Visual models are the equivalent of sensory representations in the brain: a translation of empirical phenomena into a geometric language. They should integrate colour, shape, texture, topology and motion, allowing the understanding of the causal dynamic of the represented entity.

Object perception (and colour perception as a part of it) depends on two types of abstraction: a perceptive and a cognitive process.

During the perceptive process, features like texture (composition of elements with a law of repetition), shape (with its dimension, position and orientation) and colour (hue, lightness and saturation) are identified – that is what we would call the "plastic level" in semiotics. The collected information is then analysed through a cognitive process, where memory influences the recognition of an object based on a repertoire of analogies – thus, operating at an "iconic" or "figurative level" (Greimas 1991).

The archaeologist Juan Antonio Barceló gives us a general framework for using virtual reality techniques in scientific visualisations stating: «visualising is not seeing, but an inferential process to understand reality» (Barceló 2001).

A model is the representation of some features of an entity: its components and the relationships between them. It is one of the possible valid results of a theory, not a simple surrogate for reality, but a knowledge structure.

Visualisation, in this context, is the geometric representation of the regularity in a data set, in which precise mathematical description allows to reach complexity, also adding information in what he calls "enhanced reality".

Digital technologies generate fundamental changes in forms, content, media with a seismic effect widely concerning visualisation tools.

The visual material, also due to the polysemic nature of images, is considered «a medium through which new knowledge can be created» (Ortega-Alcázar 2012) and is increasingly investigated through content analysis, semiotic analysis and discourse analysis.

This is close to other fields such as visuospatial reasoning (Tversky 2005), connected to visual thinking and decision-making (Arnheim 1969; Nutt and Wilson 2010), which analyse how information, both structural (more easily understandable) and functional (requiring expertise), is retrieved from diagrams.

Consequently, we must explore the properties and potential of these virtual worlds (Beacham, Denard, and Baker 2011), keeping in mind that visualisation is not only a graphical representation of data, but also a cognitive tool (Card, Mackinlay, and Shneiderman 1999; Ware 2004) for the acquisition of new knowledge according to three activities (Alexandre and Tavares 2010):

(1) Exploratory analysis (the discovery of new knowledge);
(2) Confirmatory analysis (the determination of evidence);
(3) Presentation (the display of characteristics of the data involved).

Every stage of the digital 3D reconstruction is connected to visualisation, from the production and description to the presentation and communication of the reconstructed object.Reconstruction, intended as the recreation of formal features and visual aspects of an object, is one of the approaches to visualisation together with simulation (the representation and study of behaviours and interactions) and the representation of scientific knowledge (the use of visual images to explain theoretical knowledge).

Visualisation to convey data «in complete accordance with facts» (Pang, Wittenbrink, and Lodha 1996) has been considered a goal since the 1990s in conferences such as the IEEE Visualization discussions on *How to lie with visualization* (Globus and Uselton 1995)[15], as well as *How not to lie with visualization* (Rogowitz and Treinish 1996) and, even before, the NCGIA initiative on *Visualization of spatial data quality* (1991)[16].

The steps for the creation of a computer visualisation – and this also applies to digital 3D models –can be summarised following this scheme[17]:

15 See also the website <https://www.vislies.org/2022/> (accessed 31.10.2024).
16 <http://www.sci.utah.edu/~kpotter/Library/Papers/beard:1991:VSDQ/index.html> (accessed 31.10.2024).
17 Taken from a presentation by Sheelagh Carpendale (accessed 07.08.2024): <https://innovis.cpsc.ucalgary.ca/innovis/uploads/Courses/InformationVisualizationDetails/09Bertin.pdf>

(1) The understanding of a system of related information and tasks;
(2) The creation of a mapping from the data to a visual representation;
(3) The "presentation" of this visual "representation" on the computer screen;
(4) The provision of methods of interacting with the visual representation, which can include methods for varying both the "presentation" and the "representation";
(5) The assessment of the usefulness of the representation, the way it is presented and/or its interaction methods.

Let's see on what visualisation – especially visualisation of colour – is grounded.

Two components are of primary interest when we speak of visualisation: the physiological one and the cultural one.

C.1. *Colour visualisation: physiological basis*

The discourses about colour often appear naïve and based on psychological and semantic theories, as if colour were a universal of semantics.

That's why some clarifications about visualisation of colour seem necessary.

There is no general colour code; however, the topic of colour palettes is of fundamental importance.

Colour is not an object of physics, but of psychophysics: it exists only when a subject perceives it, measuring sensations in a statistical way. We can say that it is in the eye (and brain) of the beholder[18], connecting the topic to studies of cognition psychology and especially "ecological psychology" (Gibson 1950; Goldstein 2005) that have emphasised the primacy of perception, meaning that what we perceive through senses is enough for us to make sense of the world.

Still, colour is also obviously related to physical quantities, for instance wavelength and energy, and to the most important physical dimensions used to analyse light in general, from luminous flux (measured in lumens) to light intensity (measured in candelas) or illuminance (measured in lux). Without light, we can neither see colour, nor perceive its variations especially according to three parameters, which can be expressed as variations in wavelength (**FIG. 43**):

(1) Hue: the predominant wavelength that arrives to our eye, evaluated as an average in a statistical way by our rods and cones;
(2) Saturation: the variance of the energy that enters, that is how much the stimuli differ from each other;
(3) Lightness: the amount of energy that enters.

The studies on optics in the ancient world are mainly related to Euclid

18 This is the title of an interview with the neuroscientist Jenny Bosten of the University of Sussex in England, published online: <https://knowablemagazine.org/article/mind/2022/science-of-color-perception> (accessed 29.10.2024).

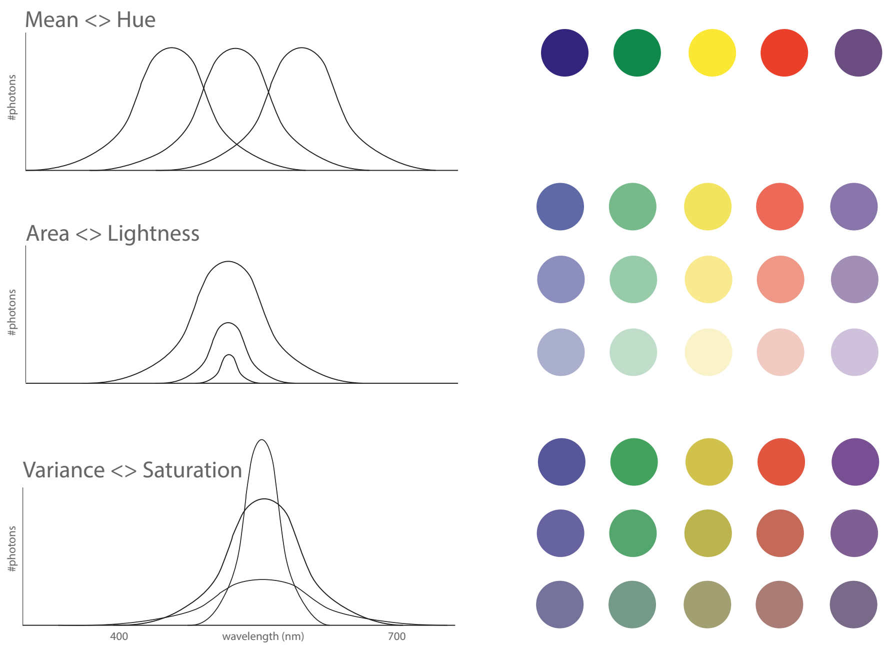

FIG. 43: Explanation of hue, lightness and saturation as variation in wavelength. Author's elaboration based on <https://www.di.univr.it/documenti/OccorrenzaIns/matdid/matdid311142.pdf> (accessed 24.09.2024).

(his Optics dates back to 300 BC) and were then developed by Ptolemy (2nd century) and, in the Islamic world, by al-Kindi, Ibn Sahl and Ibn al-Haytham (10th – 11th century)[19].

However, we know that the discovery of the visible spectrum of light is more recent: it dates from the mid-1600s, when Isaac Newton observed a ray of light passing through a prism. In this process of refraction, light takes different directions according to its wavelength and, consequently, the human-perceivable part of the spectre, between red and violet, becomes visible.

From this moment, colour can be studied as a scientific object.

The spectrum was represented in a wheel (**FIG. 44** left), where purple was located next to red: even though this colour was considered non-spectral, it was still obtained by a mixture of red and violet light.

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19 <https://academia-lab.com/encyclopedia/history-of-optics/> (accessed 03.11.2024).

He also identified red, yellow and blue as primary colours[20]. The generation of additional colours is also possible and it is visualised by connecting with a segment the two spectral colours initially used (**FIG. 44** right) and mixed in particular proportions. If a quantity of a colour A is mixed with a quantity of colour B, the result is a quantity a+b of colour M so that AM: BM=b:a. It is the same hue as the intermediate spectral colour, but paler. The rays of the circle join the spectrum colour to white, thus, along the rays, the colours are formed by a quantity of spectral colour and another of white. If the point is located in the boundary between red and violet, the generated colour is that purple which is not part of the spectrum: this already explains, in our case, why it is a complicated colour also in the uncertainty scales that we have seen before and why the proposed scale ranges from blue to red.

This theory of chromatic balance has become fundamental for many other theories through time, also to more advanced ones that better differentiate the three parameters: hue, saturation and lightness.

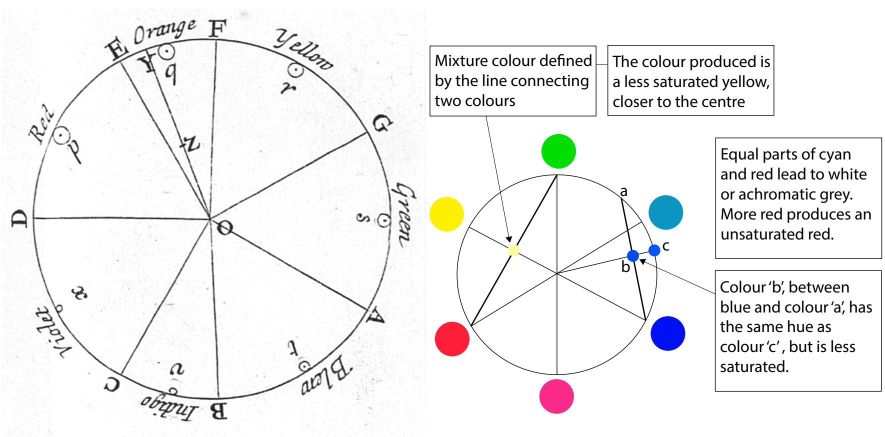

FIG. 44: On the left: the visible spectrum of light according to Newton; on the right: the formation of intermediate colours. <https://commons.wikimedia.org/wiki/File:Newton%27s_color_circle.png>; author's elaboration based on <http://hyperphysics.phy-astr.gsu.edu/hbase/vision/newtcol.html> (accessed 20.10.2024).

20 <https://munsell.com/color-blog/sir-isaac-newton-color-wheel/> (accessed 28.10.2024).

Many colour schemes have been created especially in the 1800s starting from Newton's one and generally employing circular or triangular shapes. Among the ones based on circular geometry, the ideal colour sphere (Farbenkugel) by Otto Runge (1810) is one of the most famous (**FIG. 45** left). Colours with maximum hue are positioned around the equator, while white and black are at the poles of the sphere[21]. Runge wasn't interested in the exact calculation of the relationships between colours. Conversely, James Clerk Maxwell, around 1860, measured colours quantitatively starting from three primary coloured lights from which the other colours were produced by varying the proportions of these three lights. This process was represented using a triangle with primary colours at the edges (**FIG. 45** right)[22].

Anyway, what really interests us is the process that stands behind colour perception and that explains why we there are colours that we consider "primary" and less complex than others.

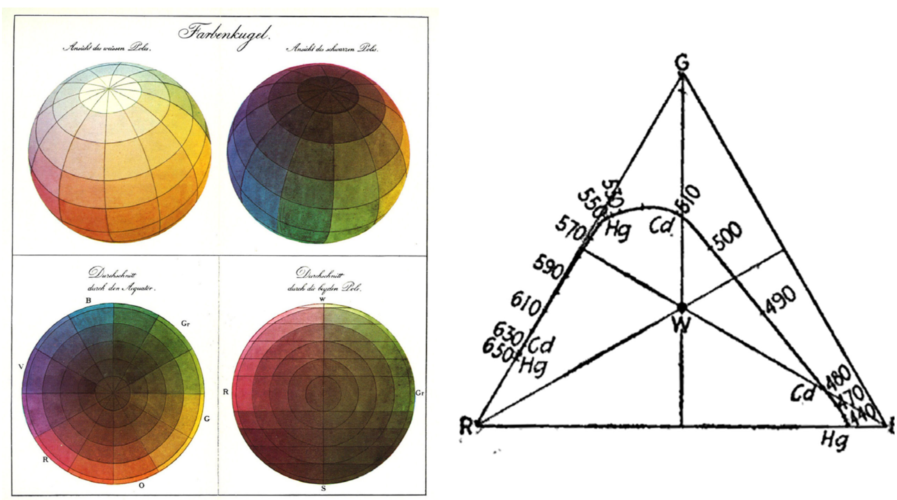

FIG. 45: The *Farbenkugel* by Otto Runge (left) and the colour triangle by James Clerk Maxwell (right). <https://upload.wikimedia.org/wikipedia/commons/9/94/Runge_Farbenkugel.jpg>; <https://upload.wikimedia.org/wikipedia/commons/4/42/Maxwell_color_Triangle_Luckiesh_1921.png> (accessed 12.08.2024).

21 These and other colour schemes are accessible here: <https://www.colorsystem.com/> (accessed 12.08.2024).
22 <https://homepages.abdn.ac.uk/j.s.reid/pages/Maxwell/Legacy/MaxTri.html> (accessed 31.10.2024).

Johann Wolfgang von Goethe first studied the psychological effect of opposed colours in his Theory of colours (Farbenlehre). He arranged them around a colour wheel similar to the one by Newton, but identifying six colours symmetrically located (**FIG. 46**): the colours diametrically opposed are therefore the ones that evoke each other (red/green, yellow/purple and orange/blue) – what we would call complementary colours – also observing that all the symmetrical intermediate gradations evoke each other as well (Goethe 1810).

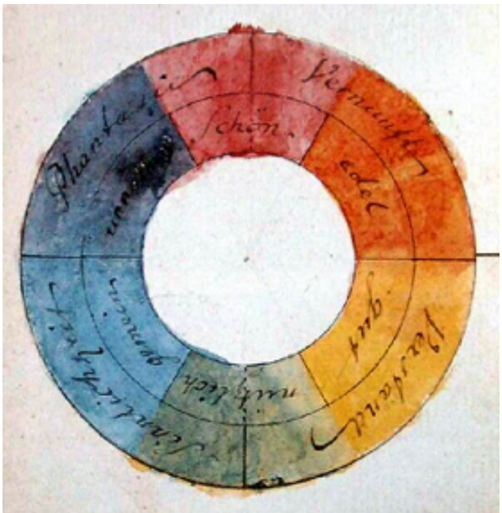

FIG. 46: Goethe's colour wheel with associated symbolic qualities, 1809. Source: <https://en.wikipedia.org/wiki/Theory_of_Colours#/media/File:Goethe,_Farbenkreis_zur_Symbolisierung_des_menschlichen_Geistes-_und_Seelenlebens,_1809.jpg> (accessed 28.10.2024).

The theories of colour perception were largely studied during the 19th century.

The trichromatic theory was proposed in 1802 by Thomas Young as a model of the perception of colour that can be coded by three main colour receptors (that is, three different spectral classes of cones) instead of thousands of them coding for individual colours (Young 1802).

Rods give the information related to brightness (they are more sensitive to vision in the dark); cones are sensitive to colours according to a trichromatic principle, directly corresponding to the primary colours of the additive mixing: the three types of cones are in fact red, green and blue. They are sensitive to determined wavelengths, evaluated as an average: this is the information that is sent to the brain (**FIG. 47**).

This theory, now supported by evidence (the physiological response of the photoreceptors, the genetic code of the cones, the identification of their spectral sensitivity by microspectrometry), suggests that a combination of the three channels explains our colour discrimination functions.

According to Hermann von Helmholtz, who further developed the trichromatic theory by Young, there are things that cannot be explained through the previous schemes, such as the achromatic part of those diagrams. Colours between yellow and green don't have complementary colours, but can be neutralised by mixing non-spectral colours between red and violet, represented by Helmholtz along a straight line (Helmholtz 1867). Thus, the shape of the colour space changes: this new diagram, which is no longer a circle, will be adopted by several other classifications up to the present time[23] (**FIG. 48**).

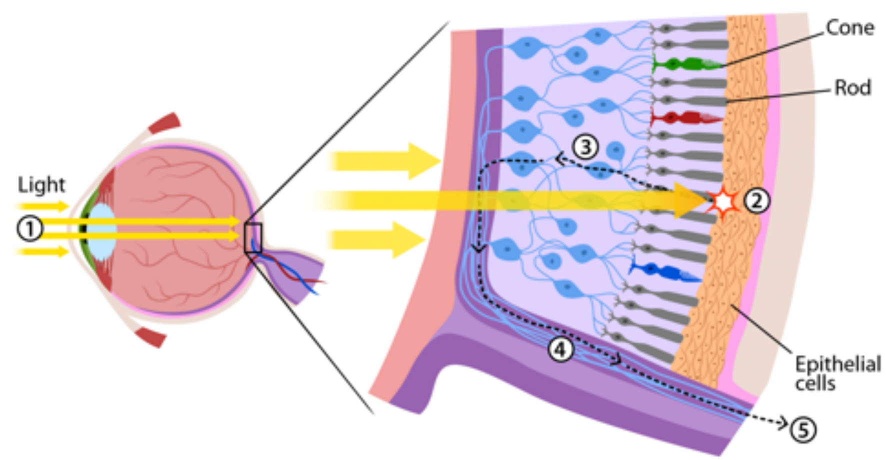

FIG. 47: Light entering the eye and arriving to the retina, where it is processed by rods and cones. <https://askabiologist.asu.edu/rods-and-cones> (accessed 28.10.2024).

23 This doesn't mean that the circle by Newton is no longer used: it is still valid in many colour theories; the colour classifications used in computer graphics such as RGB, however, are usually generated starting from a colour space similar to the one described by Helmholtz.

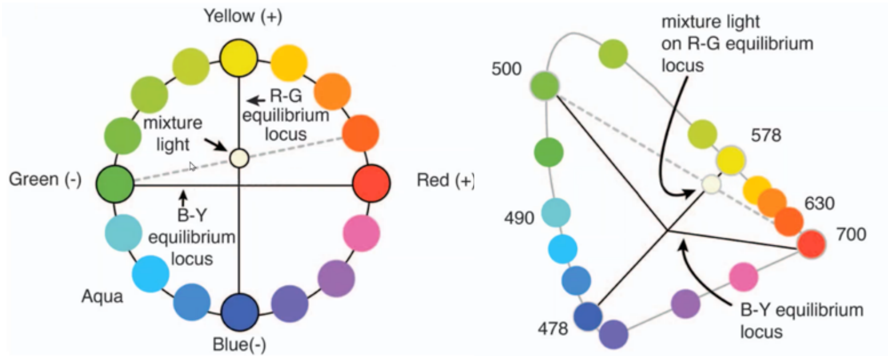

FIG. 48: Comparison between the colour spaces by Newton and Helmholtz. <https://opg.optica.org/josaa/fulltext.cfm?uri=josaa-34-7-1099&id=367369> (accessed 28.08.2024).

The trichromatic theory, however, doesn't completely convince Ewald Hering, since it fails to account for the fact that red and green, as well as blue and yellow, seem to be antagonist colours: we cannot perceive a greenish red or a yellowish blue. As a result, his psycho-semiotic "opponent colour theory" is based on four colours, plus black and white, and on the oppositions (**FIG. 49**) that are generated between them (Hering 1878).

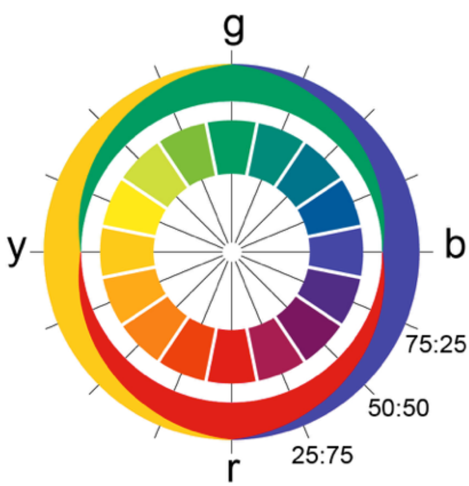

FIG. 49: Psychological theory by Ewald Hering: here the oppositional colours discovered by Hering are positioned in a circle around the one adopted by Newton, so as to complement it. <https://commons.wikimedia.org/wiki/File:Ewald_hering_colors.jpg> (accessed 29.10.2024).

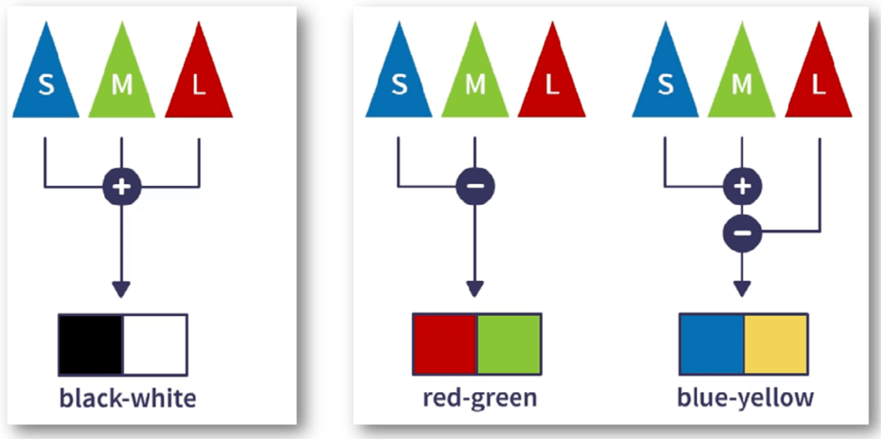

FIG. 50: The generation of colour oppositions according to Hering's theory. <https://doi.org/10.3390/su15054341> (accessed 29.10.2024).

The entire process is produced by the combination of statistical information operated by the cones through an activity of activation an inhibition: calling the red, green and blue cones respectively L, M and S (for long, medium and short wavelength), the red-green axis comes from the difference between L and M stimulation; the blue-yellow axis comes from S minus the sum of L and M; the black-white axis comes from the sum of all three.

Thus, three oppositional couples are generated: yellow/blue, red/green, black/white (**FIG. 50**). These are normally the most distinct and recognisable colours. Rather than primary colours, from a scientific point of view, we should therefore speak of primary oppositional couples.

In the chromatic diagram by Hering these oppositional couples are integrated into Newton's circle. This is very close also to the semiotic classification of colours by Felix Thürlemann, in a correspondence between the physiological and the cultural approach.

Hering never proved his hypothesis, but just supposed it – by abduction – based on examples such as negative afterimages[24]. In the 1950s Hurvich and Jameson[25] have provided quantitative data isolating the psychophysical colour opponent channels; other evidences concern the electrical recording of some retina cells in fish and primates.

Therefore, due to the fact that both the trichromatic theory and the opponent theory are supported by evidence, in more recent times they have been incorporated into a single "stage theory"[26], composed of the two intertwined processes (**FIG. 51**):

(1) An initial trichromatic stage, at the level of the receptors, with trichromatic cone cells that respond positively to one of the three frequencies exhibited by the photons arriving on their surface;

(2) A subsequent neural oppositional process stage, during which the three colour channels, activating the corresponding cells, inhibit the other ones.

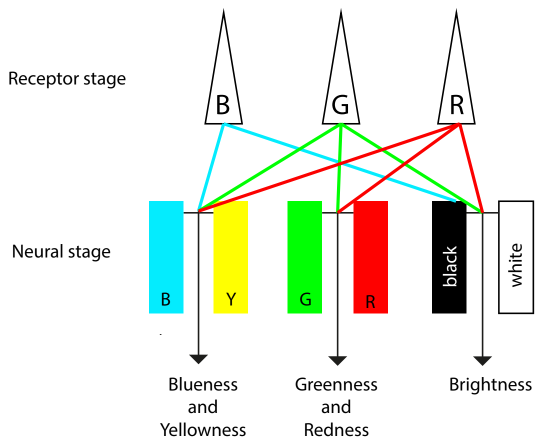

FIG. 51: The stage theory: both the trichromatic theory and the opponent theory are incorporated at different levels (respectively receptor and neural stage). Author's elaboration based on <https://www.ncbi.nlm.nih.gov/books/NBK11538/figure/ch28kallcolor.F16/?report=objectonly> (accessed 29.10.2024).

24 The phenomenon for which, after a period of exposure to a colour, when we move our eyes towards a white surface, we tend to see its opposite (complementary) colour.

25 <http://ftp.cse.buffalo.edu/pub/colornaming/diss/subsection2.7.4.5.html>; <https://www.ncbi.nlm.nih.gov/books/NBK11538/> (accessed 31.10.2024).

26 <https://www.ncbi.nlm.nih.gov/books/NBK11538/> (accessed 31.10.2024).

What we can say in the light of these studies is that these four spectral colours – red, yellow, green and blue – are normally the ones that we perceive and differentiate with the least effort. That's why we will adopt them in our colour scale for the visualisation of different levels of uncertainty related to hypothetical digital 3D models.

The studies that we have seen, besides explaining the physiological basis of our perception of colour, have also influenced modern colour theories between science and art[27], as well as the creation of colour schemes such as the ones that we now use in computer graphics.

The Munsell system in 1904 by Albert Henry Munsell made it possible to fully specify all the colours by indicating hue, saturation and lightness. In this case, the colours are arranged cylindrically around an irregular solid (based on the data he had collected about human visual responses), where hue is measured around horizontal circles, saturation is measured radially from the centre towards a point composing the circle, lightness is measured vertically (**FIG. 52** left). From models like this, other classifications derive, such as, for instance, the HSV/HSL[28] models described by Alvy Ray Smith in the 1970s, sometimes represented as a double cone where the central axis goes from white at the top to black at the bottom, the angle from the axis depicts the hue and the distance from the axis depicts saturation.

The Natural Colour System (NCS), a proprietary model developed by the Swedish Colour Centre Foundation from 1964, is based on Hering's colour opponency hypothesis, thus on human perception rather than on colour mixing. Colours are indicated by means of three values: darkness, saturation and hue. Hue is defined as a percentage between two of the opponent colours. The six colours on which it is based are the opponent couples red-green, yellow-blue and white-black, which are the colours processed by the retina's ganglion cells (**FIG. 52** right).

Other largely used systems, like the additive RGB or subtractive CMYK ones, are instead based on the reaction of the colour-receptive-cones. Modern colour spaces in most cases derive from – and are super-

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27 We refer first of all to the study of colour at Bauhaus through the theories by Johanes Itten, Wasilly Kandinsky, Joseph Albers and Paul Klee (de Coca Leicher 2018).
28 <https://en.wikipedia.org/wiki/HSL_and_HSV> (accessed 31.10.2024).

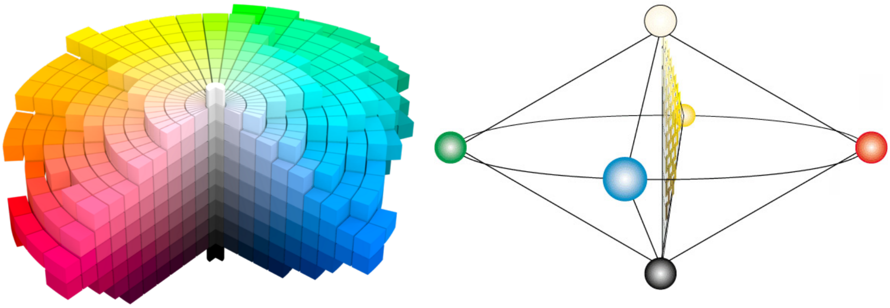

FIG. 52: The Munsell (left) and NCS (right) colour systems. <https://commons.wikimedia.org/wiki/File:Munsell_1943_color_solid_cylindrical_coordinates.png>; <https://commons.wikimedia.org/wiki/File:Animation_of_the_NCS_Colour_System.gif> (accessed 01.09.2022).

vised by – CIE (Commission Internationale de l'éclairage), which adopts a general scheme that is based on the shape elaborated by Helmholtz and on the concepts behind Maxwell's studies. It consists of a 3D map then projected in 2D, where XY coordinates indicate RGB percentages. Colour systems such as Adobe RGB, CMYK, sRGB are based on this[29] (**FIG. 53**).

These colour schemes are composed of a continuous gradient of colours obtain varying the hue, saturation and lightness parameters. Even if we consider commercial colour classifications, we see that hundreds of different colours are identified[30]. But how many colours do we really perceive?

Only a small number of colours can be accurately and promptly perceived by humans: according to Healey (1996) only 5 to 7 colours can be found rapidly and with a low error rate on a map; MacEachren (1995) has measured that the detection rate sensibly diminishes when the number of colours increases: for 10 colours, we have 98% of detection rate, but this value decreases to 72% for 17 colours.

29 <https://homepages.abdn.ac.uk/j.s.reid/pages/Maxwell/Legacy/MaxTri.html> (accessed 29.10.2024).

30 Just to mention two examples coming from different parts of the world (USA and Japan): <https://www.pantone-colours.com/>; <https://copic.jp/en/about/color-system/> (accessed 29.10.2024).

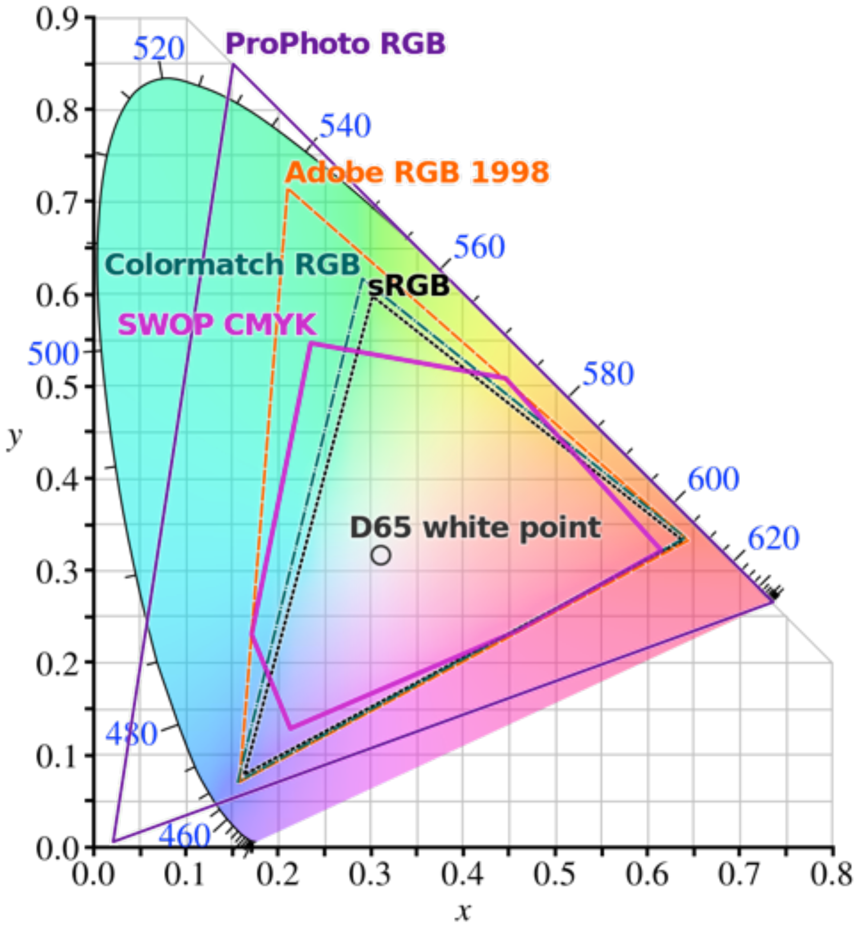

FIG. 53: Comparison of some RGB and CMYK chromaticity gamuts on a CIE 1931 XY chromaticity diagram <https://en.wikipedia.org/wiki/Color_space#/media/File:CIE1931xy_gamut_comparison.svg> (accessed 31.10.2024).

C.2. Colour visualisation: cultural basis

These examples can be considered the link between physiological and cultural ways of analysing colour, being also similar to another problem: how many colours compose the rainbow? We can answer seven; however, according to Aristotle, it is composed of only three fundamental colours: red, green, blue. He also mentions a yellow-orange area, but he says that it appears to be created by the superimposition of the red and the green ones (Maitte 2006).

Of course we know that physically the rainbow is a continuous spectrum with wavelengths that vary within the visible light range – there are no separation lines or discontinuities. The human eye can discriminate more than seven colours, but those are the ones that we can easily name, for historical and cultural reasons.

This is the relativist hypothesis, in which at least anthropology, cognitive science, linguistics, semiotics and philosophy are involved, studying the relationships between language and thought.

The Sapir-Whorf hypothesis (Edward Sapir 1963; Whorf 1956), originally formulated in 1929 by the anthropologist and linguist Edward Sapir and then also developed by his student Benjamin Lee Whorf, is the primary example to explain this point of view. It states that language affects the way a person thinks, up to the point that language would be able to determine the perception of the world[31].

The origin of this hypothesis can be found in the work of the anthropologist Franz Boas, who was Sapir's teacher.

Boas's research is especially famous for mentioning the variety of words that Eskimoes use to indicate what we would generally call "snow", differentiating "snow on the ground" (*aput*), "falling snow" (*qana*), "drifting snow" (*piqsirpoq*), etc., even though he also reports that these languages tend to allow, with respect to English, more variety

31 In other interpretations of the theory, the language structure would influence the world view of speakers of a given language, but without determining it. <https://en.wikipedia.org/wiki/Linguistic_relativity> (accessed 21.10.2024).

in the creation of single words starting from the same root (Boas 1911; Kaplan 2003).

There are also languages in which green and blue are colexified, a lexical gap that is expressed with the word "grue"[32]. Sometimes different terms exist, but, when it is too dark, a single word is used.

These arguments seem to prove, to some extent, the effectiveness of a relativistic hypothesis; however, the major criticism is that, according to this interpretation, if we didn't have a word to describe a phenomenon, we wouldn't fully perceive it.

Against cultural relativism, the anthropologist Brent Berlin and the linguist Paul Kay (1969) followed a universalist hypothesis: for biological reasons, there should be some universal restrictions on the number of basic colour terms. They analysed the way in which colours appear according to a series of stages in ninety-eight different languages. These words indicating colours had to meet particular requirements: they had to be monolexemic (not a composition of more words related to colours such as "yellow-red"), monomorphemic (not "reddish"), not included in any other colour term (not "crimson", being it a type of red), not used to indicate individual objects or only a narrow class of objects ("blonde" for hair or beer). Colour terms borrowed from other existing words (and things) are usually avoided, apart from some cases ("orange").

It follows that basic colour terms appear in a maximum of seven stages: in this process, the colours identified in an abstract way can be up to eleven (**FIG. 54**). All languages indicate "black" and "white" (stage I); if there is a third element, this is "red" (stage II); a fourth is either "green" or "yellow" (stage III); if they also contain a fifth term, both "green" and "yellow" are present (stage IV); the sixth would then be "blue" (stage V); the seventh "brown" (stage VI); if they have between 8 and 11 elements, the words for "purple", "pink", "orange", "grey" appear (stage VII).

The terms from brown onwards do not emerge until the language has made a clear distinction between green and blue.

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32 The word was initially used by Nelson Goodman in 1955, but with a different meaning (Goodman 1954; Goldstick 1989).

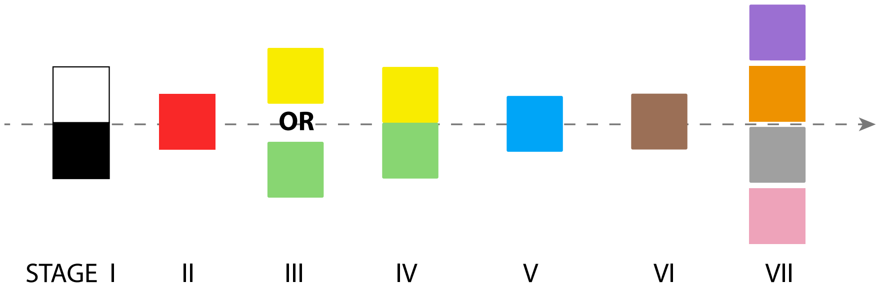

FIG. 54: The stages of colour appearance in a culture according to Berlin and Kay (1969). Author's visualisation.

The first five stages contain the primary colours (or oppositional couples according to Hering) chosen for our uncertainty scale.

Berlin and Kay also reported that each language selected about the same focal hues (that were indicated using the Munsell colour system) for each colour category. This point was especially contested: not only the used colour system, but also the translation method for the collected terms is west-centered (Saunders 2000) and do not consider the different uses that concur to the definition of the meaning of a term (Lucy 1997).

Subsequent investigations try to connect the relativist and the universalist hypotheses. According to Eleanor Rosch, who studied as well the categorisation and naming of colours in different cultures, categories work in a probabilistic way: how much they are close to a prototype (similar to fuzzy logic and to what Bayes affirmed). This is evaluated in the form of a statistical report (Rosch Heider and Olivier 1972; Joe and Gooyabadi 2021).

Probabilistic inference was also used to test the Sapir-Whorf hypothesis (Cibelli et al. 2016) in terms of probability distributions. Here the conjunction of the universalist and relativist hypotheses, both involved in colour cognition, can be seen: linguistic categorisation interacts with the non-linguistic (biological) processes of thinking from which the universal constraints derive. Dealing with this problem in terms of probabilistic inference also highlights the role of uncertainty.[33]

Another important study is the one conducted by the art historian and

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33 At this point, it seems that we have somehow come across a short-circuit: we base an uncertainty scale on theories of colour that, in turn, are subject to uncertainty. Is it semiotician Felix Thürlemann, in the analysis of the painting *Le rouge et le noir* by Paul Klee, in a theory of colour that cannot be divided from a theory of art (Thürlemann 1982).

Colour can be described in two ways:

(1) At a categorical (taxonomic) level, related to the "plane of expression", hue (especially primary colours), saturation and lightness are analysed according to a certain number of taxonomic categories that semiotics constitutes into figures contributing to the creation of meaning;
(2) At an evaluative level, related to the "plane of content", the "affective" content34 of an object is described, similarly to what Goethe did in 1810, when he first gave synesthetic attributes to colours like "warm" and "cold". Many oppositions of colours result in oppositions in meaning in semisymbolic relationships (as an example, "light : dark = happy : sad").

For the categorical description, Thürlemann takes up Hering's definition of the psychological primaries, establishing logical relationships between them. Achromatic primary colours are expressed by lightness (from white to black); chromatic ones are connected to the four psychological primaries. These can be put in a series in which each one of them is positioned among its closer ones. The series results in "red-yellow-green-blue-red…" in a circular repetition. It is exactly on the possibility of closing this series of primary chromatic terms that all the schematic representations in circles, triangles, cones, etc. are grounded. The passage from a primary colour to the following one is gradual and generates intermediate colours (**FIG. 55**).

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because every form of reduction of reality involves uncertainty? This is what we would suggest. We have a model of a lost artefact and a model to evaluate uncertainty. Both models are reductions of reality.

34 Apart from this, we know (and we just mention it briefly here) that meanings given to colours radically change from a culture to another, as in the famous examples of red – indicating luck in China, passion in Europe, anger in north America – or white – indicating hygiene and emptiness in western culture, mourning and death in some eastern cultures.

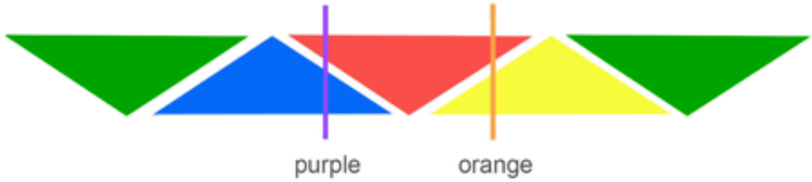


FIG. 55: Felix Thürlemann, identification of the four psychological primaries according to Hering's theory. Here they are arranged in a series that can be infinitely repeated (or closed in a circle). Coloration of the diagram that in the original paper was presented in black and white, with the names of the respective colours in each area (1982). Author's visualisation.

We should also pay attention, in our case, to the "evaluative level" and the semisymbolic relationship that sometimes is created, for which "green : red = right : wrong". An uncertainty scale with green and red at its poles should be avoided in order not to convey a too restrictive meaning.

Starting from this psychological and cultural context, studies related to the use of colour (but also shape and texture) in visualisation have been conducted.

Jacques Bertin (1967) states that in graphics (printable diagrams or maps in his case, as in **FIG. 56**), each element is defined beforehand: each sign signifies a precise thing, thus it is a monosemic system:

> «It is to dedicate a moment for reflection during which one seeks a maximum reduction of confusion; when, for a certain domain and during a certain time, all the participants come to agree on certain meanings expressed by certain signs, and agree to discuss them no further. This convention enables us to discuss the collection of signs and to link propositions in a sequence which can then become "undebatable", that is, "logical"».

In the study of graphs, he distinguishes between "invariants" (the complete and invariable notion common to all the data, often declared in the title) and "components" (the variational concepts, represented for example by quantities, time, nature of the datum). The levels of organisation constitute a hierarchy from qualitative (the most general level) to ordered and then quantitative features. They form the «domain of universal meanings, of fundamental analogies». The visual variables acquire meaning depending on where we place them, how we place them and by their retinal variables (or visual characteristics). The retinal variables that the graphic sign-system has at its disposal are eight: the two dimensions of the plane, size, value, texture, colour, orientation and shape (in computers, we would add motion, saturation, flicker, depth, illumination, transparency). Each visual variable can be selective, associative, quantitative, present ordered changes, have a maximum length beyond which changes are not perceptible.

For example, value and colour are selective and associative, but not quantitative. Their length is theoretically infinite, but practically limited: association and selection don't work with more than 7 segmentations, whereas distinction arrives at 10. While value has a determined order (from lightest to darkest or vice versa), colour doesn't have one, even though a rainbow scale is often used.

Points are used to represent for example a location, independent of the size and character of the mark; lines for boundaries or connections, independent of the width; areas for things of measurable size.

The Gestalt principles seem to guide these prescriptions (Lidwell, Holden, and Butler 2003; Wagemans et al. 2008), in which the quality of perception is generally influenced by visual parameters.

These are studies related to phenomenology (Husserl 1983)[35] that developed by opposing to the atomistic point of view (according to which a visual sensation starts from elementary sensations) a holistic one, starting from the "whole". General laws are emergent properties resulting from a global set of things.

The main rules are proximity, similarity (and orientation), closure, figure/ground, continuity, figurative familiarity (past experience), Prägnanz.

The principles themselves are intertwined in a whole.

35 First German edition dating back to 1913.

(1) Proximity: in a set of elements that are all equal, we tend to group the ones that are closer to each other;
(2) Similarity: in a set with different classes of elements, we tend to group elements that appear similar. Orientation is connected to similarity because, in the same way, we tend to group elements that are equally oriented;
(3) Closure: we tend to see shapes as limited by a continuous boundary and ignore, in case, the interruptions of this continuity. It is also based on the
(4) "Figure/ground" principle, which deals with what we perceive as negative space and what as the focal point of the representation, sometimes generating ambiguities;
(5) Continuity of direction: when we see intersecting lines, we tend to join segments forming the most continuous lines (those with minimum change in their direction);
(6) Figurative familiarity: this depends on iconic analysis and what we already know of the shapes we see. As an example, a combination of them can be perceived as a face because we are familiar with face recognition;
(7) The concept of "Prägnanz" (also known as "law of simplicity" or "good figure") keeps all the previous concepts together, saying that, when we perceive one thing, we are always looking for the simplest way of understanding it.

Edward Tufte continued these studies on visualisation of information (**FIG. 57**), especially related to infographics (Tufte 1990; 1997; 2001), with concepts such as «Escaping Flatland», reflecting on the fact that we live in a 3D world, but information lies in a 2D space: examples are given related to attempts to overcome this limit.

Maureen Stone mentions Edward Tufte (Stone 2006) recalling the concepts of «avoiding catastrophe» and the statement «above all, do no harm». There is an aesthetic component, but the essential is function. She focuses on basic principles of colour design, legibility, guidelines for picking up colours based on studies and evidences in perception.

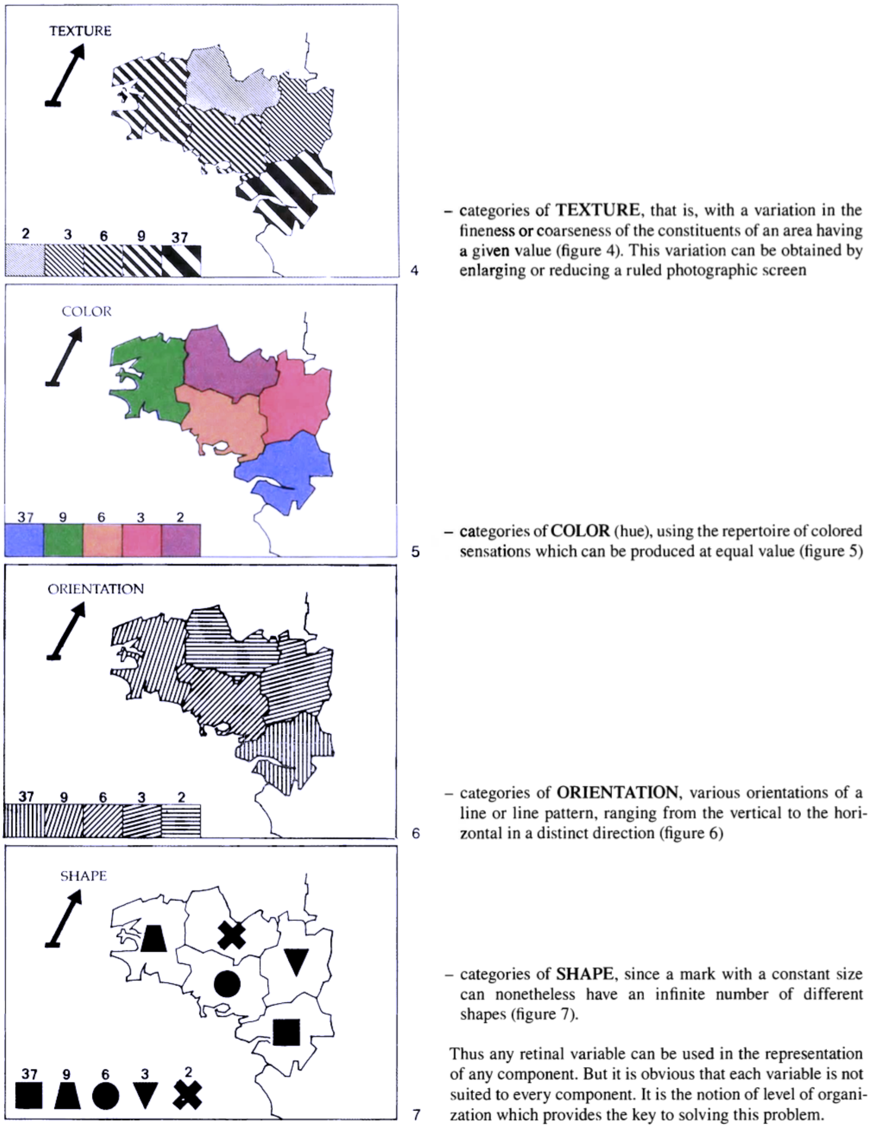
Her studies are grounded on the principle that contrast draws attention, analogy groups.

Hue, value (lightness) and chroma (saturation), represented as a circle with analogous colours close together and contrasting colours on the opposite side, are determinant when using colour to convey information. Value is, in her opinion, the most important feature for legibility and attention: it allows to easily see variations and to compare, provided that contrast is well defined. Hue has a primary role in labelling groups, but without exaggerating. All three components should be limited to a few distinguishable shades (two or three for hue). Legibility is ensured by a difference in value between symbol and background. In an ideal visualisation, all the important information would be legible even in black and white («get it right with black and white»). Anyway, as far as uncertainty scales are concerned, we know that usually we perceive more shades of colour than shades of grey, which can be an alternative, but are more problematic.

To summarise, the guidelines given by Stone for selecting colours are composed of three actions:

(1) Assigning colour according to function;
(2) Using contrast to highlight and analogy to group;
(3) Controlling value contrast for legibility.

At this point, how do we choose a palette? She suggests, first of all, using one that has already been designed and experimented by a number of people. As an example, she mentions the "ColorBrewer" (see **PARAGRAPH E2**) by Cynthia Brewer, initially designed for thematic maps, but also applicable to charts, graphs and colour visualisations in general. We need large hue difference or, in alternative, a single hue with variation in chroma and value, or even shades of grey, maybe also complemented by bright colours to emphasise particular data.



– categories of **TEXTURE**, that is, with a variation in the fineness or coarseness of the constituents of an area having a given value (figure 4). This variation can be obtained by enlarging or reducing a ruled photographic screen

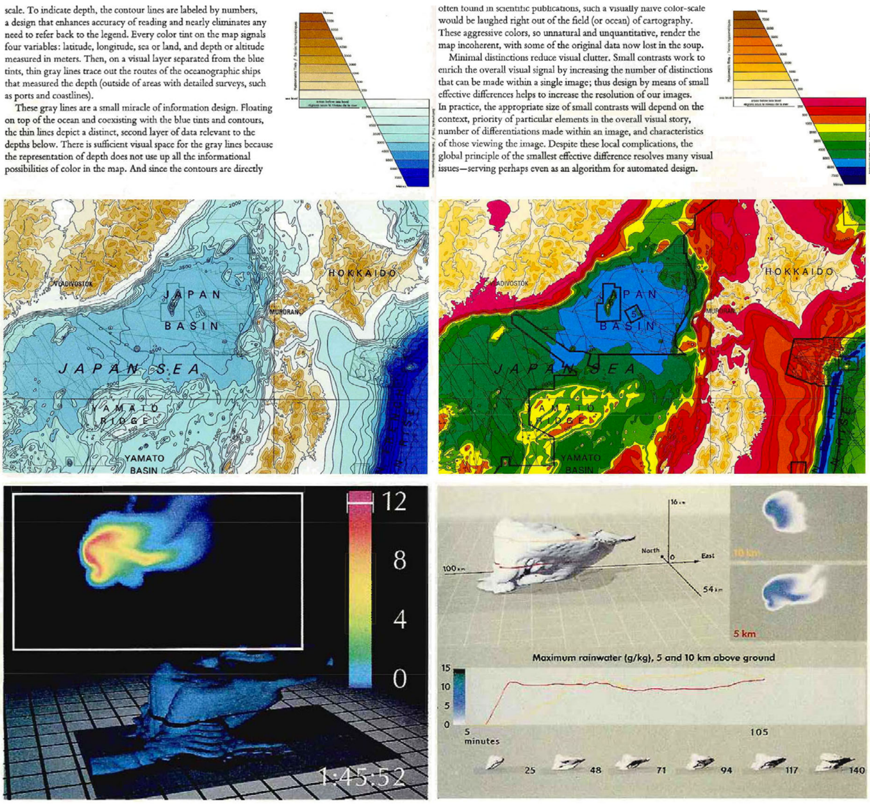
– categories of **COLOR** (hue), using the repertoire of colored sensations which can be produced at equal value (figure 5)

– categories of **ORIENTATION**, various orientations of a line or line pattern, ranging from the vertical to the horizontal in a distinct direction (figure 6)

– categories of **SHAPE**, since a mark with a constant size can nonetheless have an infinite number of different shapes (figure 7).

Thus any retinal variable can be used in the representation of any component. But it is obvious that each variable is not suited to every component. It is the notion of level of organization which provides the key to solving this problem.

FIG. 56: Different graphical tools to add information to a map (author's elaboration based on Bertin 1967).


scale. To indicate depth, the contour lines are labeled by numbers, a design that enhances accuracy of reading and nearly eliminates any need to refer back to the legend. Every color tint on the map signals four variables: latitude, longitude, sea or land, and depth or altitude measured in meters. Then, on a visual layer separated from the blue tints, thin gray lines trace out the routes of the oceanographic ships that measured the depth (outside of areas with detailed surveys, such as ports and coastlines).

These gray lines are a small miracle of information design. Floating on top of the ocean and coexisting with the blue tints and contours, the thin lines depict a distinct, second layer of data relevant to the depths below. There is sufficient visual space for the gray lines because the representation of depth does not use up all the informational possibilities of color in the map. And since the contours are directly

often found in scientific publications, such a visually naive color-scale would be laughed right out of the field (or ocean) of cartography. These aggressive colors, so unnatural and unquantitative, render the map incoherent, with some of the original data now lost in the soup.

Minimal distinctions reduce visual clutter. Small contrasts work to enrich the overall visual signal by increasing the number of distinctions that can be made within a single image; thus design by means of small effective differences helps to increase the resolution of our images. In practice, the appropriate size of small contrasts will depend on the context, priority of particular elements in the overall visual story, number of differentiations made within an image, and characteristics of those viewing the image. Despite these local complications, the global principle of the smallest effective difference resolves many visual issues—serving perhaps even as an algorithm for automated design.

FIG. 57: Studies on visualisation styles and tools (Tufte 1990; 1997): above, two different colour scales have been applied to the same map to show how, in that case, the one with minor colour variation with respect to reality (on the left) works better and has become a standard in cartography; however, this is different from the use of false colours in 3D digital models. As we can see below, there are some fields in which a colour scale proves to be more effective, such as in the animation of this thunderstorm. This means that choosing a correct visualisation depends on the aim of our work.

We have therefore explained, at both a physiological and cultural level, the visualisation theories at the basis of the uncertainty scale that we will adopt, composed of a few, well-perceivable spectral colours (blue, green, yellow, red), from red indicating the maximum uncertainty to blue indicating the minimum (still existing things), avoiding colours such as purple or scales varying from green to red, which can be perceived as a variation from right to wrong. Apart from the scale done by Pablo Aparicio Resco and his research group, it is frequent to indicate with red the maximum uncertainty: this is the reason why that order was kept. The scale, at the same time, is not intended to be too strict: variations of colours and granularity, to some extent, should also be possible (cf. **PARAGRAPH D4**).

At this point, after having analysed the issue of uncertainty visualisation, we have to explain on which criteria uncertainty assessment is based, especially when we don't only consider a differentiation between certain and uncertain, but also between different levels of uncertainty.

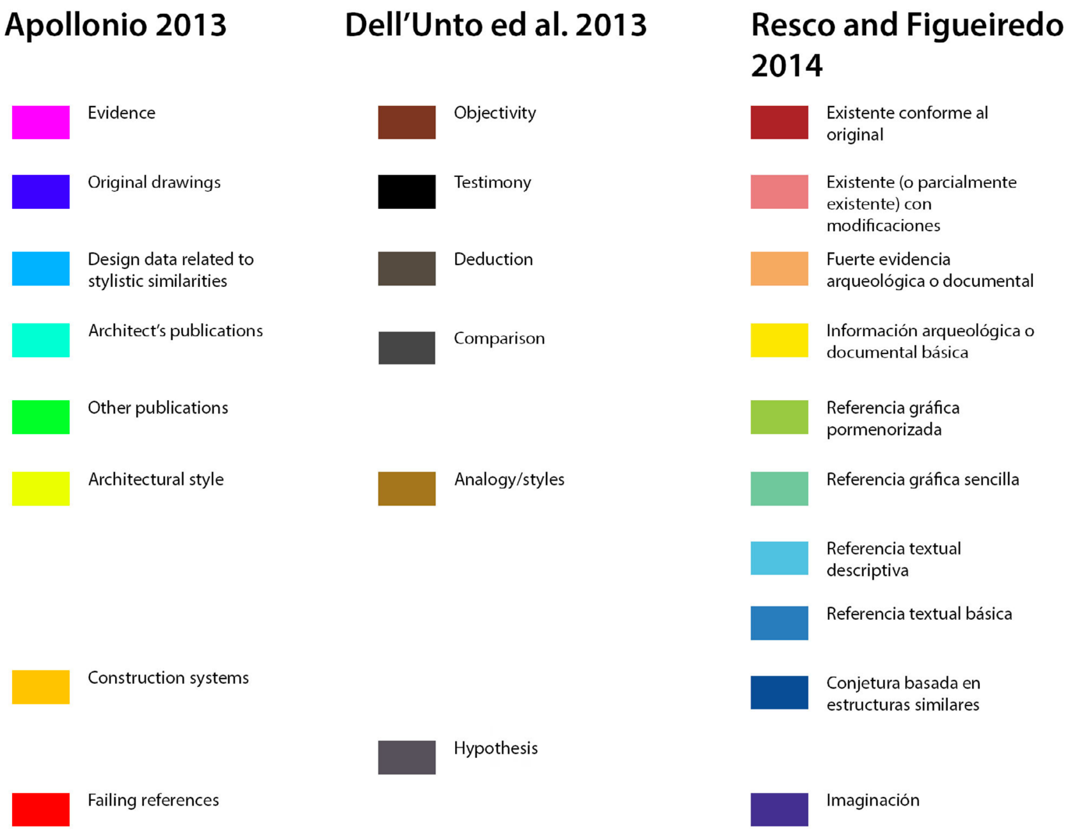
D.
CLASSIFICATION OF UNCERTAINTY

It is clear, at this point, that the problem of uncertainty visualisation is, even before, a problem of categorisation and classification that has to take into account 3D models at different scales (from the artefact to the urban scale) and at different levels of detail, allowing their use in different disciplines (art history, architecture, archaeology…).

The comparison of different uncertainty scales (**FIG. 58**) is possible only to some extents: besides the fact that the categories can be more or fewer according to the way of segmenting reality, sometimes they are not in the same order or they do not mean exactly the same thing. This is due to many factors: the translation in different languages, the fact that some scales are more source-based, whereas others are based on subjective judgements, but also the fact that they often depend on the discipline they refer to.

Mathematically speaking, uncertainty refers to statistical variations, spread, errors, differences, noisy or missing data and can appear in different phases of the reconstruction (Pang, Wittenbrink, and Lodha 1996): during the acquisition of data (due to the sensitivity of the instruments, to the difficulty in human observation, to the fact that the model is always a simplification), in the transformation of data (that can be converted in other formats or can be processed creating new data as an output), in their visualisation (due to the techniques used to create the digital model and to rendering algorithms).

These phases are recognisable in the creation of hypothetical models for cultural heritage as well, but, unlike for hard sciences, «for objects reconstructed based on archaeological assumptions, statistical measures are not appropriate» (Landes et al. 2019). We would say that uncertainty about lost artefacts, not only in archaeology, but also in architecture and history of art, cannot be mathematically measured and can refer to more parameters, among which subjectivity is also involved: this has to be always reported to understand how the collected data are interpreted, thus how much they are influenced by the decisions of the model creators.


Apollonio 2013
Evidence
Original drawings
Design data related to stylistic similarities
Architect's publications
Other publications
Architectural style
Construction systems
Failing references
Dell'Unto ed al. 2013
Objectivity
Testimony
Deduction
Comparison
Analogy/styles
Hypothesis
Resco and Figueiredo 2014
Existente conforme al original
Existente (o parcialmente existente) con modificaciones
Fuerte evidencia arqueológica o documental
Información arqueológica o documental básica
Referencia gráfica pormenorizada
Referencia gráfica sencilla
Referencia textual descriptiva
Referencia textual básica
Conjetura basada en estructuras similares
Imaginación

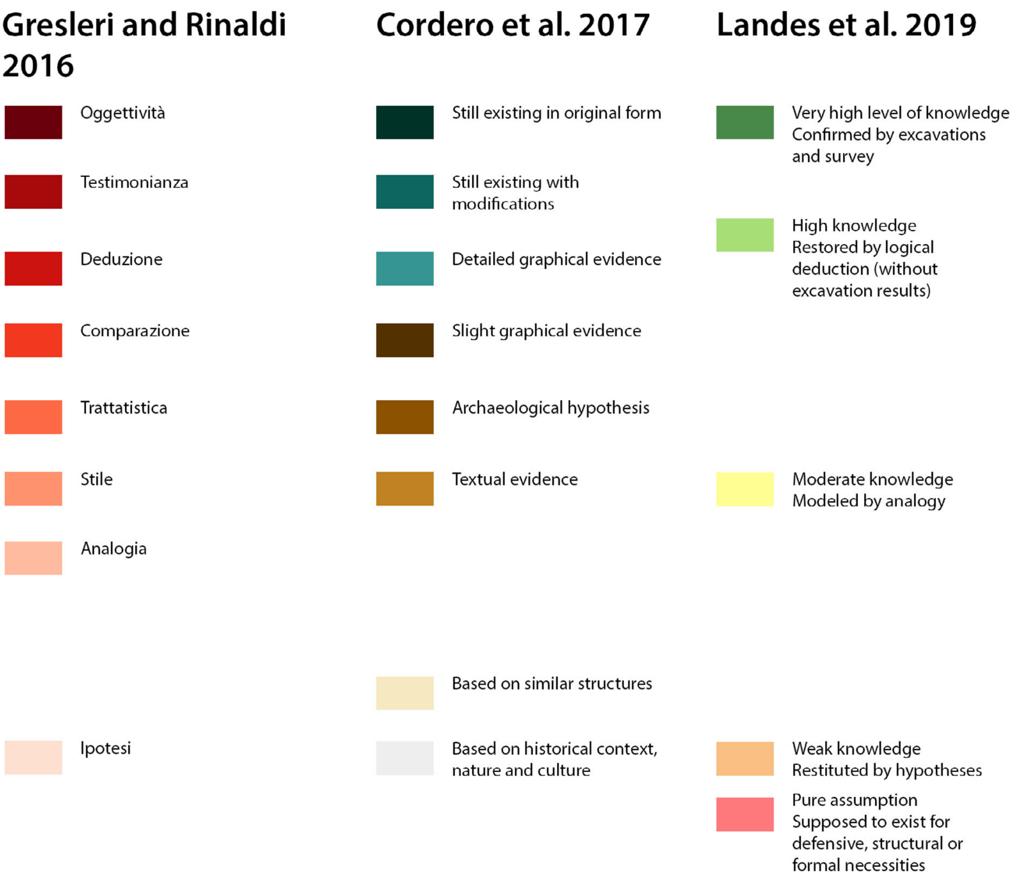


FIG. 58: Comparison between uncertainty scales used in different domains (mainly architecture and archaeology) with descriptions in different languages. Author's visualisation.

Apart from this similarity, we have to take into account the background of the different experts involved and their way of dealing with sources: archaeological inferences are based on a collection of findings; the approach of architects is more oriented towards graphic and photographic material; art historians have, first of all, solid knowledge about bibliographic research and historiography[36].

This can be considered an obstacle – thus, in our opinion, a stimulus – to the development of a hopefully shared system for uncertainty assessment that overcomes, as far as possible, the several and hardly comparable uncertainty classifications, which are also sometimes overlapping.

We can see, indeed, that some scales reflect a source-based segmentation (Apollonio 2015); other scales (Dell'Unto et al. 2013; Apollonio, Fallavollita, and Foschi 2021) highlight the type of work we have to do to reconstruct an element: survey, deduction, analogy, hypothesis. Hybrid scales maintain a distinction based on sources (archeological, graphical, textual documentation), but where evidence is connected to processes of deduction, hypothesis, etc. (Resco 2014; Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018). Some scales also give a qualitative assessment of the level of knowledge: high, moderate, low, etc. (Landes et al. 2019)[37].

The reason why a standard for uncertainty assessment lacks is due to the fact that the tools used to evaluate it are often applied to a particular case or, in the best-case scenario, to a particular field.

36 This may be considered a generalisation: in effect we know that disciplines are not strictly divided one from another; we just wanted to identify the focus of each one of them, provided that the same sources are often (and should be) analysed by more than one expert.

37 Also the scale by Pollini and Cipolla mentioned in **PARAGRAPH A3** (**FIG. 12**).

D.1.
Scales based on the type of source

In source-based uncertainty scales, classification has been often related to the concept of iconicity, defined as the degree of similarity of an image with respect to the objects it refers to. This is also oa technique used to understand which is the best way to convey a particular message.

The concept was firstly elaborated by Charles Sanders Peirce (1935) and then developed in a scale of 12 levels (**FIG. 62**) by Abraham Moles[38] (1971; 1981). The scale puts in a hierarchical order the different degrees of analogy from the most similar to its referent to the most abstract one. The iconic traits are thus classified according to their degree of stylisation and simplification measured as the gap between real and represented object.

We should also consider, however, that a representation, first of all, is the act of deciding what to exclude (Anceschi 1992). Even when we make a 3D representation or take a photograph, we are choosing which kind of (and how much) information we want to convey; therefore, it is not obvious that a picture describes reality better than a drawing. Reasons like this have guided the production of several uncertainty scales over time, in which it is often difficult to reduce uncertainty classification to a single parameter.

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38 First explained in the report of a seminar held in 1965 at Hochschule für Gestaltung, Ulm. The classification was obtained in an empirical way, by grouping a series of examples according to a general similarity criterion. Finally, a unifying criterion, based on the iconic-abstract axis, was identified (Anceschi 1992).

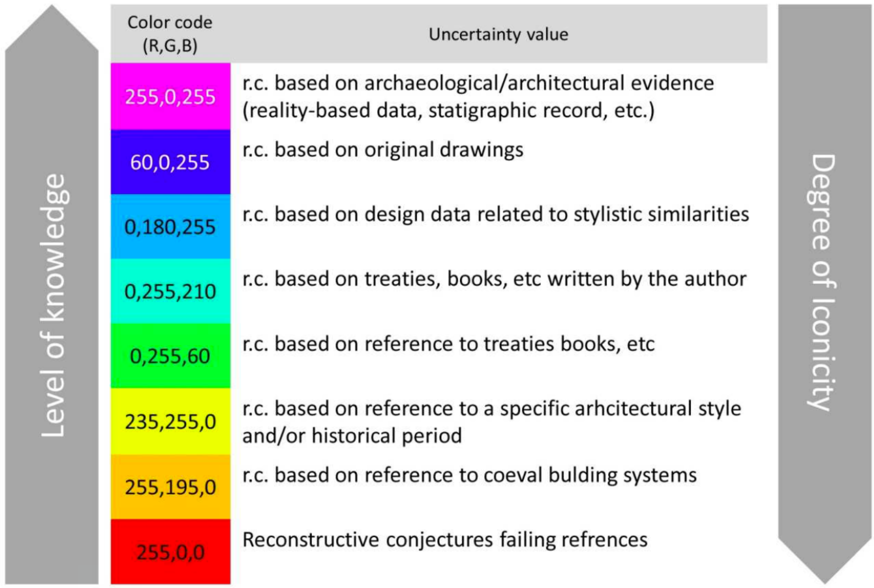

FIG. 59: Source-based uncertainty scale (Apollonio 2015)

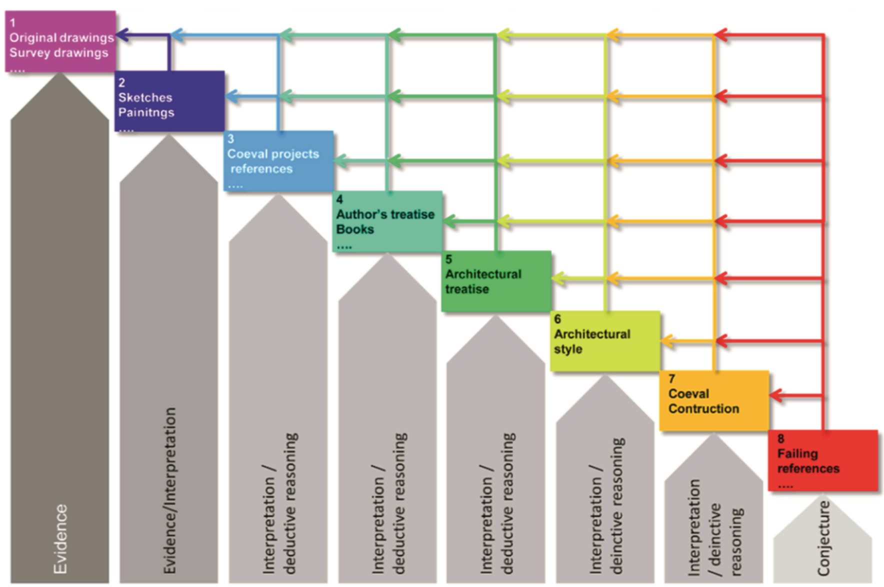

FIG. 60: Relationships between a source-based uncertainty scale and the operations done to reconstruct an element: interpretation, deduction, conjecture, etc. (Apollonio 2016).

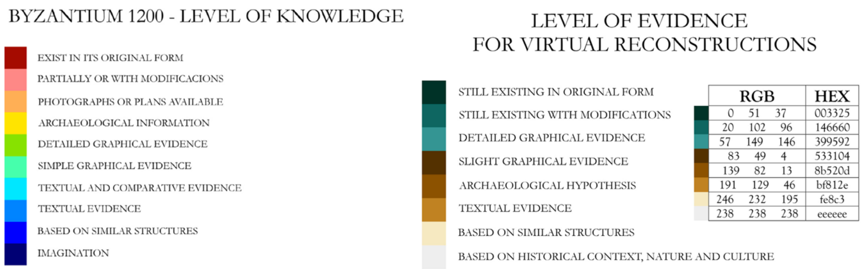

FIG. 61: left: Byzantium 1200 source-based scale of knowledge for virtual reconstructions; right: Modification of the scale on the left by changing the colours and reducing the levels from 10 to 8. The scale is still source-based, with some adjustments in the description and order of the levels (Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018).

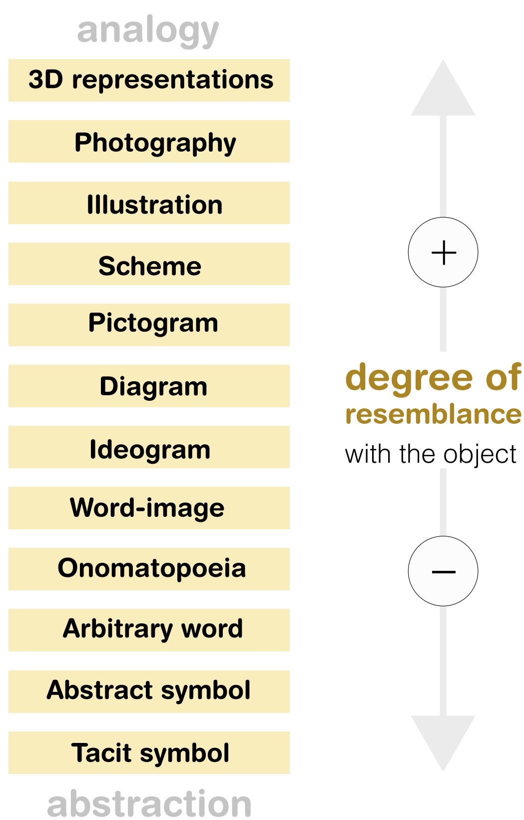

FIG. 62: Iconicity scale according to Moles (1971). From the representation with higher degree of similarity to the referent, we have: 3D representation, photography, illustration, scheme, pictogram, diagram, ideogram, word-image, onomatopoeia, arbitrary word, abstract symbol, unspoken symbol. Author's visualisation based on <https://visualdsgn.fr/degre-iconicite-representation-visuelle/> (accessed 29.10.2024).

D.2.
Scales based on a qualitative judgement

These scales give a simple judgement to uncertainty levels such as "very high", "moderate", etc.

It is, for example, what we have seen in the tool for the exploration of the Mausoleum of Augustus (high, medium, low reliability) or in Sciedoc (substantiated, probable, possible).

Landes et al. (2019) give an overall qualitative judgement, but motivated by archaeological evidence according to their scheme.

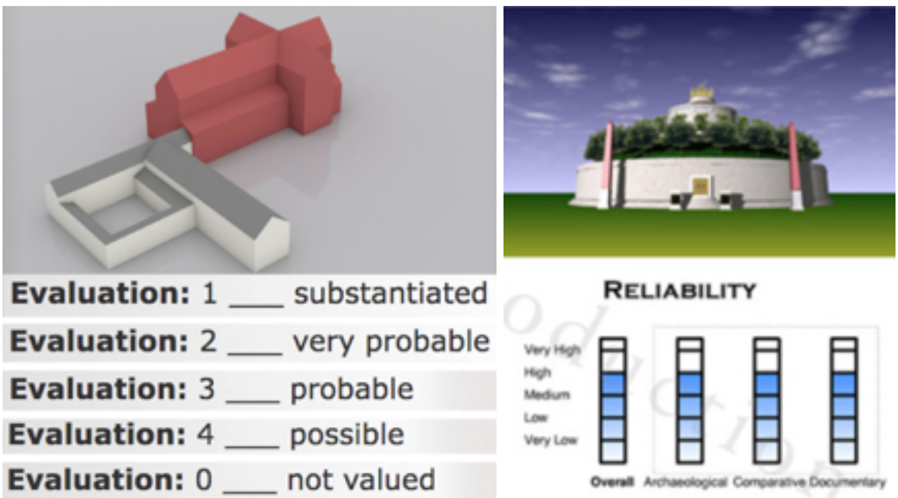

FIG. 63: Qualitative uncertainty scales: on the left, evaluation of reconstruction variants in Sciedoc; on the right, evaluation of overall, archaeological, comparative and documentary reliability (high, medium, low) in the 3DVisa platform. <http://www.sciedoc.org/>, <http://3dvisa.cch.kcl.ac.uk/project6.html> (accessed 31.10.2024).

	Level of knowledge				
	Pure assumption (LoU5)	Weak knowledge (LoU4)	Moderate knowledge (LoU3)	High knowledge (LoU2)	Very high knowledge (LoU1)
Wall	No remain, nor iconography or document. But supposed to exist for defensive, structural or formal necessities	Remain of low height (< 1m). But no data about initial height nor shape or function of the wall	Remain of more than 1 m. But no data about initial height, nor shape or function of the wall	Proven existence with uncertaintie s : uncertain height but shape / function known	Proven existence with known height (or assessable) and shape/functi on known

FIG. 64: The level of knowledge is expressed by a qualitative judgement (high, moderate, weak), but correlated to archaeological uncertainty through a description (Landes et al. 2019).

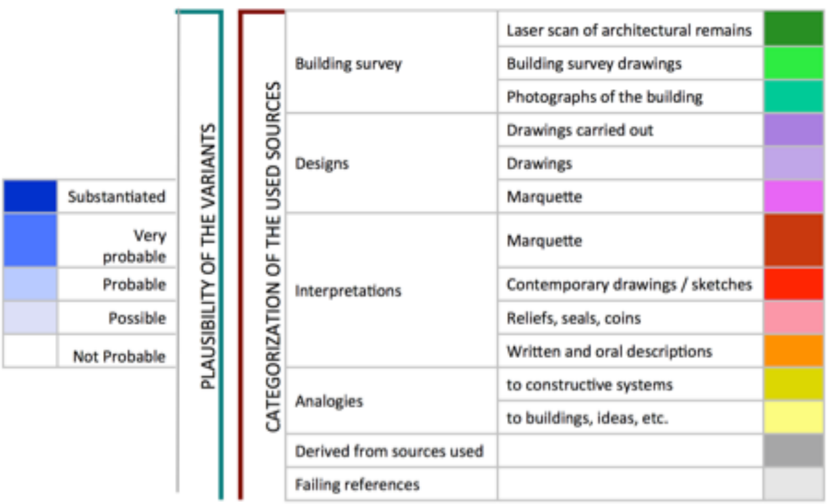

FIG. 65: Another example of correlation: the two scales used for defining the plausibility of the variants and the categorisation of the used sources (Grellert et al. 2019).

D.3.
Scales based on the type of work done to reconstruct an element

In this case, the levels correspond to the activity performed during a reconstruction process: deduction, analogy, hypothesis, etc., leading to more or less objective reconstructions.

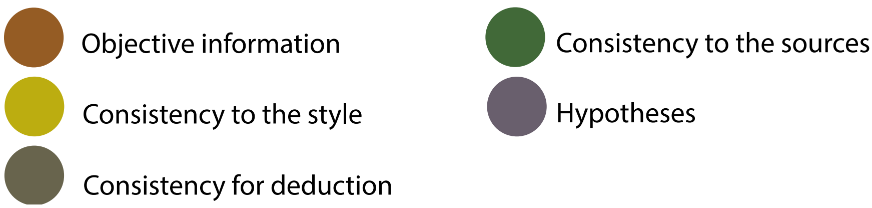

FIG. 66: This scale concerns the relationship between a source (no matter which kind) and a reconstruction element involving more or less objectivity, consistency, deduction, hypothesis (Dell'Unto et al. 2013).

Table 1. Level of uncertainty scale, with 7 + 1 steps, descriptive explanation of each level.

		Description
	1	Reliable assumption derived from reality-based data (i.e. the full real object or parts of it, well preserved archaeological founds, direct surveys, laser scans).
	2	Reliable conjecture based on clear and accurate direct/ primary sources* when the real object or parts of it are not available.
	3	Conjecture based on stylistic/ structural references by SAME AUTHORS when direct/ primary sources are available, but unclear/ damaged/ inconsistent/ inaccurate. Or logic deduction/selection of a variant derived by inconsistent direct sources.
	4	Conjecture based on stylistic/ structural references by DIFFERENT AUTHORS when direct/ primary sources are available, but unclear/ damaged/ inconsistent/ inaccurate.
	5	Conjecture based on stylistic/ structural references by SAME AUTHORS when direct/ primary sources are not available.
	6	Conjecture based on stylistic/ structural references by DIFFERENT AUTHORS when direct/ primary sources are not available.
	7	Conjecture based on personal knowledge due to missing or unreferenced sources.
	\	Not relevant/ not considered/ left unsolved/ missing data and missing conjecture (it does not count for the calculation of the average uncertainty).

* Direct/primary sources: all the sources where the object is directly represented, reported, recorded with any level of accuracy (i.e. drawings, sketches, surveys, pictures, paintings, texts, books, coins, medals, reliefs, physical models, sculptures)

FIG. 67: Here we can see as well the connection to the sources, but the stress is on the type of conjectures we do in analysing them (Apollonio, Fallavollita, and Foschi 2021).

The classification we will follow in **CHAPTER III** belongs to this latter group of uncertainty scales and is based on the following levels:

(1) Hypothesis: we imagine the presence of an element in a given location, even though no sources are available;
(2) Analogy: indirect sources or other similar findings located elsewhere that can help reconstruct the missing parts;
(3) Deduction: this level groups all the non-extant elements that are reconstructed by direct sources;
(4) Still existing: all the elements that are on site and can be reconstructed by survey.

We will also add an extra level to indicate the elements that are not considered in the uncertainty assessment.

D.4. Granularity of the scale and semantic segmentation of the model

Uncertainty and semantic segmentation are somehow related.

First of all, we should notice that we basically refer to two distinct kinds of segmentation: one related to the partition of a 3D model into more or less components; another related to the uncertainty scale, which can be divided in more or less levels.

Granularity, in uncertainty classifications, also depends on the variety of the available sources (findings, ruins, drawings, literary sources) and can be divided in the multiple ways that we have seen before, among which we have chosen the approach based on evidence, inference, conjecture and leading to differences in the "degrees of certainty" (Apollonio 2015).

These levels are used to assess our reconstruction, but how do we define the elements to which the uncertainty values and colours are applied? First of all, this depends on the level of detail of the model: if this is high, we can think of applying a different uncertainty value even to small components of them. This also depends on the semantic segmentation of the model. A building can be divided into parts such as roof, ceiling, floor, walls, columns, doors, windows. Then, if we want to go more into detail, we can divide the column into shaft, base and capital. Thus, the uncertainty scale can be applied to different hierarchical levels according to the structure of our model. If we think of broader models, representing entire cities or parts of them, it can be reasonable to apply the uncertainty scale at the level of the building (a value applied to each building, without going more in detail).

An "optimised scale of uncertainty" (Apollonio, Fallavollita, and Foschi 2021) should contain as little ambiguities as possible and allow the segmentation in more or less levels, also according to the detail of the reconstruction and the variety of sources that have been employed. For this reason, the scale proposed by Fabrizio Apollonio, Federico Fallavollita and Riccardo Foschi, enabling variants with different granularity, is used, in this work, as a general guideline.

In their proposal, there are actually three different scales, with (from the most complex to the simplest case) 7+1, 5+1 and 3+1 levels. They are associated with easily recognisable colours varying from blue to red, according to the visible spectrum of light, in a maximum of six steps (hues): blue, cyan, green, yellow, orange, red[39]. To these colours, black and white (or light grey) are added to indicate respectively the elements for which uncertainty is not considered and the ones that are still existing and whose reconstruction is reality-based, corresponding therefore to the minimum degree of uncertainty. If available, white can also be replaced with the actual texture of the on-site element. The simplest scale is reduced to only three hues (blue, yellow, red), plus black for the not considered elements.

The proposed colours are not associated to a precise RGB[40] or RAL[41] code, so that everyone can choose them according to the project palette.

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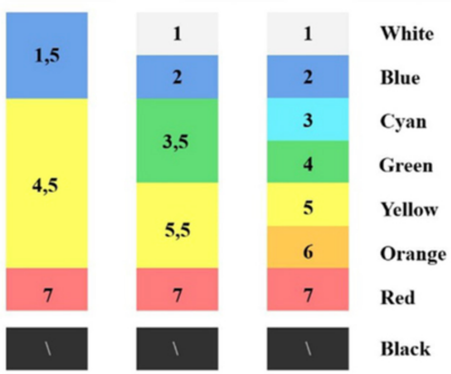
39 The number is compliant with the studies by Healey (1996), already mentioned at the end of **PARAGRAPH C1,** enabling to keep a strong differentiation between colours and ensure the maximum recognisability.
40 <https://www.rapidtables.com/web/color/RGB_Color.html> (accessed 19.10.2024).
41 <https://www.ralcolor.com/> (accessed 19.10.2024).

A number from 1 to 7 is given to every uncertainty level, apart from the black one that is represented with a slash (\). In this way, an average (numerical) uncertainty value for each model can be obtained. Different calculations are proposed to extract this number: in the most objective case, a weighted average results from the application of each uncertainty value to the surface of the related element; other methods take into account multipliers according to the perceived importance of the elements, which is a more subjective process and, if applied, should be well documented to understand how the most relevant elements were chosen.



	Real object	Direct\primary sources: Clear/ consistent	Direct\primary sources: Damaged/ unclear	Other sources: Same author/s	Other sources: Other author/s	Reliability
1	✓	\	\	\	\	Reality
2	✗	✓	\	\	\	Reliable conjecture
3	✗	✗	✓	✓	\	Conjecture
4	✗	✗	✓	✗	✓	Conjecture
5	✗	✗	✗	✓	\	Conjecture
6	✗	✗	✗	✗	✓	Conjecture
7	✗	✗	✗	✗	✗	Conjecture
\	\	\	\	\	\	Abstention

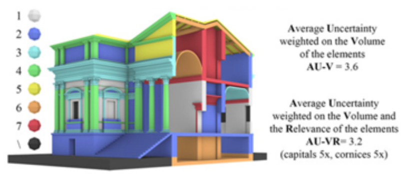


FIG. 68: Different granularity in the uncertainty scales proposed by Apollonio et al. (2021). In the scale with 5 levels, the 3-4 and 5-6 are collapsed (differentiating the authors of indirect sources is no longer relevant in this case). In the scale with 3 levels, 1-2 are collapsed, as well as the levels from 3 to 6: in this case, the only differentiation that remains is between direct sources, indirect sources and pure hypotheses. This might be used when the maximum accuracy is not required or the range of available sources is not so wide.

The scale used in **CHAPTER III** is a variation of this proposal with different granularity.

Besides the segmentation of the scale, also the segmentation of the reconstruction itself has been taken into account in that case.

TAB. 5: Integration of the proposed uncertainty scale (highlighted by a black rectangle) as a variation of the ones adopted by Apollonio et al. (2021).

Still existing	Still existing	Still existing	Original source
Direct	Direct, well understandable	Deduction	
Direct – not high quality	Direct, difficult to interpret		
Other source, same author		Analogy	Analogy
Other source, other author	Indirect		
Similar construction			
Hypothesis	Hypothesis	Hypothesis	Hypothesis

D.5.
Using matrices to assess uncertainty based on several parameters

Among the first examples of a matrix to represent uncertainty in spatial data, we can find the one explained by Paradis and Beard (1994) and applied to Geographic Information System (GIS) data and visualisations. This is composed of two sets of parameters:

The observation requirements by Sinton (1978): according to him, to obtain useful information from casual observations, it is necessary that the following attributes be reported:

(1) Theme: the recording of the object or phenomenon according to some measurable units;
(2) Location: we should indicate where the observation took place in order to obtain useful data;
(3) Time: similarly, we should also indicate the moment or period of observation.

The data quality standards[42] for transferring information, as reported by Fegeas et al. (1992): here the problem is exchanging vector or raster data, models and associated attribute data between different systems, always in the GIS framework. For the conceptual model of spatial data, that is the model of the spatial phenomena with attributes, five components for assessing the quality of data[43] have been identified:

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42 The standard to which they refer is the FIPS (Federal Information Processing Standard), that provides solutions to the problem of exchanging greographical and cartographical data between different systems, approved on July 29, 1992 (Fegeas, Cascio, and Lazar 1992).

43 It has been noted that «data quality has an inverse relationship with data uncertainty» (Pang, Wittenbrink, and Lodha 1996), therefore the two definitions can take advantage one from the other.

(1) Lineage: the processing history from the collection of data to their transformations and derivations;
(2) Positional accuracy: how precisely the collected locational data represent the objective locations;
(3) Attribute accuracy: precision about other non-locational data;
(4) Logical consistency: fidelity in the relationships within the structure of the collected data;
(5) Completeness: selection criteria to identify the portion of territory useful for the analyses.

This has been slightly simplified in the matrix presented by Paradis and Beard (**FIG. 69**), with four components for the analysis of quality: the main modification is that "positional accuracy" and "attribute accuracy" are collected into the general category "accuracy" and then declined, in the other direction of the matrix, according to the "theme/location/time" categories introduced by Sinton.

In the proposal by Paradis and Beard, the matrix formed by the intersection of these two sets of parameters is used as a data-quality filter relating data quality information to the visualisation of data: only information that pass a threshold, which can be adjusted by the user, becomes visible.

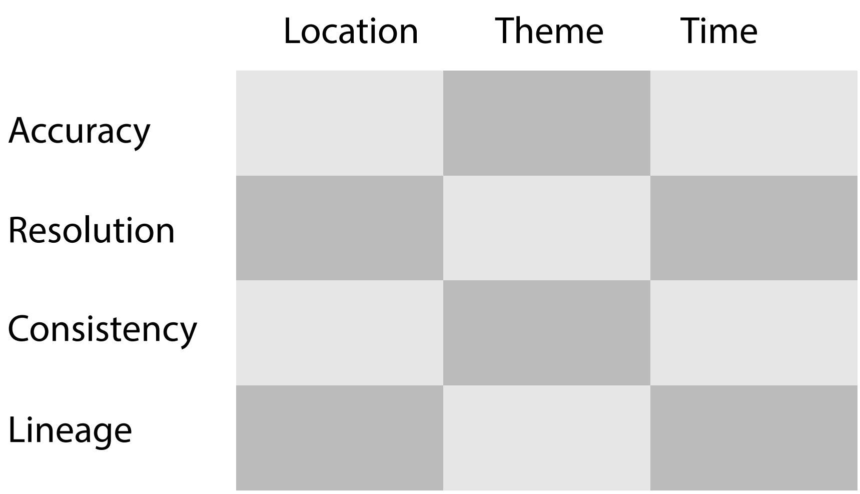


FIG. 69: The matrix proposed by Paradis and Beard (1994) with the two sets of parameters indicating the basic requirements for casual observation to become useful data (location, theme, time) and the evaluation of data quality (accuracy, resolution, consistency, lineage). Author's visualisation.

This allows the integration of quality in information processing and the interaction of the user with the data.

In the matrix, each cell represents a quality component, for instance the resolution of location is the minimum mapping unit, the location accuracy is how precise the location identification is, the thematic accuracy corresponds to the probability of having correctly identified the function of a part of territory, the temporal lineage is the measure of the time intervals in the collection of data.

Pang et al. (1996) classify the different types and sources of uncertainty in scientific visualisation:

(1) Value a datum with its value of uncertainty;
(2) Location of a datum with its positional uncertainty;
(3) Extent of a datum: the range over which it is valid;
(4) Visualisation extent: the individual (discrete) or continuous data. Individual data can be represented with glyphs or points; continuous ones with curves, surfaces, volumes.
(5) Axes mapping: different variables are mapped together or to different axes.

From these different types of uncertainty, some of the visualisation methods that we have already seen arise, connecting classification and visualisation of uncertainty:

(1) The addition of glyphs with a shape or a colour to encode information;
(2) The addition of geometry such as contour lines or isosurfaces to show the difference between values;
(3) The modification of geometry e.g. through translations or rotation;
(4) The modification of attributes to control shading and colour, for instance using pseudo-colouring;
(5) Animation: an undulating motion, for example, can show the difference between values, thus the extent of uncertainty;

(6) Sonification: mapping uncertainty to sound;
(7) Psycho-visual approach, e.g. a 3D stereo effect produced with two slightly different images.

Let's see how these uncertainty types can compose a scale or be integrated with each other in matrices for a more complete analysis.

D.6.
Single parameter

In the previous paragraphs we saw some examples of uncertainty scales configured as the variation of a unique parameter. When an uncertainty scale is proposed, in fact, in most cases (for simplicity reasons) it deals with a single parameter, be it a qualitative judgement (very good, good, sufficient), an assessment of the type of source or also of the operation done to reconstruct an element.

This is the most intuitive way of communicating uncertainty: the scale, based on a few recognisable colours, can be used in combination with false-colour models, to allow the understanding of information with minimum effort. It is better if the colour scale is accompanied by a progressive value and a short description and potentially also documentation tables in which the reconstruction process for each element can be retraced. In this way, uncertainty can be communicated in a clear way and to a wide audience, also to people with visual deficiencies (in this case we may think of alternatives in visualisation, see **PARAGRAPH E2** and **CHAPTER III**).

Nonetheless, we should observe that uncertainty has subcategories. Thus, when we say that uncertainty is high or low, this is an average of multiple factors, among which objectivity, quality, coherence, but also evaluations on structure, material, spatial and temporal uncertainty.

We can therefore imagine some examples of more complex scales, that relate the type of source that has been used to its quality, or that integrate more parameters, as we will see now.

D.7.
Two parameters

Usually, to convey uncertainty data in the most accessible way, a scale with a single parameter is used.

However, if we need a more documented and grounded work on the collected sources, we can imagine more complex scales that take into account the issue of uncertainty from more than one point of view. The simplest way of integrating this data is working with two parameters in a Cartesian space.

Uncertainty can be evaluated, for instance, based on quality, coherence and objectivity (Favre-Brun 2013). A matrix that connects the range of used sources with these features can consequently be created starting from this classification, which may be applied to each reconstructed element, based on the documentation we have (**TAB. 6**).

		Scan	Photograph	Drawing	Written text	Oral source
Quality	Accuracy					
	Precision					(3-high)
	Completeness	(1-low)				
Coherence	Consistency	(3-high)				
	Lineage					
	Currency		(2-medium)			
Objectivity	Credibility					
	Subjectivity					
	Interrelatedness					

TAB. 6: Matrix relating the uncertainty evaluation (quality, coherence, objectivity) to the type of sources: this can be used to make qualitative assessments to the various sources according to the parameters in column, by means of a colour, a term (e.g. very high/high/medium/low/very low) or even a value. The assessments here are just examples, deliberately chosen to remind that an oral source can have qualities that other sources don't have – and vice versa. Author's visualisation.

A simple matrix can also evaluate the sources based on their relationship (direct or indirect) with the object that is reconstructed.

In this case (**TAB. 7**), columns contain information about the type of source used to reconstruct an element; rows explain if they are directly related to the object of the reconstruction or not. A third parameter – quality of sources, as an average of all the factors seen in the previous table – can also be represented by colouring the related cells according to a scale representing the higher quality in blue and the lower in red, but also using terms and values as we did before.

	Scan	Photograph	Drawing	Written text	Oral source
Direct sources					
Indirect sources					

TAB. 7: A simple matrix to assess uncertainty according to two parameters, which become three if we add colour to assess quality. The assessments are just examples; they may be performed for each cell, if documentation is available. Author's visualisation.

Another issue to take into account is that shape, material and appearance have been identified as the three parameters that «concur to define the digital consistency» of a reconstruction process (Apollonio 2016).

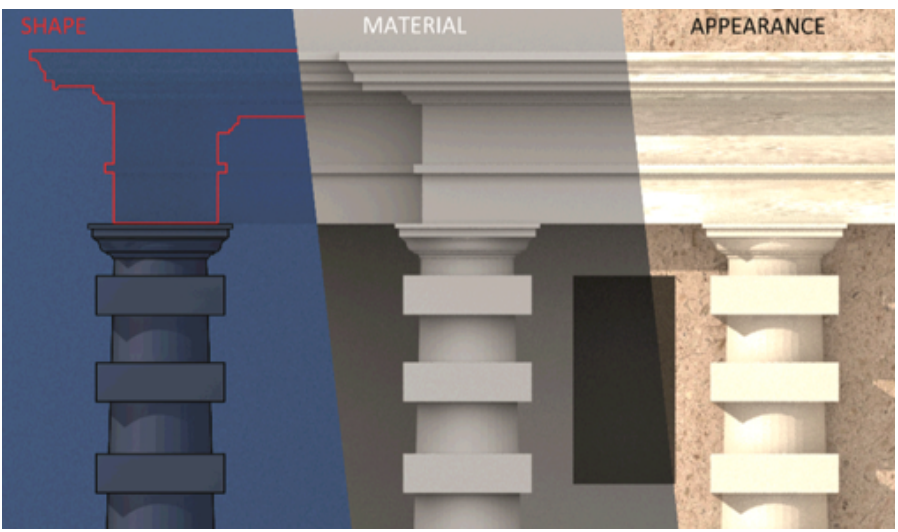


FIG. 70: Shape, material and appearance concur to the definition of uncertainty (Apollonio 2016).

Therefore, we can also relate these three features to the type of source (**TAB. 8**), always retaining the possibility of declaring the quality of the sources using colours, terms, values.

	Scan	Photograph	Drawing	Written text	Oral source
Shape					
Material					
Appearance					

TAB. 8: In the same way, a matrix can relate the three parameters concurring to digital consistency (shape, material, appearance) with the type of source. The assessments are just examples; they may be performed for each cell, if documentation is available. Author's visualisation.

It is clear that other matrices may be created by combining the various sets of data that have been used in these tables. This will eventually result in other examples of 2-parameter tables, but also in visualisations that integrate a higher number of parameters, as we will see here below.

D.8.
Three (or more) parameters

As we already know from many examples of infographics, it is possible (and we have already seen it in some of the previous examples) to work with more than two parameters, combining the two Cartesian coordinates with a range of colours and symbols.

Here below we present and discuss a series of uncertainty matrices with different degrees of complexity, elaborated starting especially from (Favre-Brun 2013; Grellert et al. 2019; Apollonio, Fallavollita, and Foschi 2021). These complex evaluations are based on a variety of parameters (type of sources, quality, location, shape, texture, temporal uncertainty) that are in some cases interrelated, concurring to a global (or, at least, as general as possible) definition of uncertainty (**FIG. 71**).

analytic uncertainty typology

category	subcategories	examples
accuracy/error	collection accuracy processing errors deception	translation errors errors in identifying objects
precision	precision of collection	resolution of images
completeness	composite completeness information completeness incomplete sequence	availability of documents clearness of documents
consistency	multi-INT conflict model/observation	conflict between sources reality/model difference
lineage	translation transformation interpretation	machine processing human processing
currency/timing	temporal gaps versioning	time between event, report, availability of information
credibility	reliability proximity appropriateness	possibility of disinformation expertise on a subject second-hand information
subjectivity	analytic judgement	amount of interpretation
interrelatedness	source independence	influence of other sources

FIG. 71: Uncertainty classification according to more than one parameter. The table on the left (author's elaboration from Thomson et al. 2005) has been then taken up by Aurélie Favre-Brun, who groups the nine categories into three macro-categories (Favre-Brun 2013): quality (accuracy, precision, completeness), coherence (consistency, lineage, currency), objectivity (credibility, subjectivity, interrelatedness). The diagram on the right is an elaboration by Fabrizio Apollonio identifying the connections between terms composing these three macro-categories (Grellert et al. 2019).

As pointed out on many occasions, hypothetical reconstruction isn't a binary process for which a result can generically be "right" or "wrong". On the contrary, we have already seen that it requires more complex evaluations and interpretations based on a number of different parameters, essentially grouped as follows:

(1) Quality: the accuracy, faithfulness, error or precision of sources;
(2) Coherence: the integrity and consistency of sources, the presence of contradictory ones, filiation and currency of them;
(3) Objectivity: the credibility and reliability of sources, based on interpretations, deductions, conjectures, generating, to some extent, subjectivity.

The interconnection of these features is represented by means of a triangular diagram in **FIG. 71**, where the nodes correspond to the different relationships between quality, coherence and objectivity (Grellert et al.

2019). This is an elaboration starting from the table by Thomson et al. (2005), also taken up by Favre-Brun (2013).

These visualisations remind us that, even though we might assume that a survey is more precise and exhaustive than other sources, this is not taken for granted. When taking into account all these parameters, we can see that the evaluation depends on many factors: a drawing can be too schematised and less precise than a written description; a photograph can be at a low resolution or present chromatic aberrations, thus be less precise than other sources and making the reconstruction challenging.

In addition, we have already mentioned other parameters that can influence the evaluation of a reconstruction, such as the nature of the element, its position and texture. Dating an object can also produce uncertainty.

To try to combine, as far as possible, all these parameters, we might use graphical tricks, for instance colour to indicate quality and a symbol for each type of source (**FIG. 72**).

These are the most complete scales, but they may be not so immediate to understand, therefore they are probably more suitable for expert users rather than for a wider public.

A 4-parameter representation (**TAB. 9**), to be applied to the whole reconstructed building, has been elaborated. In this case, the single elements are found along the y- axis (according to the semantic segmen-

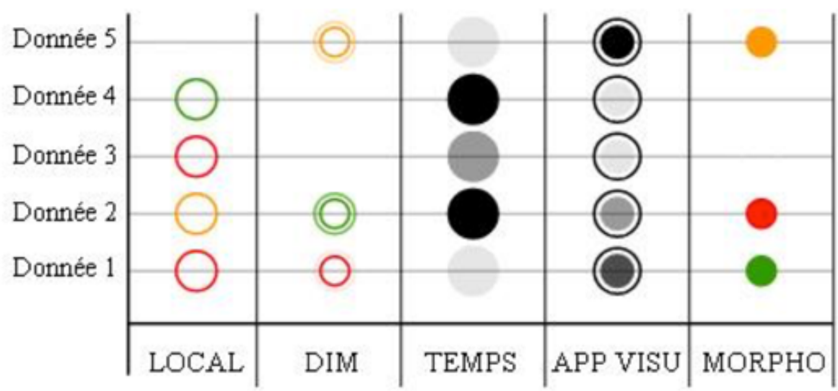
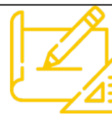


FIG. 72: A similar matrix (Favre-Brun 2013) to evaluate the information corresponding to each element in which the construction is segmented. The evaluation is done by attributing different values to spatial, dimensional, temporal, visual and morphological uncertainty.

tation based on the detail of the sources we had), whereas along the x-axis the aspect to which uncertainty refers can be read (this may be the position of an element, its shape, its historical period…).

Additionally, icons indicate the kind of document that has been used to obtain that information and the colour indicates the level of uncertainty according to the work done to reconstruct that element (survey/deduction/analogy/hypothesis).

	Morphology	Position	Dimensions	Texture	Historical period
Element 1					
Element 2					
Element 3					
Element *n*				X	

TAB. 9: A 4-parameter uncertainty scale with the indication of the element along the y-axis, the feature to which uncertainty assessment is related along the x-axis, a colour indicating the level of uncertainty, an icon (or more) indicating the type(s) of source(s) used for the reconstruction. For pure hypotheses not bases on sources, it is suggested to mark the cell with a red X. There may be some elements reconstructed by means of a hypothetical description or drawing, as in a few cases in **CHAPTER III**, for which a red icon can still make sense. Author's visualisation.

An application of a similar matrix can be found in **CHAPTER III**. However, if we think of a way of communicating uncertainty at a wide scale, these matrices would be too time-consuming and difficult to read: for these reasons, on many occasions, a simplified scheme to evaluate it is going to be preferred. This depends on – and raises issues connected to – the audience involved in the process.

E.
UNCERTAINTY LEVELS: CHALLENGES AND CRITIQUES

A scale to assess the uncertainty level of a model should consider the visualisation and classification issues seen before, but also a series of physiological, cultural and technical issues.

The proposal of a simplified scale based on four levels corresponding to the work done to reconstruct an object (survey of still existing elements, deduction based on direct sources, analogy with similar objects, pure hypothesis)[44] helps us focus on the challenges that inevitably arise when dealing with this topic.

On the one hand, the scale should be easily understandable by users with different backgrounds; on the other hand, uncertainty data should be shareable and, hopefully, both human- and machine-readable.

For these reasons, each category of the proposed scale is associated with a highly recognisable colour (to facilitate visualisation) and a progressive value (represented by the numbers 1-4 to be integrated to documentation). These features have to be applied to the entire model and/or to each element of it, according to its level of detail and semantic segmentation, hopefully ensuring flexibility. In order to allow interoperability, this data should be then integrated in the 3D data set and shared through standard exchange formats such as IFC for models based on Constructive Solid Geometry or City GML for models based on Boundary Representation.

Thus, we can see how, even working with the simplest scale and on simple examples (see **CHAPTER III**), the conjunction of these many issues generates particular challenges that we will analyse in the next three paragraphs.

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44 As reported by Aurélie Favre-Brun, this is a constant of many uncertainty scales, which differentiate “in situ material” / “iconographic material or findings” / “analogy” / “pure imagination” (Favre-Brun 2013).

E.1.
Granularity of the scale and semantic segmentation of the model

As far as perception of colour is concerned, there are issues connected to the fact that human vision is tricky: it is always relational because each one of us may perceive colours differently, but also because we can recognise the same colour, within certain limits, also in different conditions, for example in light or shadow.

These issues have been addressed in the creation of the ColorBrewer, designed by Cynthia Brewer, which has proved to be effective and understandable by a wide audience[45]. It consists of more colour scales based on different gradients (sequential multi- or single-hue, divergent, qualitative) that can be changed by users according to their needs and to what they think is the best scheme to show information. It is also designed with an eye to colour-blindness.

While navigating on the site, an alternative scale with respect to the one proposed in the present work, but colourblind safe, has been identified (**FIG. 73**).

Examples like this make us consider that the individual problems connected to the perception of colour are manifold and cannot be generalised. A range of different scales, as in the case of the ColorBrewer, may be proposed; in addition, when dealing with 3D models, alternatives concerning other visualisation techniques (as seen in **PARAGRAPH B**) may nonetheless be tested in case of users with particular needs.

A comparison between different visualisation techniques is shown in the case study in **CHAPTER III**.

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45 Based on studies conducted by Cynthia Brewer, also referring to previous research and surveys in cartography (Brewer 1994a; 1994b).

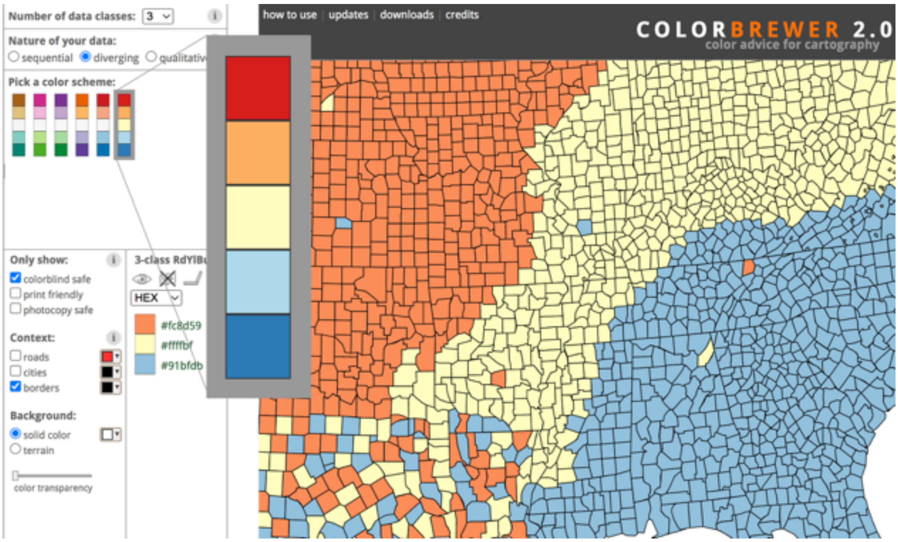

FIG. 73: Some of the colour scales found in the ColourBrewer. The selected one is colourblind safe.
<https://colorbrewer2.org/#type=diverging&scheme=RdYlBu&n=3> (accessed 19.10.2024).

E.2.
Cultural issues

The creation of a workflow for digital reconstructions, first of all, depends on the domain and target.

We have mentioned the different disciplines that may be involved, trying to set up a common terminology, methodology and uncertainty scale (as far as possible).

However, target differences also concern the level of expertise of the audience. The balance between complexity and adaptation of a methodology, and of an uncertainty scale as well, depends on differences between expert and general users, or between teachers and pupils, besides the fact that, as we saw in the previous paragraphs, every scholar tends to use his/her own uncertainty scale.

Scholars and, in general, expert users who are confident with the analysis of sources, would help (and are already helping) discuss and define a standard in the scientific community, inside which we would benefit from the use of a shared bibliography and methodology in order to document the reconstruction and identify its uncertainty level.

The following question is how students and general users will approach these tools.

The colour scale proposed in **CHAPTER III**, as part of a handout for hypothetical reconstructions, has been and will be tested on students[46]. By now, the results, collected by means of a survey[47], are just a few, but they already show the actual difference, according to the level of expertise, in the way of approaching the various stages of the workflow.

Although instructions were defined very clear by all the participants in the survey, some users (especially students) have had problems in following the process: this shows that not only an accurate methodology,

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46 The same issues are the focus of the *CoVHer* project: this has resulted in a first publication (Münster et al. 2024) with guidelines that are now being tested in workshops for university students.

47 The survey has been conducted by Igor Bajena in June 2022 to test the effectiveness of the workflow and of the given documentation, with a particular focus on the DFG repository upload process.

but also clear information should be given to students and, at the same time, the support of an instructor is also needed.

As far as uncertainty visualisation is concerned, when students are free to choose a colour scale based on their studies and/or experience, the main questions[48] that are usually asked to them are: how a specific colour scale was chosen, how a specific number of steps was defined and how a colour was attributed. Generally, primary, pastel or gradient colours are adopted and the number of levels varies between five and ten. The classification of the levels is often decided based on the examples shown during the lessons, which somehow guide their choices. However, the purpose of the activity, besides studying if there any constants in the documentation of uncertainty, is also spreading a method and making students understand the principles on which a particular visualisation is based.

Similar issues have been studied in engagement at least since 1956, when a taxonomy was developed to differentiate the learners' depth of understanding according to six increasingly complex levels (Bloom et al. 1956):

(1) The "knowledge" level: it consists in the mere recall of what has been learnt;
(2) The "comprehension" level: the meaning of the learnt material can be discerned;
(3) The "application" level: the learnt material is applied in specifically described new situations;
(4) The "analysis" level: the ability of breaking a problem in smaller parts is acquired;
(5) The "synthesis" level: the problem is generalised, so that new conclusions can be drawn;
(6) The "evaluation" level: more ideas can be compared, with the ability of discriminating among them.

48 Especially observed during the course "Architectural Drawing and Graphic Analysis" held by prof. Fabrizio Apollonio at University of Bologna, academic year 2019-2020.

This taxonomy has then evolved into a set of best practices concerning visualisations in computer science (Naps et al. 2002):

(1) Provide resources that help learners interpret the graphical representation either by using text/narration or by explaining the topic during the course;
(2) Adapt to the knowledge level of the user49. If they are not expert, too many details and complexity should be avoided and interactive tools should be privileged;
(3) Provide multiple and coordinated views to show consistent information;
(4) Include performance information, by collecting data about the algorithm efficiency;
(5) If a visualisation involves more stages, include the execution history, so that a learner can see the previous stages again;
(6) Support a flexible execution control in the case of animations (stop, pause, etc.);
(7) Support learner-built visualisations to gain insights into what is important about them;
(8) Support dynamic questions (e.g. “pop quiz”);
(9) Support dynamic feedback;
(10) Complement the visualisations with explanations.

We can therefore understand the importance of learner-built visualisations, which in the case of our 3D models have been and will be experimented in courses and workshops, in order to advance through the levels of the taxonomy by Bloom et al. and complying with the best practices by Naps et al. These concepts are also in line with other studies (Stasko, Badre, and Lewis 1993; Byrne, Catrambone, and Stasko 1996).

The levels of student engagement, in a field in which technology has «advanced faster than our understanding of how such technology im-

49 Adaptation is undoubtedly a good practice; having said this, we would argue that the task of a good instructor is *starting* from the knowledge level of the user, with the aim of increasing it.

pacts student learning» have been compared (Grissom, McNally, and Naps 2003), proving that learning increases as the level of engagement does: this has a high impact especially when students go beyond the mere visualisation and are required to perform additional activities related to it. Visualisation especially helps at the first two levels of Bloom's taxonomy; the interaction between student and instructor is then usually necessary to progress.

When dealing with a heterogeneous audience, the studies in social inquiry may be important to gain deeper understanding of society based not only on academic research, but also on "documentary" research on site (Stanczak 2007).

The concept of "cultural presence" (Pujol-Tost 2017) should also be taken into account in this context, as it connects "presence" (the sense of "being there")[50] to "cultural heritage", especially addressing its pedagogical aims. The scope of this concept (Champion 2011; Pujol and Champion 2012) has been tested, for instance, in a virtual environment related to the neolithic archaeological site of Çatalhöyük, now in Turkey, obtaining a set of results that led to some considerations. First of all, "interaction" has different meanings for different people, depending on their confidence with digital tools and on what they expect from a virtual environment. Moreover, when it comes to "evoking the sense of another culture", it emerges that this doesn't strictly depend on a photorealistic experience, in which many cultural elements cannot be fully understood through action. 3D reconstructions have to become interactive learning environments, grounded on cultural and scientific plausibility and possibly complemented by written information.

All these studies seem to confirm that no single visualisation system is suitable for every learner and visualisations alone may not increase the communication of knowledge. Engagement is fundamental, as well as the communication with the instructor and the presence of further explanation in the light of scientific accuracy.

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50 "Presence" is actually a field of study, even though it «is not a formal academic discipline» <http://www.being-here.net/page/494/presence-research> (accessed 21.10.2024).

E.3. Technical issues

Technical issue/1: How to visualise uncertainty in complex objects (single elements/entire object)

In the example shown below, only a simple "certainty" matrix was integrated in the documentation of the process. This was related to the entire object and based on a double scale of values: the type and the quality of the sources.

Starting from this example, the challenge is trying to attribute an uncertainty level not only to the entire model, but also to each element identified in the semantic structure of the model itself.

Therefore, a single documentation report (a short table) is required for each type of element, with information about its uncertainty level.

This should also be included into the model according to the possibilities given by the used software (for instance the use of different values in the element attributes in BIM software, the use of different layers in non-BIM software, the use of different colours in the visualisation in both cases if possible). The translation in IFC[51] or CityGML[52] standard exchange formats is recommended in order not to lose information about uncertainty, otherwise only available in the native model. This is discussed in **CHAPTER III**, where an uncertainty value is applied not only to entire buildings, but also to the elements that compose them, thus at different hierarchical levels.

The produced data should be stored and accessible online: for this purpose, we will use the *DFG repository*. By now, there is no option to visualise uncertainty directly by means of the integrated viewer, but the possibility has been discussed based on the investigations presented in the following pages.

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51 <https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/> (accessed 29.10.2024).
52 <https://www.ogc.org/standards/citygml> (accessed 29.10.2024).

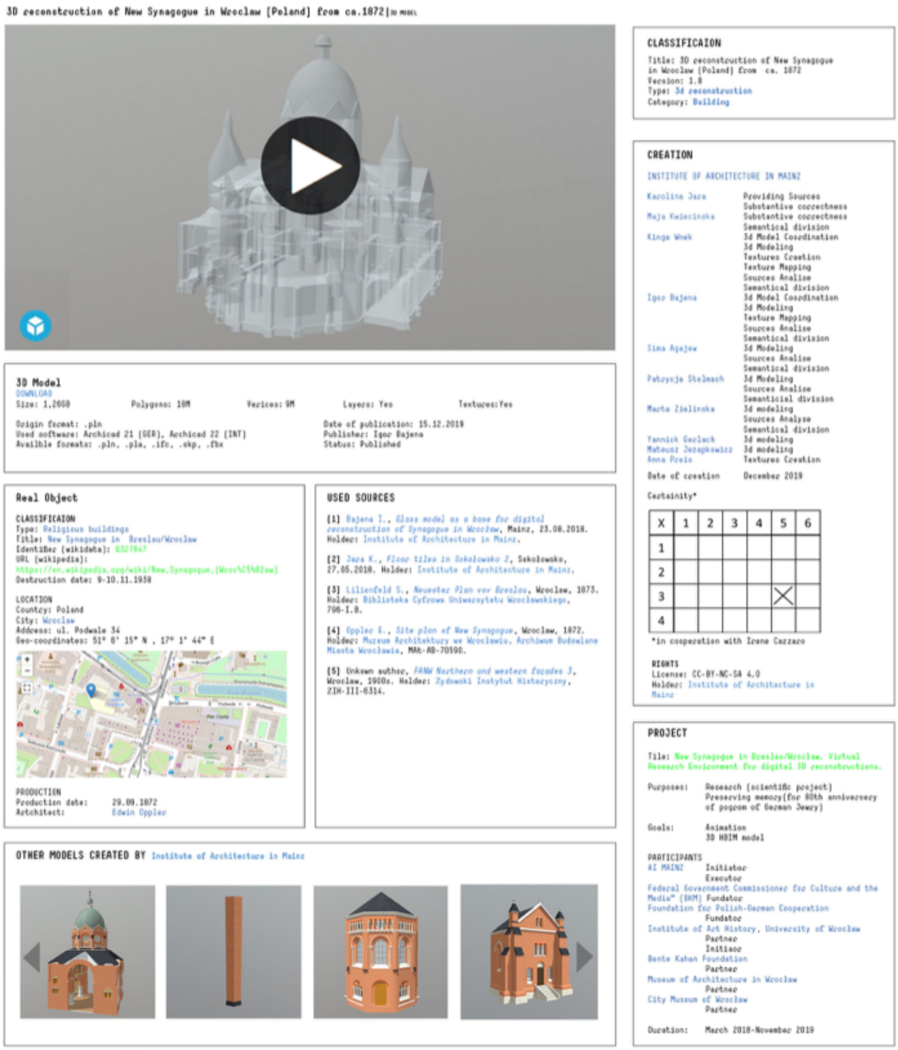

FIG. 74: Example of documentation for the model of the new synagogue in Wroclaw (Poland), in which a simple "certainty" matrix related to the entire structure was included. Information and sources of the project are accessible here: <https://www.new-synagogue-breslau-3d.hs-mainz.de/> (accessed 28.10.2024). Visualisation by Igor Bajena.

Technical issue/2: Uncertainty representation in an online platform

This brief paragraph[53] studies how uncertainty is part of the issue of determining the required features of repositories (and connected 3D viewers) in the field of cultural heritage.

First of all, an analysis of the existing viewers is undertaken on the basis of the existing literature (Champion and Rahaman 2020; Bajena et al. 2022). At the end, different ways of embedding uncertainty in documentation and visualisation are mentioned, dealing with the cultural and technical problems analysed before.

In order to avoid confusion between terms, we quote the definitions given by Champion and Rahaman (2020):

> «*Repository* here means a centralized location where aggregation of data is kept and maintained in an organized way. "3D repository" here refers as a website for uploading, finding and downloading 3D models (such as *TurboSquid*).
> *Depository* is here defined as a location where things are deposited for storage or safeguarding.
>
> A web *portal* is usually a single point of access website which links to information from diverse sources, like metadata, 3D and images, in a consistent and uniform fashion. A portal can assemble disparate information from various sources but with shared formats and an overall theme, for example, the *Europeana* portal.
> An *archive* is a collection of data moved to a repository; often the data is kept separate for compliance reasons or for moving from primary storage media. Archived data is not a copy, but rather inactive and rarely altered data that needs to be retained for long periods. Archiving is typically required to store large amounts of data, for long periods at a low cost».

Portals and online repositories have been considered by Champion and Rahaman, first of all, by means of a distinction between institutional

53 This topic is only marginally discussed here, just to mention its relationships with uncertainty visualisation in this context. A thorough investigation of repositories and 3D viewers will be the focus of Igor Bajena's dissertation.

and commercial ones. We can see that, despite the numerous examples of platforms of this kind on the web, just a few of them are specifically designed for cultural heritage.

In this context, rather than analysing in more detail the possibilities of the main repositories, depositories, portals or archives, we will focus on the 3D viewers that are often embedded in these interfaces, trying to understand which possibilities they offer and how uncertainty can potentially be visualised.

Among the institutional ones, the viewer of the *Smithsonian*[54] portal is one of the most developed, allowing the following functions: "view", "material", "environment", "lights", "measure", "slice", "interactive tours", "read more", "annotations", "share". Another well-known example of institutional portal *Europeana*[55], connected to a number of external repositories. *Three D Scans*[56] just allows rotating a model and downloading it. *NASA 3D Resources*[57] and *GB3D Type Fossils*[58] just have a picture and the possibility to download the model, which is not displayed.

We will see, in the next pages, some screenshots related to *3D Hop*[59], developed by ISTI-CNR, which in some cases allows choosing which parts of an artefact to visualise; *Potree*[60], developed by TU Wien, including filters to decide what to visualise and with which colours; *Plas.io*[61], which served as a basis to develop *Potree* and similarly gives the possibility to apply colours to the model.

Among the commercial repositories, the most used and advanced one seems to be *Sketchfab*[62]; we also mention *MyMiniFactory*[63], *Blendswap*[64],

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54 <https://3d.si.edu/> (accessed 31.10.2024).
55 <https://www.europeana.eu/it/search?query=3d%20model&page=1&view=grid> (accessed 31.10.2024).
56 <https://threedscans.com/> (accessed 31.10.2024).
57 <https://nasa3d.arc.nasa.gov/> (accessed 31.10.2024).
58 <http://www.3d-fossils.ac.uk/> (accessed 31.10.2024).
59 <http://vcg.isti.cnr.it/3dhop/> (accessed 31.10.2024).
60 <http://potree.org/potree/examples/classifications.html> (accessed 31.10.2024).
61 <https://plas.io/> (accessed 31.10.2024).
62 <https://sketchfab.com/feed> (accessed 31.10.2024).
63 <https://www.myminifactory.com/pages/explore> (accessed 31.10.2024).
64 <https://www.blendswap.com/> (accessed 31.10.2024).

3D Warehouse[65], *Turbosquid*[66], *p3d.in*[67]. Even in this case, these tools offer different possibilities, deriving from the features they have.

In this regard, the features that should be considered for a 3D viewer would be, first of all, those that generally allow to explore the model, not only used in cultural heritage, but also in other fields, among which:

(1) Zoom in, zoom out, rotate, change the field of view;
(2) Walk around/through;
(3) Different visualisation styles;
(4) Take screenshots;
(5) Embed in an external web page;
(6) Possibility of exporting in a range of file formats.

Other features are especially important in the field of Cultural Heritage[68]:

(1) Enable annotations;
(2) Add/remove parts;
(3) Measure the 3D model;
(4) Work with timelines;

To this list, we would also add "consider uncertainty".

Based on this list, three groups of 3D viewers are identified (**FIG. 75**): those that just visualise a rotating model or a still image, without possibilities of interaction (*Three D Scans*, *Nasa 3D*, *GB 3D*), those offering basic functionalities such as "zoom", "rotate", "pan" (*MyMiniFactory*, *p3D.in*, *3D Warehouse*) and the most advanced ones, integrating many of the features listed above (*Smithsonian*, *Sketchfab*, *CyArk* – this latter, however, uses the *Sketchfab* viewer). Many of these features are also already present in the *DFG Viewer*.

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65 <https://3dwarehouse.sketchup.com/?hl=it> (accessed 31.10.2024).
66 <https://www.turbosquid.com/> (accessed 31.10.2024).
67 <https://p3d.in/> (accessed 31.10.2024).
68 <https://www.ogc.org/standards/citygml> (accessed 31.10.2024).

FIG. 75: Classification of some of the most used 3d viewers according to their features: above we can see the most developed ones (Smithsonian, Sketchfab, CyArk); in the middle those offering basic possibilities (MyMiniFactory, p3d.in, 3D Warehouse), below we have interfaces that generate previews of the downloadable models, without allowing further interaction. Author's visualisation.

However, none of the consulted viewers offers possibilities related to uncertainty visualisation.

One of the closest examples, with respect to what we are looking for, is the already mentioned Sciedoc (**FIG. 76**), which seems to be more suitable for experts in cultural heritage than for general public. In this interface, argumentation and reasons that guided each uploaded reconstruction are accessible. A minimum standard for documentation is defined, with the possibility of documenting also more variants for the same object or element composing it. Among the documentation fields, the evaluation of uncertainty is available, even though it is not graphically displayed.

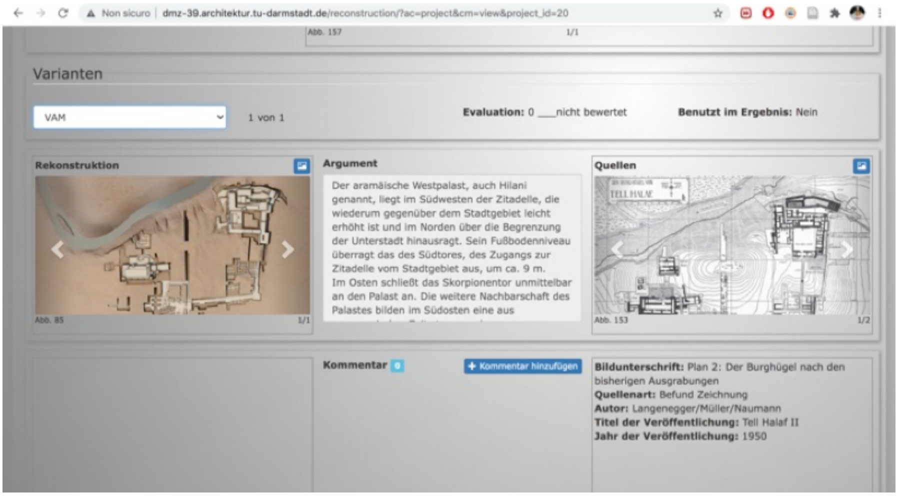

FIG. 76: The ScieDoc interface traces the process that led to the reconstruction by means of sources and argumentation. A numerical evaluation of uncertainty is also allowed. <http://www.sciedoc.org/> (accessed 31.10.2024).

Another tool that has been used for the visualisation of uncertainty is the "probability map" (Perlinska 2014), initially developed in 3DStudio Max and then imported into ArcGIS (**FIG. 77**), where the object is connected to a database with further information about the process.

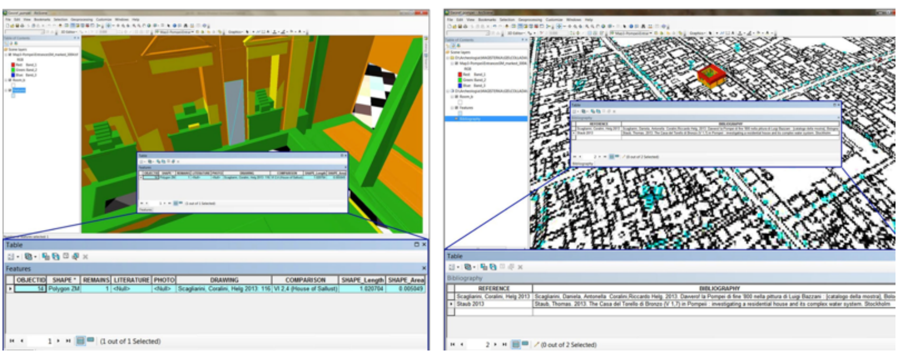

FIG. 77: Uncertainty data visualised on the model once imported in ArcGIS (Perlinska 2014).

A limit of this tool seems to be the fact that is not really "open" and accessible by all users: it requires a license and also a certain level of expertise.

That's why we chose to focus on open exchange formats and repositories, even though an interface to directly visualise uncertainty using a colour scale, in this case, is still under development.

Techniques to directly visualise the uncertainty information in online 3D viewers may be based on the following examples: the first one just distinguishes reality-based (certain) and source-based (uncertain) elements (**FIG. 78**); the second one uses colour to visualise continuous gradients corresponding to information such as the height of a point (**FIG. 79**); the third one (probably the most suitable for our purpose) assigns a uniform colour to each group of elements, classified according to their function, with the possibility of changing it according to the user's preferences (**FIG. 80**).

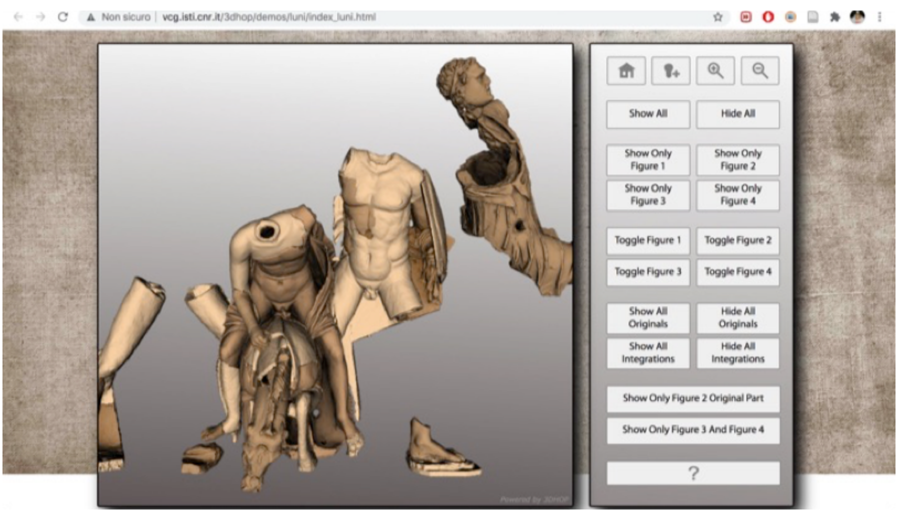

FIG. 78: Visualisation of the "missing parts" of a sculpture reconstructed and uploaded to 3D Hop. Here the user can choose which elements to display: the original ones (which are reality-based, therefore certain) and/or the integrations, which are always, to some extent, hypothetical. <http://vcg.isti.cnr.it/3dhop/> (accessed 31.10.2024).

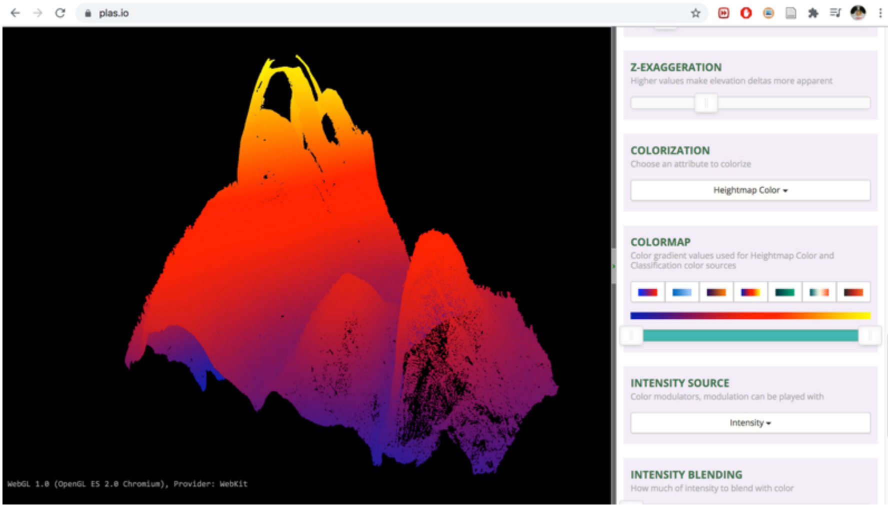

FIG. 79: The use of colour scales (in the form of gradients) in Plas.io. Gradients are not exactly what we are looking for; still, a colour is attributed to a parameter – height, in this case. Attributing colours according to a value is what we also seek for uncertainty visualisation. <https://plas.io/> (accessed 31.10.2024).

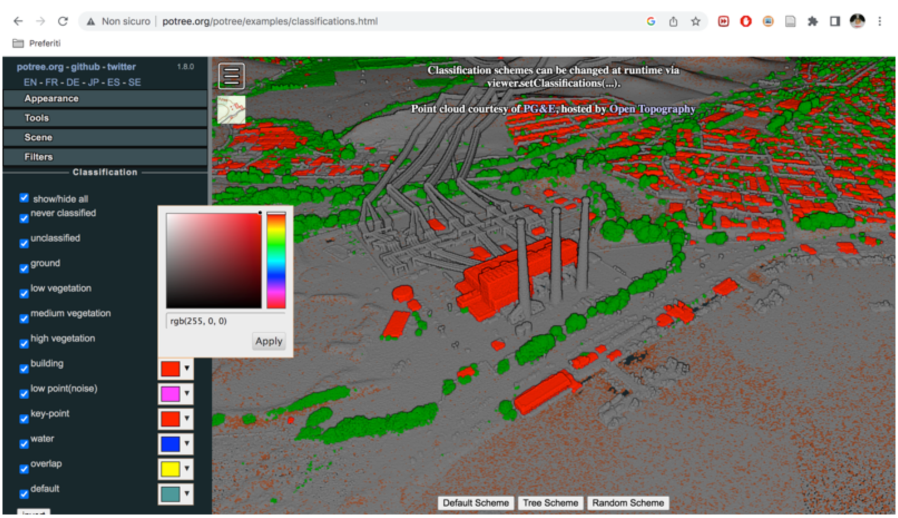

FIG. 80: The application of colour to different elements based on their nature in Potree. A similar visualisation can also indicate uncertainty levels. Here the colours can be changed according to the user's needs. <http://potree.org/potree/examples/classifications.html> (accessed 31.10.2024).

Technical issue/3: integration of uncertainty into CIDOC CRM

An implementation of uncertainty in a human- and machine-readable system would help solve the problem of communicating it. The level of "certainty" should, first of all, be included in the metadata of the reconstruction and there have been some proposals in this regard (Statham 2019). Ideally, an extension of the CIDOC CRM ontology would be the most effective thing, since it is one of the standard reference models (probably the best-known one) used in the Cultural Heritage field, even though it especially concerns extant artefacts. Still, new attributes in CIDOC CRM can be discussed and created: in our case, we would think of a property with a numerical value, in order to store information about the uncertainty level.

Niccolucci and Hermon have tried to incorporate data related to fuzzy logic into CIDOC CRM taking advantage of different properties (Niccolucci and Hermon 2017).

They use, as an example, a function to attribute the gender to a skeleton. They firstly analyse the existing properties that can fit reliability:

E20 Biological Object "skeleton R001"
P41 was assigned by
E17 Type Assignment
P3 has note
E62 String "I am not so sure of this assignment"
P42 assigned
E55 Type "male"
(but there's the risk that the note isn't read)

Another attempt they make is adding question marks to indicate different uncertainty levels:

E20 Biological Object "skeleton Z001"
P2 has type
E55 Type "male?"
P2 has type
E55
Type "female??"
(but it cannot be further processed)

Then they consider the property "E16 Measurement", for which the subclass "Z1 Reliability Assessment" is proposed; similarly, the subclass of "E54 Dimension" called "Z2 Reliability" is introduced.

An example is:

E20 Biological Object "skeleton Z001"
P2 has type
E55 Type "male"

P140 was attributed by
E13 Type Assignment
T1 was assessed as regards reliability by
Z1 Reliability Assessment
T2 assessed as reliability
Z2 Reliability

P90 has value

E60 Number "0.7"

Other properties that may be useful for hypothetical reconstructions are:

P15 was influenced by (to declare the motivation);

P33 used specific technique – connected to *E29 Design* or procedure (to document the technique supporting interpretation);

P70 is documented in – connected to *E31 Document* (for the background documentation);

P14 carried out by – connected to *E39 Actor* (to declare the author of that hypothesis).

Considering the application of similar scales to digital 3D reconstructions, a scheme similar to the latter seems to be the best solution, therefore an extension of the properties of CIDOC CRM becomes necessary.

The extension CRMinf[69] goes in this direction, allowing the integration of metadata about argumentation and inference making.

In the next chapter it will be shown, by means of some simple examples, how these challenges may be addressed. Some perspectives for future research will also be mentioned at the end.

69 General information can be found here: <https://www.cidoc-crm.org/crminf/> The last version to date was published in October 2019: <https://www.cidoc-crm.org/crminf/sites/default/files/CRMinf%20ver%2010.1.pdf> (accessed 31.10.2024).

III case study

The “SpSya1250” project, conducted between January and May 2021, reconstructed the Speyer synagogue’s second Romanesque phase using various software.
A handout detailing the reconstruction workflow was created and to be applied to that reconstruction, but with the aim to make the process replicable also in other cases. Models were tested across different software and then uploaded to the DFG repository together with documentation referring to it. Uncertainty levels were documented employing different techniques.
A proposed uncertainty scale categorises reconstructions based on available sources and work required, aiding in visualising uncertainty levels in the models.

‘Solving a problem simply means representing it so as to make the solution transparent.’

Herbert Simon, *The Sciences of the Artificial*, Cambridge: M.I.T. Press, 1968.

III

case study

dfg viewer and uncertainty scale

In the framework of the project *SpSya1250*, developed from January to May 2021, the Speyer synagogue in its second Romanesque phase has been reconstructed with different software: Blender, Rhinoceros, SkecthUp, Archicad (**FIG. 82**). The participants in the project were the author of this dissertation together with Igor Bajena and Stefan Wetherington. The coordinator was prof. Piotr Kuroczyński.

A handout[1] was set up with the workflow to adopt to reconstruct this synagogue, even though it can also be – and it has been – applied to other reconstructions. The models resulting from this process have been uploaded to the DFG repository (**FIG. 81**). Using different kinds of software, it was also possible to test the application of the workflow in a range of digital environments.

The part of work here presented is the one initially done with Rhinoceros. Every step of the work has been documented with screenshots and descriptions; every reconstructed element was added in the documentation tables with data about uncertainty and explanations of the choices that have been made[2]. Since Rhinoceros is not a BIM and a parameter related to uncertainty could not be added, layers were used to assign uncertainty values. Colours are the simplest ones according to the RGB scale: maybe not the most appealing, but those with the most easily shareable codes. Other visualisations with different techniques to

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1 Presented in Appendix 3: Handout for the reconstruction of the Speyer Synagogue (1250)

2 See Appendix 4: Workflow and documentation of the reconstruction of the Speyer synagogue.

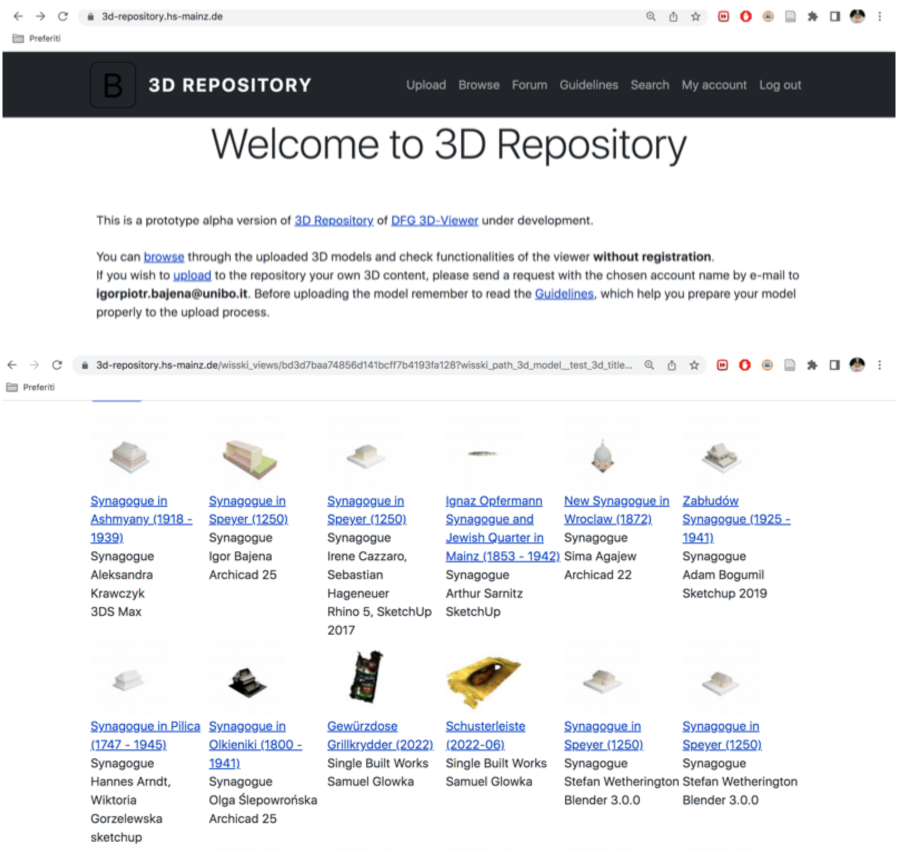

FIG. 81: The interface of the DFG viewer and some of the uploaded models. <https://3d-repository.hs-mainz.de/> (accessed 14.11.2023).

show uncertainty have also been produced, but, as the studies by prof. Fabrizio Apollonio and his research group have already proved, the use of a colour scale seems to be the most effective technique in this context. Different colour scales, transparencies and/or patterns may be an alternative for colourblind and people who don't properly perceive colours, even though these cases are difficult to standardise and should be treated almost case-by-case (Apollonio, Fallavollita, and Foschi 2021).

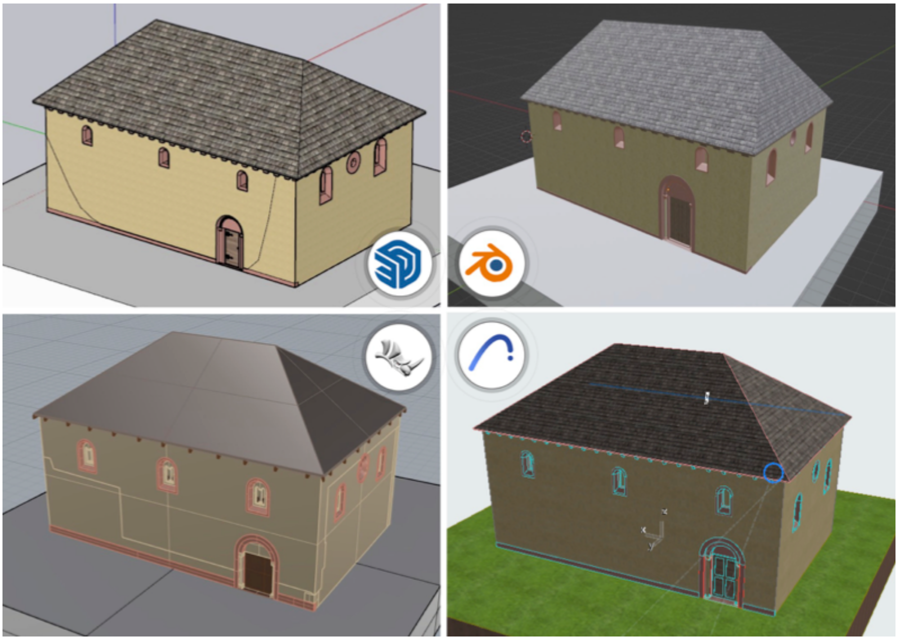

FIG. 82: Virtual reconstruction of the Speyer synagogue in its second Romanesque phase (about 1250), in the context of the project SpSya1250. The different kinds of software that have been used are, from top left clockwise: SketchUp, Blender, Rhinoceros, Archicad.

A.
DESCRIPTION FOR WIKIPEDIA AND WIKIDATA

The following description, written by the author, is being published as a Wikipedia page with the aim of connecting the reconstruction and its metadata to the main sources referring to the reconstructed object on the web. All the hyperlinks have been deliberately maintained.

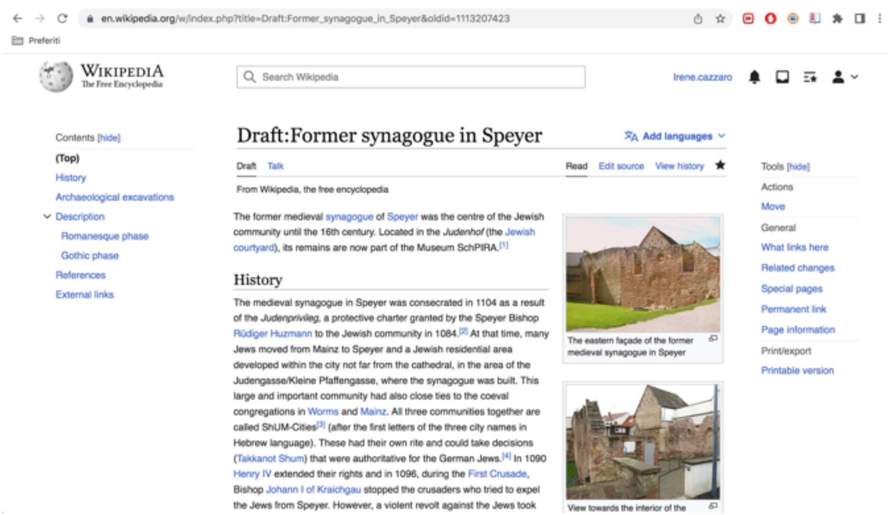

FIG. 83: Screenshot of the Wikipedia page that is under development (accessed 25.01.2023).

Former synagogue in Speyer[3]

The former medieval synagogue of Speyer was the centre of the Jewish community until the 16th century. Located in the *Judenhof* (the Jewish courtyard), its remains are now part of the Museum SchPIRA.[1]

History
The medieval synagogue in Speyer was consecrated in 1104 as a result of the *Judenprivileg*, a protective charter granted by the Speyer Bishop Rüdiger Huzmann to the Jewish community in 1084.[2] At that time,

3 The title proposed for the Wikipedia page is the same already used in the Wikidata page.

many Jews moved from Mainz to Speyer and a Jewish residential area developed within the city not far from the cathedral, in the area of the Judengasse/Kleine Pfaffengasse, where the synagogue was built. This large and important community also had close ties to the coeval congregations in Worms and Mainz. All three communities together are called ShUM-Cities[3] (after the first letters of the three city names in Hebrew language). These had their own rite and could take decisions (Takkanot Shum) that were authoritative for the German Jews.[4] In 1090 Henry IV extended their rights and in 1096, during the First Crusade, Bishop Johann I of Kraichgau stopped the crusaders who tried to expel the Jews from Speyer. However, a violent revolt against the Jews took place in 1195 and the synagogue was destroyed. It was rebuilt in the following years in Romanesque style, like the previous one. Only in the second half of the 13th century the Jewish community was again prosperous: in this period, a Gothic women's synagogue was built next to the men's one, which was converted in Gothic style as well. In the following centuries, especially in 1282, 1343 and from 1435, there were other persecutions (pogroms) against the Jews and by 1500 only a small number of Jews still lived in Speyer. After the dissolution of the Jewish community, in the early 16th century, the area fell into municipal ownership and the synagogue was converted into an armory. In 1689, when the whole city of Speyer was destroyed in the Palatinate War of Succession (in the framework of the Nine Years' War), the former synagogue also fell into ruins.[5]

Archaeological excavations

In 1999 the city of Speyer managed to acquire the synagogue, making it possible to do research on it. An archaeological excavation carried out in the spring of 2001 primarily served to clarify questions about the former interior design and furnishings. The preserved outer walls were partially renovated and could thus be examined in terms of building history. The work was stopped in 2004 and resumed in 2010.[6] On November 19, 2004, the Historical Museum of the Palatinate opened the exhibition „Europas Juden im Mittelalter" („Europe's Jews in the Middle Ages").[7]

The remains of the Speyer synagogue are still visible, making it one of the best preserved synagogues of the 12th century in Europe. The perimeter walls are partially standing, whereas the roof is completely destroyed. The two windows on the western façade are copies of the original ones, now preserved in the nearby Judenhof museum. Those windows are part of the second construction phase that took place after 1195. A portal was situated on the northern wall. On the eastern façade the remains of an arch that was part of the Torah ark are still visible. The two windows located above it were replaced with higher ones during the reconstruction in Gothic style after 1250.[8] We can thus recognize two construction phases: the Romanesque and the Gothic one.

Romanesque phase

The synagogue, consecrated in 1104, was a hall building with a barrel-vaulted niche protruding to the east by a little more than the thickness of the wall. Large parts of the walls of this first building have been preserved to this day. In the eastern wall, a layer of fire, which can be traced back to 1195, shows the upper end of the masonry built up to 1104. The western wall of the synagogue had been rebuilt after the destruction in 1195. The Christians who had to rebuild the synagogue after 1195 evidently used the existing building material and also put the windows from 1104 back into the masonry. The windows, consisting of two coupled round arches, were removed in 1899 and kept in the Historical Museum of the Palatinate. Only a small amount of masonry has survived from the north and south facades, so that there are no findings related to windows and doors. The Romanesque entrance must have been on the northern side. The fact that the synagogue was probably plastered was shown by small remains of plaster that could be found on the exterior. The design of the interior turned out to be much more complicated, because here meaningful findings in the rising were hardly preserved. The location of the bimah was identified in the middle of the room in the archaeological findings as a defect in the Romanesque sandstone slab floor. The original extent of the Torah niche could only be seen in outline on the rising masonry.[9]

Gothic phase

Around the middle of the 13th century, a brick women's synagogue was added to the southern wall of the men's synagogue, following the example of Worms, where a separate synagogue for women was built in 1212-13. Around the same time, the men's synagogue was also renovated in Gothic forms. The eastern wall received a large round window with a trefoil tracery above the Romanesque oculus. The smaller Romanesque windows that were probably originally present on the right and left of the round windows were replaced by larger Gothic ones, whose upper end is not preserved. Six listening slots were installed in the southern wall towards the women's synagogue, through which the women could follow the men's service acoustically. Two of them are still preserved. In the first construction phase, the eastern facade of the women's synagogue had a high-lying window with a round arch in the middle of the wall. This is bricked up, nothing of the walls is visible. There were two entrances on the west side, one of which led into a small courtyard and the other directly to the outside. Both entrances are clogged today. Similar to the Romanesque building phases, the finds on the interior decoration are only sparse. As in the women's synagogue, the men were also given brick benches, which have been preserved in a very fragmented form. The Torah shrine was probably redesigned in Gothic forms. Whether the bimah was also renewed was not clear from the findings. In the women's synagogue, large parts of the brick bench are still well preserved. It originally ran along the northern, eastern and southern walls. The women's synagogue received a vault in 1349. The window in the central axis was bricked up and replaced by two new, tall, rectangular windows divided by mullions. Two fragments of a keystone, which, however, did not fit directly together, and several vault ribs were found during the excavations.[10]

References

[1] "Museum SchPIRA_Stadt Speyer". Retrieved 7 June 2022.

[2] Heberer, Pia (2004). "Die mittelalterliche Synagoge in Speyer, Bauforschung und Rekonstruktion". Europas Juden im Mittelalter. Ausst.-Kat. Speyer (in German): 77–81.

[3] "ShUM-Sites Speyer, Worms, Mainz". Schum-Städte. Retrieved 4 July 2022.

[4] "Speyer (Rheinland-Pfalz) Mittelalterliche Judengasse - Synagoge und Judenbad". Alemannia Judaica. Retrieved 4 July 2022.

[5] Museum SchPIRA. "Mittelalterliche Synagoge". https://nat.museum-digital.de/index.php?t=objekt&oges=51446. Retrieved 30 June 2022. {{*cite web*}}*: External link in* |website= *(help)*

[6] Heberer, Pia (2010). ""... war gezieret an den getünchten Mauern mit Gemählden". Die Synagoge in Speyer". Befund und Rekonstruktion (22): 182.

[7] Europas Juden im Mittelalter. Ausst.-Kat. Speyer (in German). Hatje Cantz Verlag. 2004. ISBN 978-3775791908.

[8] Preißler, Matthias (2013). Die SchUM-Städte Speyer - Worms - Mainz. Schnell & Steiner. p. 34.

[9] Heberer, Pia (2010). ""... war gezieret an den getünchten Mauern mit Gemählden". Die Synagoge in Speyer". Befund und Rekonstruktion (22): 182.

[10] Heberer, Pia (2010). ""... war gezieret an den getünchten Mauern mit Gemählden". Die Synagoge in Speyer". Befund und Rekonstruktion (22):182.

The Wikipedia page will be then linked to the already existing Wikidata entry “Former synagogue in Speyer”[4] (**FIG. 84**).

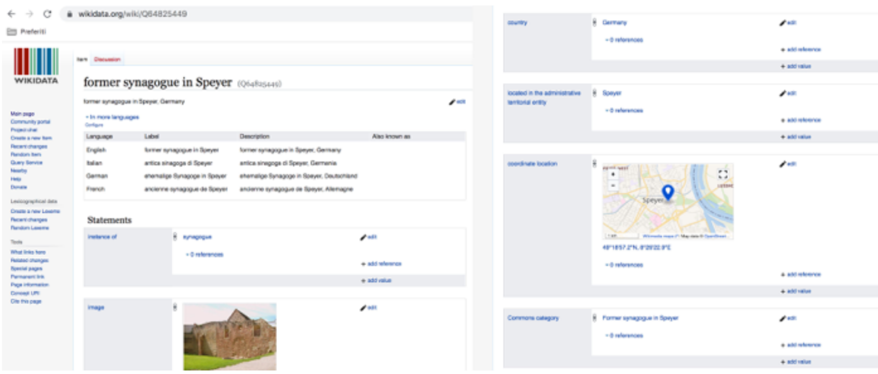

FIG. 84: The already existing Wikidata page about the former synagogue in Speyer.

During on-site analyses and surveys a part of documentation was collected: we especially refer to photographs, drawings extracted from the archaeological reports, findings and related documentation available in the Judenhof museum in Speyer.

Bibliographic and archival research integrated the collection of sources with written texts and drawings, but also photographs of similar buildings useful for analogies.

The previous reconstruction by Architectura Virtualis (2004)[5] was also consulted, as well as the documentation related to the reconstruction for the “Digital Urban History Lab” exhibition at Landesmuseum in Mainz (2021)[6], developed by the Institute of Architecture of the Hochschule Mainz under the supervision of Piotr Kuroczyński.

All the collected sources have been grouped into tables and sorted

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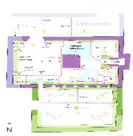
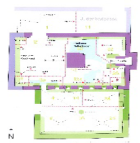
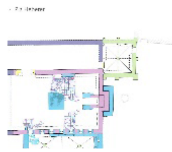
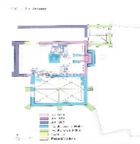
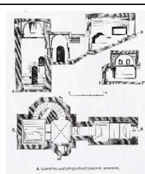
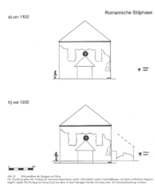
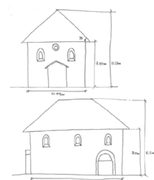
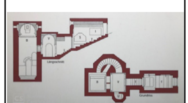
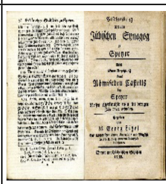
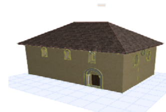
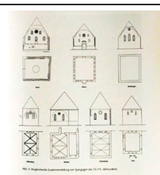
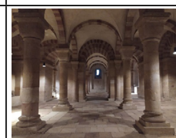
4 <https://www.wikidata.org/wiki/Q64825449> (accessed 04.11.2024).

5 In cooperation with the University of Darmstadt, for the exhibition „Europas Juden im Mittelalter“ in Speyer. <http://www.architectura-virtualis.de/rekonstruktion/synagogespeyer.php?lang=de&img=0> (accessed 04.11.2024).

6 In cooperation with the General Directorate for Cultural Heritage of Rhineland-Palatinate. <https://architekturinstitut.hs-mainz.de/projects/mainz-worms-speyer> (accessed 04.11.2024).

out according to their nature (photograph, drawing, etc.); we present a selection here and the complete list in Appendix 3.

Photographs				
	All pictures taken by Irene Cazzaro, January 2021			
Archaeological reports				
	On-site information	After the 2000-2001 archaeological excavations	From the book „Die SchUM-Gemeinden Speyer, Worms, Mainz“	From the book „Die SchUM-Gemeinden Speyer, Worms, Mainz“
Drawings				
	Floss 2005	Engels 2001	AI Mainz archive	On-site information
Written texts				
	Litzel 1759	Porsche 2003	Heberer 2012	Pia Heberer and Ursula Reuter (eds.), 2013

Previous recon-structions				
	Banner in the building location (*Architectura Virtualis*)	Recon-struction by *Architectura Virtualis*	Model for animation, AI Mainz	Model for 3D printing, AI Mainz
Analogies				
	Eastern portal of the Mainz cathe-dral	Portal of the Worms syna-gogue	Structure of medieval Ger-man synago-gues	Crypt of the Speyer cathe-dral

The proposed methodology, which leads to the creation of a "scientific reference model" (Kuroczyński et al. 2023)[7], starts therefore with the identification of the object to be reconstructed and the collection of the related sources.

At this point, based on the documents that have been found and to the level of detail we want to reach, the structure of the model has to be accurately defined: its semantic segmentation into a hierarchy of elements will be at the basis of the scientific documentation of the reconstruction and of the process that led to it.

Similarly, during these initial stages, texturing (i.e. issues related to the visualisation of the materials that are assumed to compose the object) has to be considered, together with context, that is whether – and, in case,

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7 The paper S*cientific reference model – defining standards, methodology and implementation of serious 3D models in archaeology, art and architecture history* by P. Kuroczyński, F. I. Apollonio, I.P. Bajena and I. Cazzaro, has been presented in the conference CIPA 2023 *Documenting, Understanding, Preserving Cultural Heritage* – Florence, June 25-30, 2023.

how – to represent the surroundings and whether there are elements that are excluded from the reconstruction.

It is important to use a controlled vocabulary when defining the elements and the relationships between them: in this case, the Art & Architecture Thesaurus Online developed by the Getty Research Institute[8] has been employed. The synagogue has been structured into a 3-level hierarchy (categories, elements, types) as explained in **FIG. 85**.

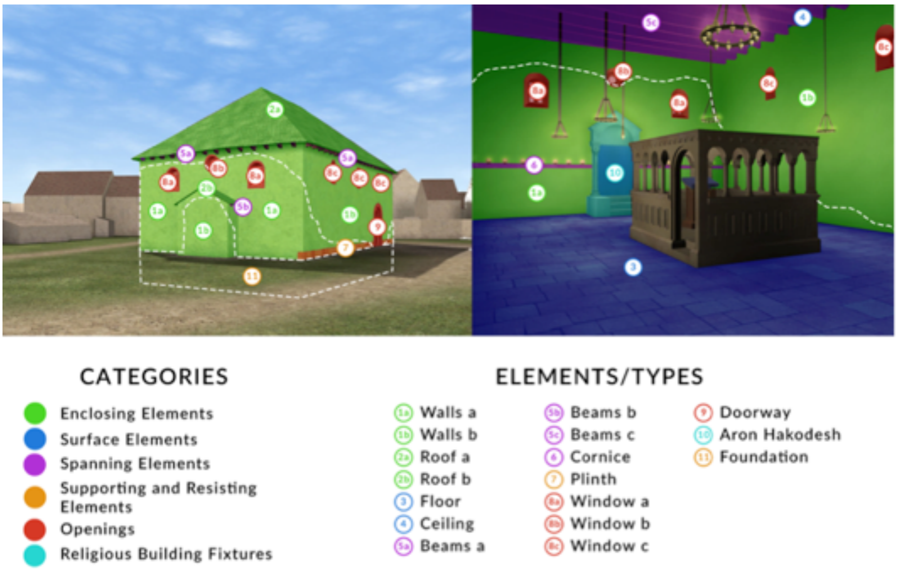

FIG. 85: Applying different structural categories to the building and identification of the types of structural elements. Visualisation by Igor Bajena.

8 <http://www.getty.edu/research/tools/vocabularies/aat/> (accessed 04.11.2024).

B.
PROPOSAL OF A METHOD TO DECLARE UNCERTAINTY

The need for clear documentation of the uncertainty level in the reconstruction of the Speyer synagogue had already been expressed (Heberer 2012)[9]:

> «In the course of the processing, it was repeatedly discussed whether and – if so – how the viewer can be informed about how far the reconstruction is secure and where more or less daring hypotheses begin. It seemed urgently necessary, at least on the behalf of the researchers, to find a way of differentiation. However, the demand for an atmospheric [photorealistic] model left little room for manoeuvre. As a result, Architectura Virtualis suggested superimposing the images of the current situation with those of the reconstruction, so that it becomes clear what is still existing and what is reconstruction [...]. Although this solved one of the problems, there was still no distinction made between the reconstruction secured by sources and the highly hypothetical reconstruction».

In order to declare to which extent the collected documents allow an accurate reconstruction, we propose the use of an uncertainty scale[10] (**FIG. 86**), which has been included in the handout for the reconstruction of the synagogue addressed to scholars, researchers and students who

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9 Author's translation. Original version: «Im Lauf der Bearbeitung wurde immer wieder diskutiert, ob und – wenn ja – wie dem Betrachter vermittelt werden kann, wie weit die Rekonstruktion gesichert ist, und wo mehr oder weniger gewagte Hypothesen beginnen. Es schien, zumindest von Seiten der Forschenden, dringend notwendig, eine Möglichkeit zur Differenzierung zu finden. Der Anspruch an ein atmosphärisches Modell ließ hier aber kaum Spielraum. Im Ergebnis kam von Architectura Virtualis der Vorschlag, die Bilder der heutigen Situation mit denen der Rekonstruktion zu überblenden, so dass deutlich wird, was Bestand und was Rekonstruktion ist […]. Damit war zwar eines der Probleme gelöst, allerdings war immer noch nicht zwischen der durch Quellen abgesicherten und der stark hypothetischen Rekonstruktion unterschieden» (Heberer 2012).

10 Based on (Apollonio, Fallavollita, and Foschi 2021), as already declared in **CHAPTER II**.

contributed to the project. In our example, the uncertainty level of an element is not attributed according to the nature of the sources that are used (photographs, drawings, written descriptions...), but rather according to the physical (on the object) or mental (on the sources) work we have to do to reconstruct an element, following this classification into four (plus one) levels:

- **4- blue**: survey and/or physical analysis of the still existing elements;
- **3- green**: deductions or inferences based on sources that are directly related to the object (written texts, drawings, photographs) or on other elements still on site that are similar to the missing ones;
- **2- yellow**: analogies based on similar structures or sources, which are not directly related to the analysed building, but they may refer to the same historical period or structural system;
- **1- red**: hypotheses concerning the elements for which no sources are available;
- **0- black**: if necessary, an additional level groups those elements that are not taken into consideration in the uncertainty assessment. This could be the case of the 25x25 m fragment of terrain where the model of the synagogue is situated.

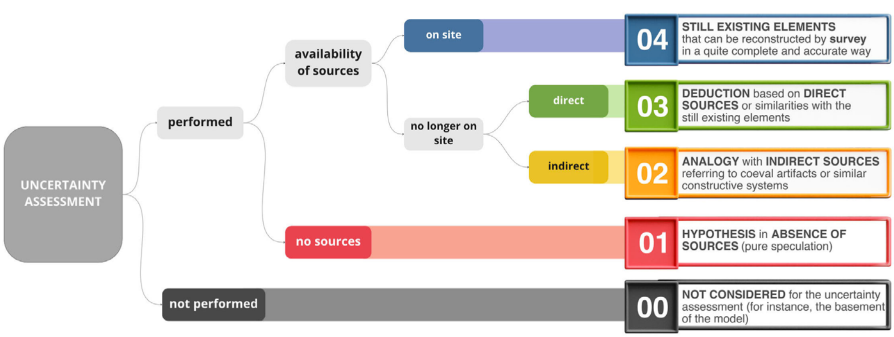


FIG. 86: Simple uncertainty scale elaborated for the models to be uploaded to the DFG viewer. Author's visualisation.

Uncertainty visualisation also depends on the level of detail (geometry) of the model: in the case of the Speyer synagogue, a level of uncertainty is assigned to each element that composes the structure of the model. The only exception is the external wall, which is only partially standing: in this case, a distinction is proposed between the existing part, reconstructed by survey (from the documented still existing remains) and the missing part, reconstructed by inference (assuming that it is similar to the still existing one).

Both a colour and a value are associated with each uncertainty level: if possible[11], the colour should be implemented in the visualisation of the model, the numerical value in the attributes of each element.

C.
APPLICATION AND VALIDATION

The main elements have been identified and modelled. Some documentation sheets have been produced in order to keep track of all the decisions made during the modelling phase.

In particular, for each phase of the activity a screenshot and a short description have been collected. In addition, for each identified element a description of the process was added highlighting the sources that have been used, their uncertainty level and any other useful information for modelling it.

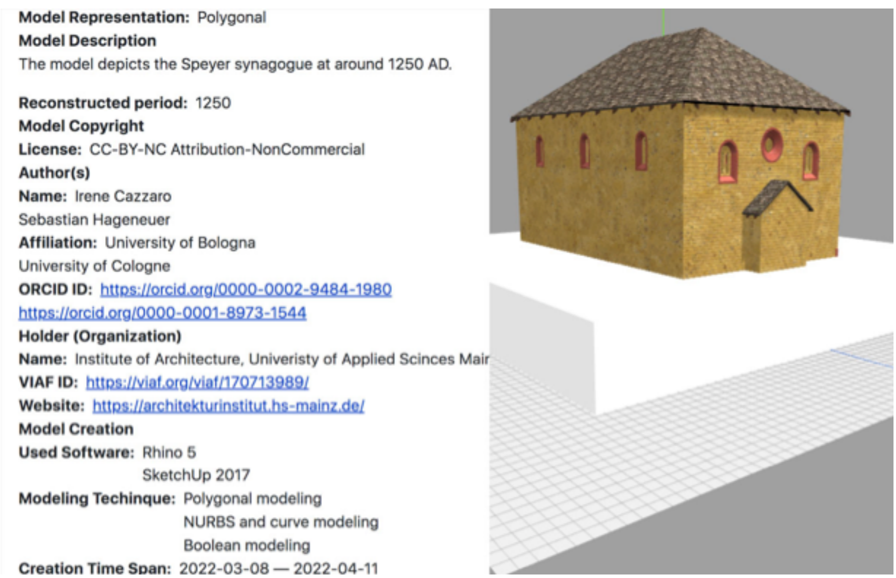
11 Depending on the possibilities of the used software: in the cases here analysed, Rhinoceros doesn't allow the creation of attributes; BIM software such as Archicad have a lot of possibilities as far as attributes are concerned; Sketchup needs an extension for City GML: we will analyse this in **CHAPTER III**.

D.
RESULTS

At the end, the output was uploaded to the DFG repository, where all the metadata and documentation of the process were included (**FIG. 87**), enabling the online publication of the results.

This takes place through an interface where the information about the model (metadata) is entered by the user in pre-formatted fields and the 3D data set is attached.

Some renderings of the model (**FIG. 88**) were also uploaded to Wikimedia Commons and linked to the Wikipedia page that had been created.


Model Representation: Polygonal
Model Description
The model depicts the Speyer synagogue at around 1250 AD.

Reconstructed period: 1250
Model Copyright
License: CC-BY-NC Attribution-NonCommercial
Author(s)
Name: Irene Cazzaro
Sebastian Hageneuer
Affiliation: University of Bologna
University of Cologne
ORCID ID: https://orcid.org/0000-0002-9484-1980
https://orcid.org/0000-0001-8973-1544
Holder (Organization)
Name: Institute of Architecture, Univeristy of Applied Scinces Mair
VIAF ID: https://viaf.org/viaf/170713989/
Website: https://architekturinstitut.hs-mainz.de/
Model Creation
Used Software: Rhino 5
SketchUp 2017
Modeling Techinque: Polygonal modeling
NURBS and curve modeling
Boolean modeling
Creation Time Span: 2022-03-08 — 2022-04-11

FIG. 87: The model of the Speyer synagogue uploaded to the DFG Repository, with its metadata.

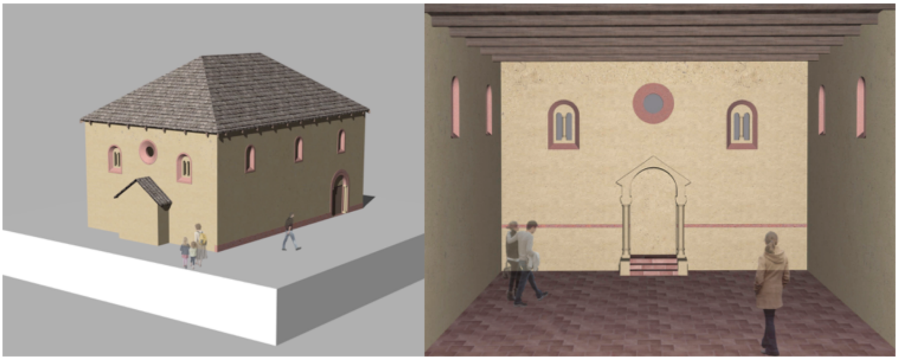


FIG. 88: External and internal view of the synagogue. Renderings uploaded to Wikimedia Commons. Author's visualisations.

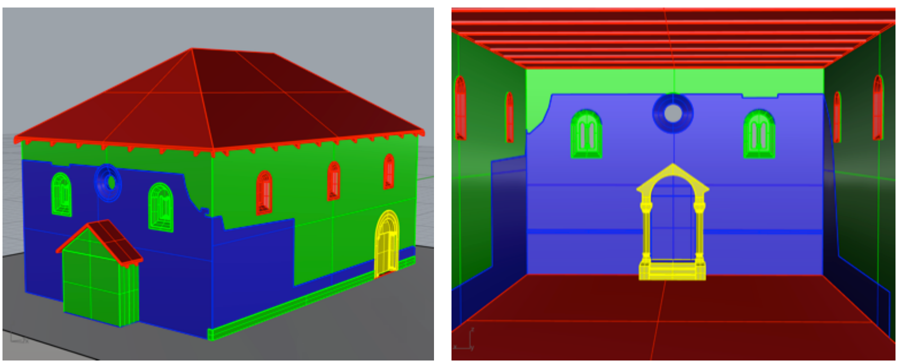


FIG. 89: Application of the uncertainty scale to the exterior and interior of the synagogue. Author's visualisations.

The decisions made during the reconstruction process have been captured by screenshots, so that the entire activity can be retraced step by step. The scientific documentation of the reconstruction process is delivered together with the 3D model in the form of tables – one for each element defined in the semantic segmentation. These tables have been provided as a template, which had to be filled out with the list of sources used for the reconstruction of every element, an evaluation of the level of uncertainty and argumentation in the form of a short text (**FIG. 90**).

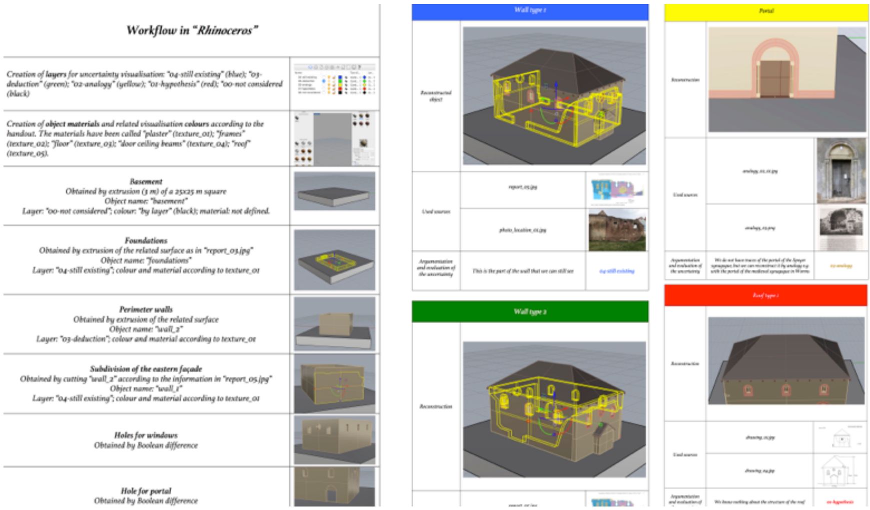


FIG. 90: Tables documenting the reconstruction steps and the choices made to reconstruct every single object as defined in the semantic segmentation. Author's visualisations.

D.1.
Uncertainty evaluation in detail

Our uncertainty scale based on 4+1 levels is an extreme simplification of an assessment grounded on multiple factors.

As we saw in **CHAPTER II**, uncertainty can refer to the position of an element, its shape, its texture, its historical period, etc.; it can be assessed by analysing different sources, such as physical remains, pictures, drawings, written texts. It is also connected to the semantic segmentation of the model, thus it depends on its level of detail.

Here we explain how the various elements have been evaluated using a more complex matrix (**FIG. 91**).

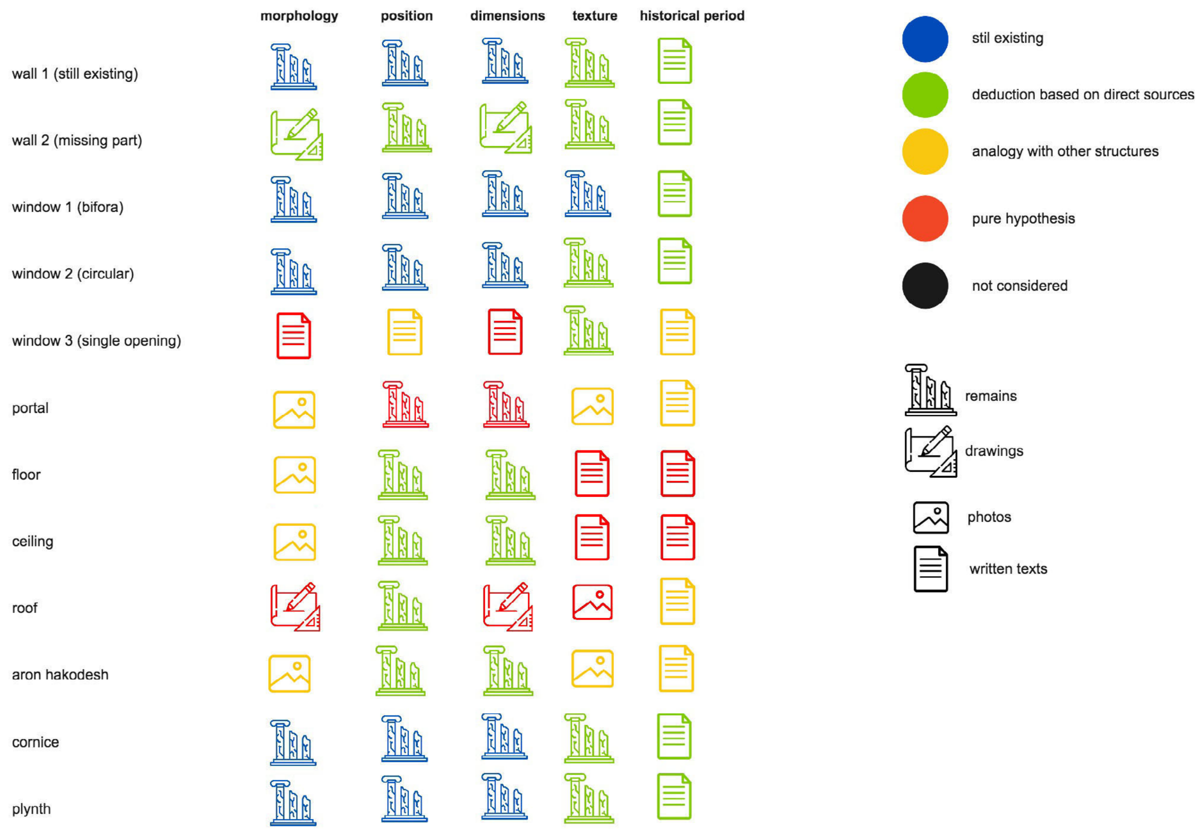
"Wall 1" refers to the part of the perimeter wall that is still on site. Its morphology, position and dimension have been reconstructed starting from the remains themselves. The corresponding uncertainty level is thus "4-still existing". The texture is deduced from some traces of plaster, thus the uncertainty level is "3-deduction". The historical period has the same uncertainty level and is deduced from the archaeological report.

"Wall 2" is the missing part of the wall, whose position is deduced from the remains, as well as the texture. The dimension and shape are found in drawings and reconstructions made starting from the archaeological report. The historical period is also indicated in texts connected to the archaeological excavations. Therefore, all the five parameters belong to the uncertainty level "3-deduction".

"Window 1 (bifora)" is the type of window that we can see in the eastern and western façade. There are four windows of this type and two of them are preserved in the SchPIRA Museum. Thus, in this case we can be sure about their morphology, dimension and texture, but also about their position: the original ones were replaced by copies that occupy the same position. The historical period is deduced from written texts.

"Window 2 (circular)" is still existing, therefore we can be sure about

FIG. 91: Evaluation of uncertainty based on five parameters: morphology, position, dimensions, texture, historical period. Author's visualisation.



morphology, dimension and position. The texture can be deduced from some traces, the historical period from written texts.

"Window 3 (single opening)" is quite hypothetical. The position and historical period can be inferred by analogy from written texts concerning similar buildings, the texture is assumed to be similar to the one of the other windows, but dimension and shape are highly hypothetical: we have some written descriptions that mention the presence of windows on the northern and southern façade, but we don't know them in detail and it is believed that originally they could also have been circular such as "window 2". A variant of the model has been made in order to consider this hypothesis.

"Portal" has been reconstructed starting from images of morphologically similar structures, which have been also used to try to reproduce the texture. The historical period has been retrieved from written texts connected to these examples used for analogies. We don't know its position and dimension in detail: we can try to guess them starting from the archaeological findings, but this remains a hypothesis.

"Floor" and "Ceiling" have been reconstructed with similar operations. We can deduce their position and dimensions in relation to the other elements of the building and their morphology from images of analogous structures, whereas the other features remain hypothetical, as confirmed by the written texts we have.

"Roof" is completely hypothetical for its morphology, texture and dimensions, especially its height. The (hypothetical) sketches and images from the previous reconstruction projects have nonetheless been considered to reconstruct it. Its position is derived from the other elements of the building. The historical period is attributed in analogy with similar structures.

"Aron Hakodesh" can be deduced from foundations and traces on the eastern façade, at least as far as its dimensions and position are concerned. Its morphology and texture is derived from images of similar structures and the historical period from written texts about them, as far as possible.

"Cornice" and "Plynth" still exist in large part and the reconstruction process is analogous to the one described for "Wall 1" and "Window 2 (circular).

The only parameter that remains excluded from the 4-parameter matrix that we have presented is the evaluation of quality according to Thomson et al. (2005). The evaluation, in this case, has been performed separately and applied to the single elements. Four of them, belonging to different uncertainty categories (still existing, by inference, etc.) have been selected and compared in **FIG. 92**.

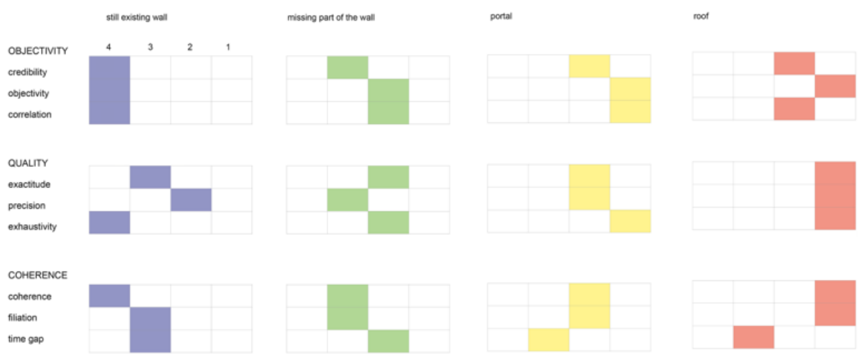


FIG. 92: Uncertainty evaluation based on the assessment of objectivity, quality and coherence parameters, according to Thomson et al. (2005). This evaluation has been performed on four elements belonging to different categories: "still existing", "reconstructed by inference based on direct sources", "reconstructed by analogy", "reconstructed by hypothesis". Author's visualisation.

D.2.
Second Romanesque phase: a variant with circular windows

A variant with circular windows is proposed to fill the information gap observed by Pia Heberer (2012):

> «The Romanesque entrance must have been on the northern side. A wide driveway was created there during the conversion to the armory. It was «9 feet [2.6 m] wide, and 13 feet high [3.76 m], with a round stone arch». Nothing remains of the Romanesque door. Litzel was able to describe the Romanesque and Gothic round windows in 1759: «Up [on the eastern side] in the middle [...] there is a round window, which has a diameter of 4 feet [1.15 m], and, below it, a small round [window] measuring 1 feet [...]». He also adds that in the north [on the northern façade] there are «exactly such round windows of exactly such size». Since he describes three Gothic windows on the northern side and the structure of the façade with the Romanesque round windows was still preserved, it can be deduced that the Gothic windows had obviously replaced the smaller Romanesque windows on this side as well. Unfortunately, the oculi mentioned by Litzel were forgotten during the reconstruction [by Architectura Virtualis]. Since this detail is of great importance for the synagogue construction, an improvement would be desirable».

This model has also been uploaded to the DFG Repository as a variant of the previous one. It has also been imported into SketchUp, so that a City GML file with uncertainty information could be created. The same has been done for all the structural variants of the synagogue here presented.

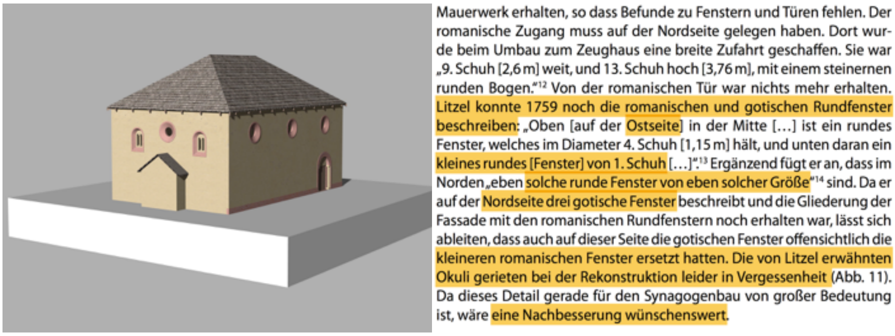

Mauerwerk erhalten, so dass Befunde zu Fenstern und Türen fehlen. Der romanische Zugang muss auf der Nordseite gelegen haben. Dort wurde beim Umbau zum Zeughaus eine breite Zufahrt geschaffen. Sie war „9. Schuh [2,6 m] weit, und 13. Schuh hoch [3,76 m], mit einem steinernen runden Bogen."[12] Von der romanischen Tür war nichts mehr erhalten. Litzel konnte 1759 noch die romanischen und gotischen Rundfenster beschreiben: „Oben [auf der Ostseite] in der Mitte [...] ist ein rundes Fenster, welches im Diameter 4. Schuh [1,15 m] hält, und unten daran ein kleines rundes [Fenster] von 1. Schuh [...]".[13] Ergänzend fügt er an, dass im Norden „eben solche runde Fenster von eben solcher Größe"[14] sind. Da er auf der Nordseite drei gotische Fenster beschreibt und die Gliederung der Fassade mit den romanischen Rundfenstern noch erhalten war, lässt sich ableiten, dass auch auf dieser Seite die gotischen Fenster offensichtlich die kleineren romanischen Fenster ersetzt hatten. Die von Litzel erwähnten Okuli gerieten bei der Rekonstruktion leider in Vergessenheit (Abb. 11). Da dieses Detail gerade für den Synagogenbau von großer Bedeutung ist, wäre eine Nachbesserung wünschenswert.

FIG. 93: Variant of the Speyer synagogue with circular windows. Author's visualisation.

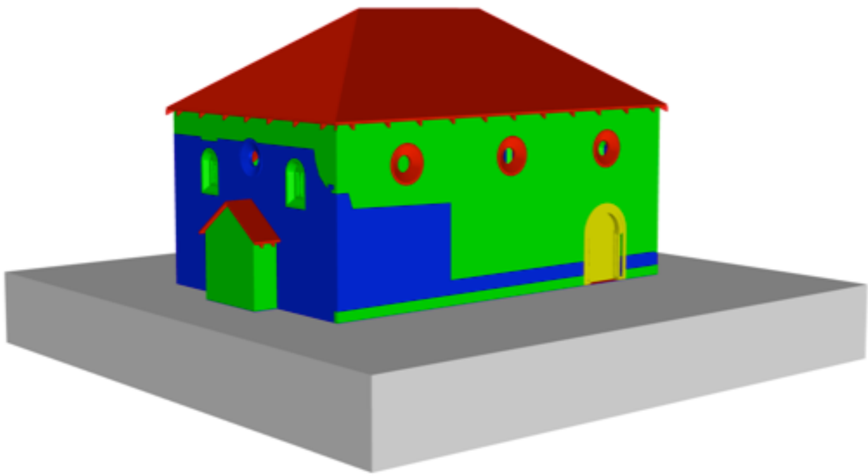


FIG. 94: Variant with circular windows: levels of uncertainty applied using Rhinoceros. The levels of uncertainty are still the same; just the shape of the windows has been changed. Author's visualisation.

D.3.
Gothic phase: the synagogue in 1350

During the Gothic phase, the Frauensynagoge (women's synagogue) was added and connected to the southern façade of the Romanesque building; a lower construction had also been added on the northern façade, where the entrance was supposed to be located.

The roof also had probably changed its shape. This model (**FIG. 95**), uploaded into the DFG Repository, was elaborated with SketchUp, from which the CityGML file was created.

In the SketchUp file the colours to indicate uncertainty have also been included (**FIG. 96**).

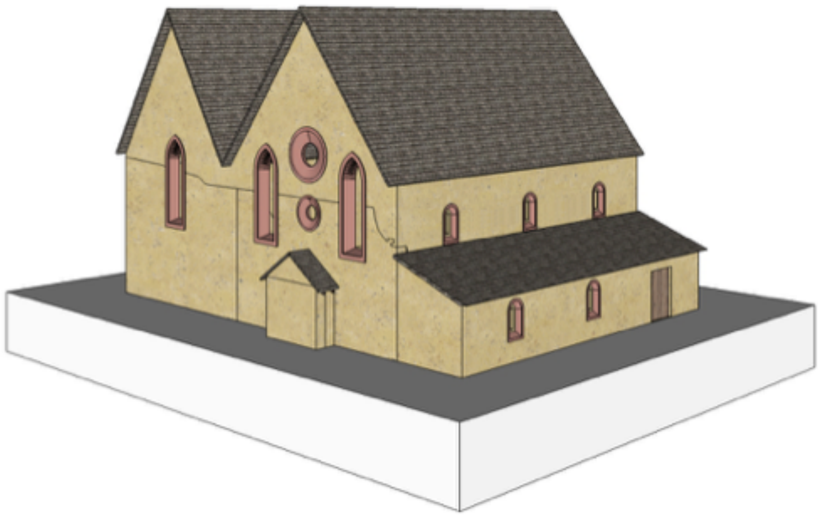


FIG. 95: Variant of the synagogue in its Gothic phase (around 1350). Author's visualisation.

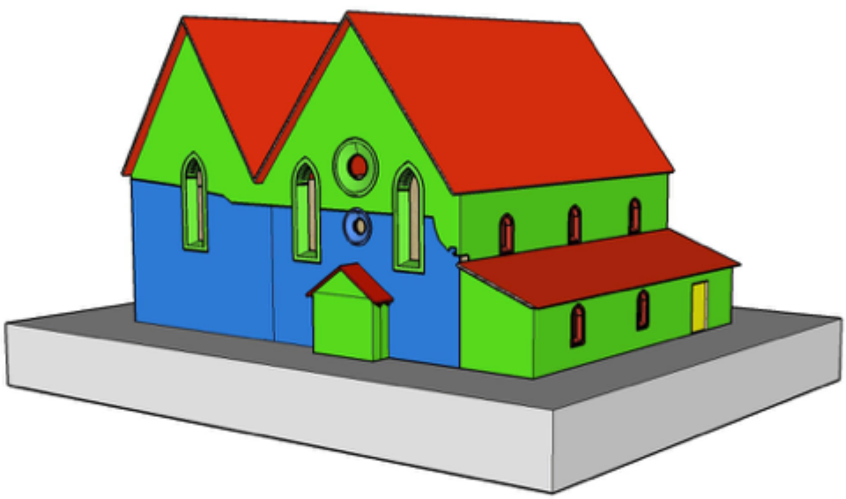
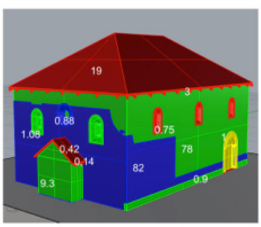


FIG. 96: The uncertainty scale applied to the 1350 Gothic variant using SketchUp. Author's visualisation.

E.
UNCERTAINTY AND LEVEL OF DETAIL

The calculation of the average uncertainty of the model has been performed (**FIG. 97**): this means that at another level of detail (**FIG. 98**) – imagining of putting it into a larger model of the city of Speyer where buildings are reconstructed at LOD 1 or 2, without closures – its average uncertainty would be 3.

This is why we should also consider the level of uncertainty in relation to the LOD. According to the semantic segmentation of the model, we can apply the parameter of uncertainty at different levels, also to a more detailed one, even though the portal here below (**FIG. 99**) is just an example and we don't have accurate sources that allow us to work at this level: from a scientific point of view, this would be a nonsense.



HYPOTHESIS
(19+0.42+3+0.14+0.75*6)*1 = 27.06

ANALOGY
1*2 = 2

DEDUCTION
(78+9.3+0.9+1.08*2)*3 = 271.08

STILL EXISTING
(82+0.88*2+1.08*2)*4 = 343.68

hypothesis + analogy + deduction + still existing = 643.82

total volume = 204.34 m^3

weighted average = 643.82 / 204.34 = **3.15**

FIG. 97: Calculation of the average uncertainty for the model of the Speyer synagogue. Author's visualisation.

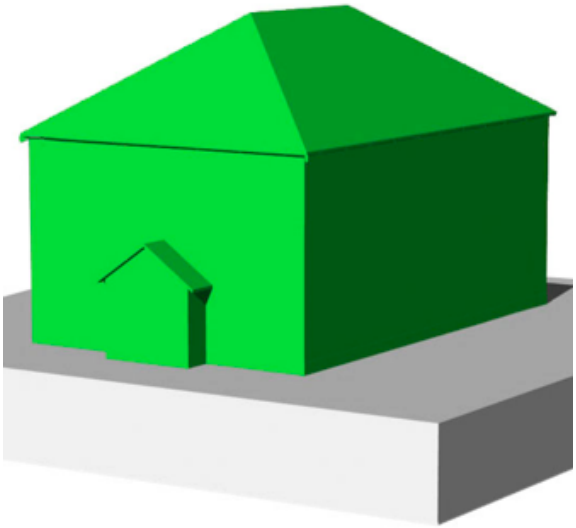


FIG. 98: At LOD 1 or 2, we would consider the (average) uncertainty level of the entire building, without differentiating it according to its elements. In this case, the average uncertainty level would be 3. Author's visualisation.

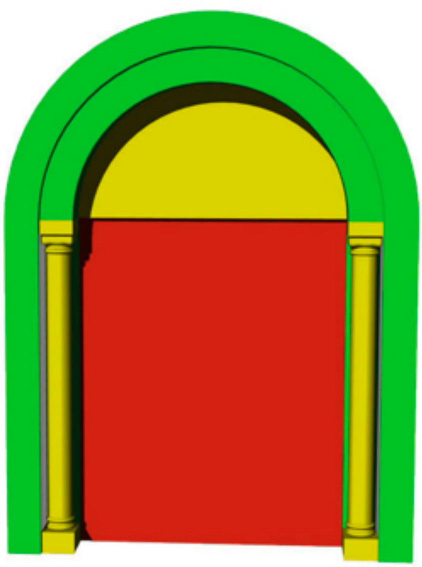


FIG. 99: If we imagine working at the detail of the single element, in this case the portal, a further subdivision into parts is probably necessary: in this case, we would indicate the level of uncertainty of each single sub-element. This visualisation is a pure example: the sources that we have to reconstruct the portal don't allow reasoning at this level. Author's visualisation.

F.
UNCERTAINTY VISUALISATION VARIANTS

In the previous part of the study we have focused on the visualisation scheme that seems to be the most effective one to graphically keep track of uncertainty; here we take into account a number of visual variants, sometimes to prove that the chosen scale works better, sometimes to propose alternatives that may be useful on particular occasions.

F.1.
Recognisability of the used colours

In the handout for the SpSya1250 reconstruction, we defined precise RGB colours in order to avoid misunderstandings; however, the scale should remain, to some extents, flexible and allow variations in colours, always enabling their recognisability. Here below, the model on the right has been coloured according to the scale by Apollonio et al. (2021); still we can recognise red, yellow, green and blue and we can say that the scale is almost analogous to the one used for the model on the left.

F.2.
A colourblind-safe variant

The colour scheme previously found on the ColourBrewer has been used here to generate a visualisation variant for colourblind people. Among the colourblind-safe schemes, this was the closest one to the scale we have proposed.

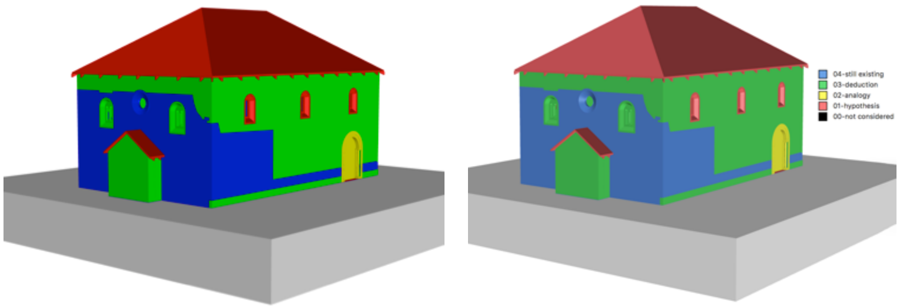


FIG. 100: On the left: the model with the "pure" RGB colours identified in the hand-out. Variations, however, may be possible. In the model on the right, the colours are still perceived as blue-green-yellow-red. These have been taken from the colour scale by Apollonio et al. (2021). Author's visualisations.

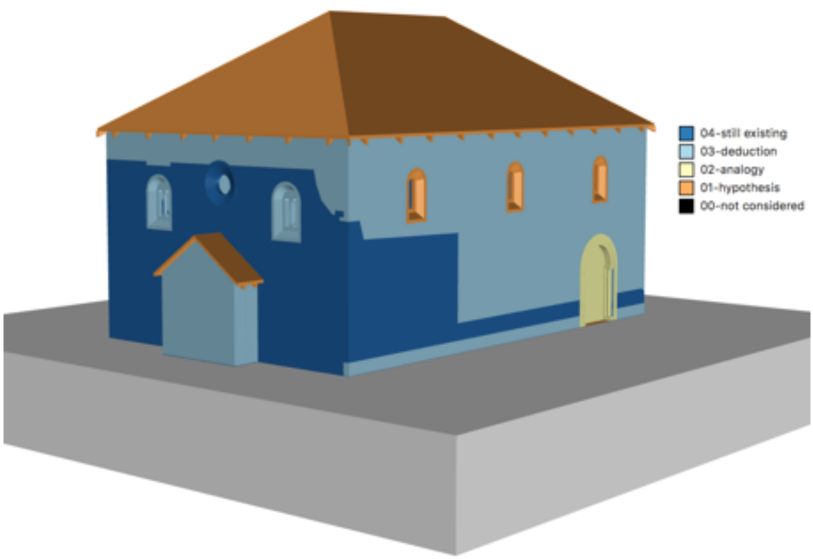


FIG. 101: A colourblind-safe uncertainty scale according to the ColorBrewer by Cynthia Brewer. Here the four colours used in the previous visualisations have been replaced by the series "blue", "light blue", "yellow", "orange". Author's visualisation.

F.3.
Different degrees of lightness

Greyscale may be used, as an example, in all the cases in which colour printing is not available. However, shading generates the problems that we can clearly observe on the roof: according to the orientation, two different shades of grey are perceived.

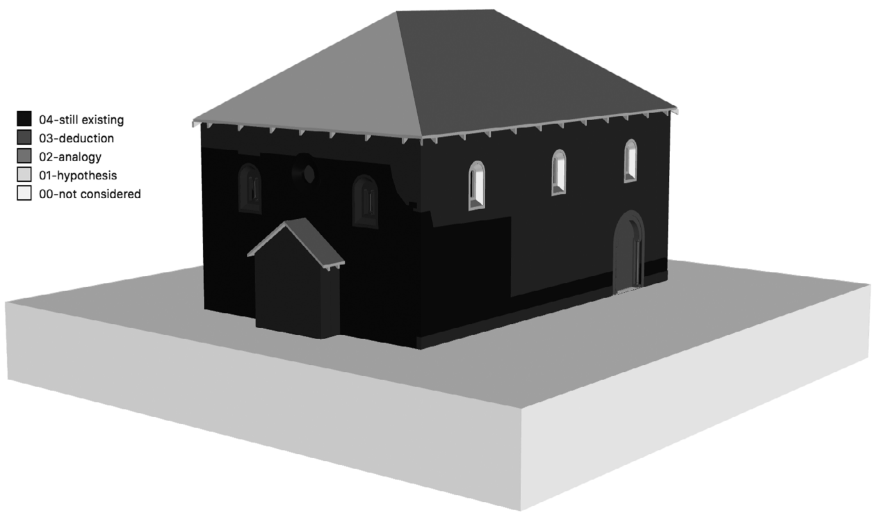


FIG. 102: Adoption of a scale based on the variation in lightness from black to white. Author's visualisation.

F.4.
Use of textures

Textures (in this case stripes and dots) together with simple plain colours as black and white can be can already define a four-level scale that may be used, for instance, by people who don't properly perceive colour.

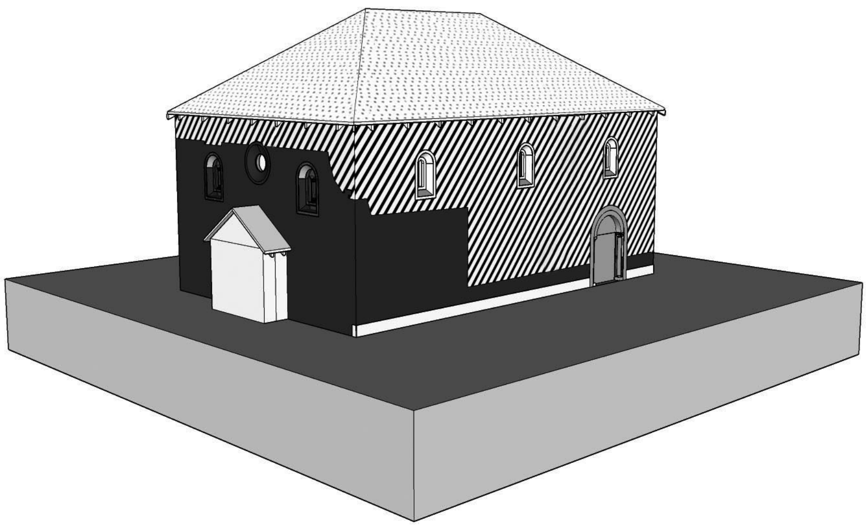


FIG. 103: The application of textures (stripes and dots) besides plain colours may define all the levels of the scale. Author's visualisation.

F.5.
Colours with different lightness

Different shades of red, green and blue may be used. Even in these cases, the problems of the black and white scale are still visible, especially in the difficult distinction between levels 01 and 02.

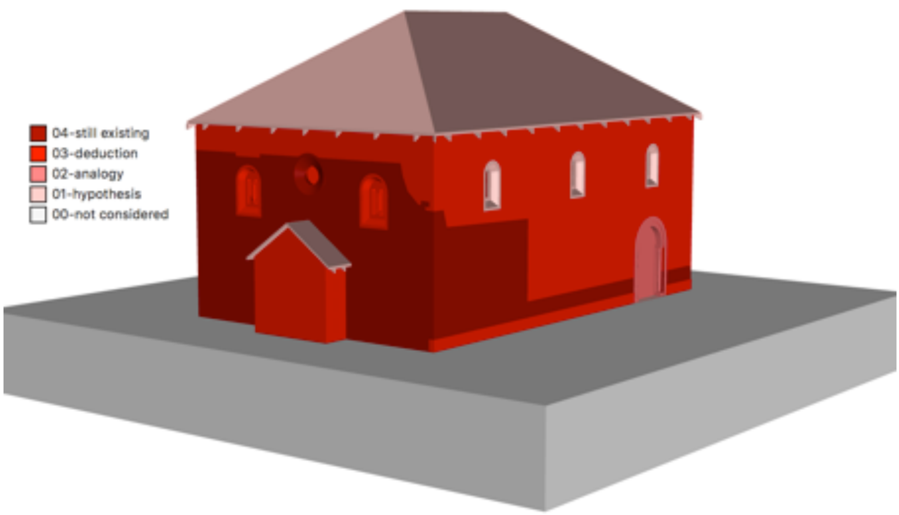


FIG. 104: Adoption of a scale based on the variation in lightness from red to white. Author's visualisation.

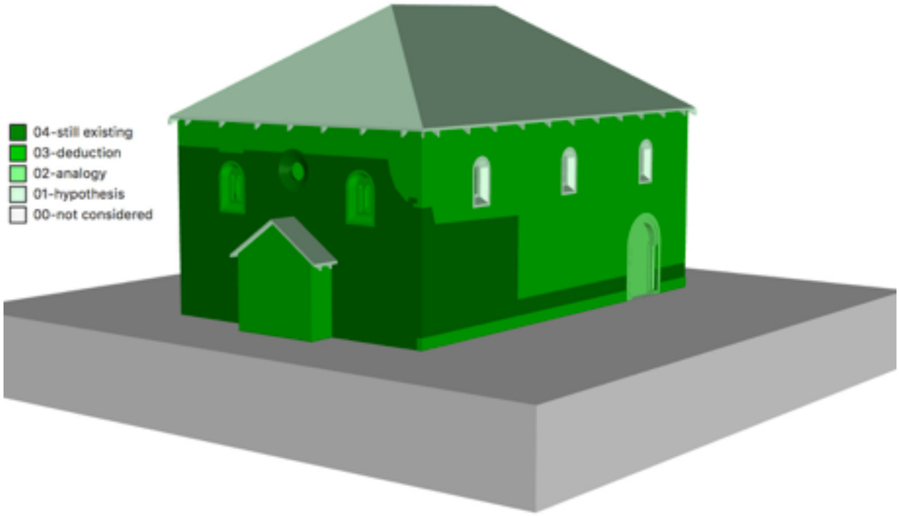


FIG. 105: Adoption of a scale based on the variation in lightness from green to white. Author's visualisation.

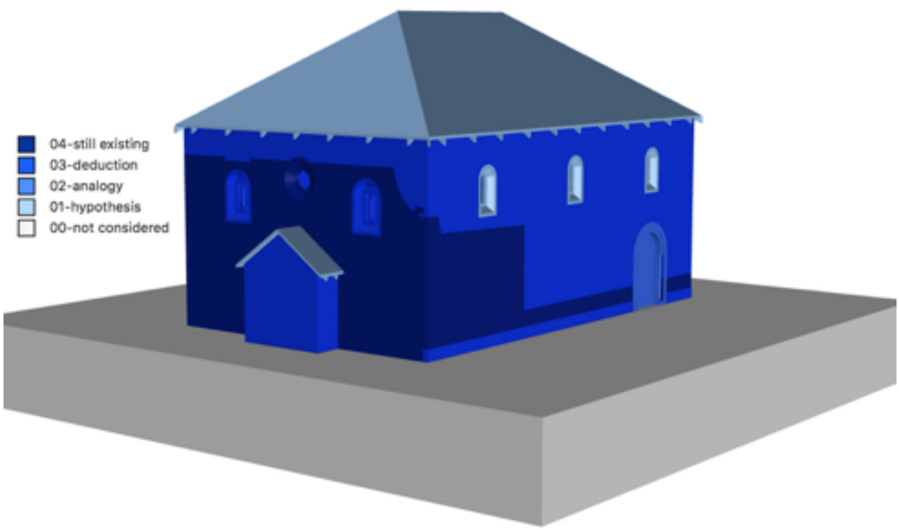


FIG. 106: Adoption of a scale based on the variation in lightness from blue to white. Author's visualisation.

F.6.
Different degrees of transparency

An alternative may also be the use of transparency, but this technique is especially employed when we have to simply distinguish what is reality-based and what is source-based, since we hardly perceive multiple variations in transparency.

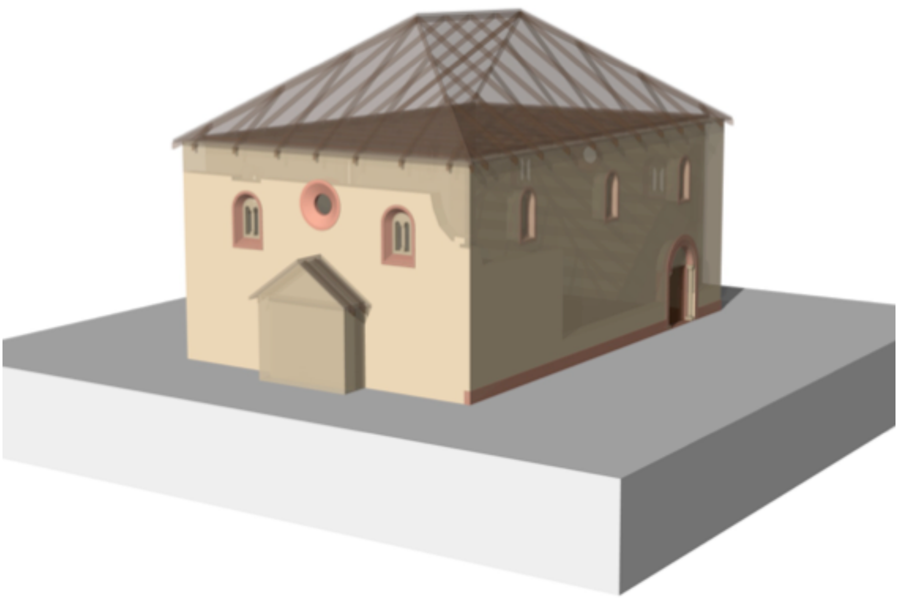


FIG. 107: Uncertainty expressed through different degrees of transparency – as far as they can be distinguished. Author's visualisation.

F.7.
Wireframe and transparency

Therefore, if we want to visualise more variations, a combination of different techniques may also be considered.

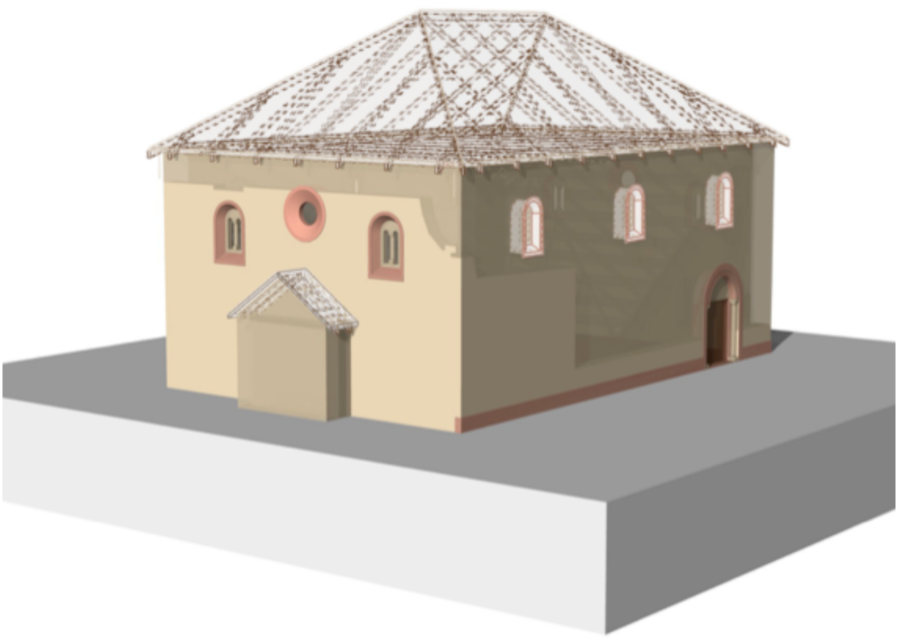


FIG. 108: Combination of opacity, transparency and wireframe to visualise more uncertainty levels. Author's visualisation.

F.8.
Use of a mesh to represent the still existing parts of the building

If we just want to distinguish what is still on site and what has been reconstructed starting from archival sources, a solution would be replacing the still existing elements with their actual (reality-based) mesh obtained by survey.

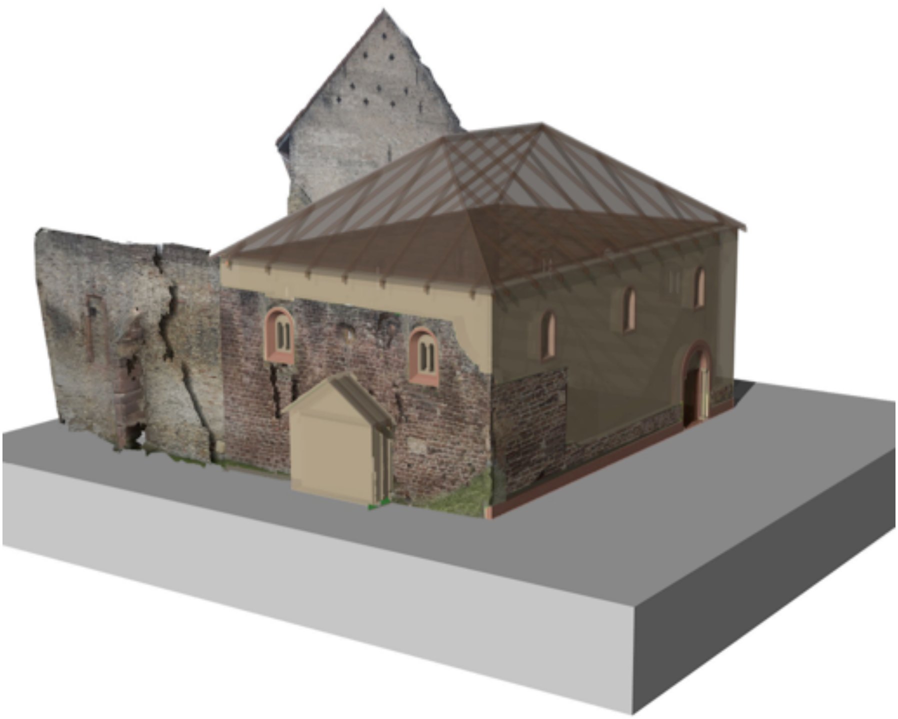


FIG. 109: Mesh produced by prof. Sander Münster and elaborated by the author. The pictures taken by the author have been initially used.

F.9.
Combination of the mesh with the levels of uncertainty

The levels of uncertainty, for the source-based part of the model, can still be indicated by using colours or a combination of the techniques described before.

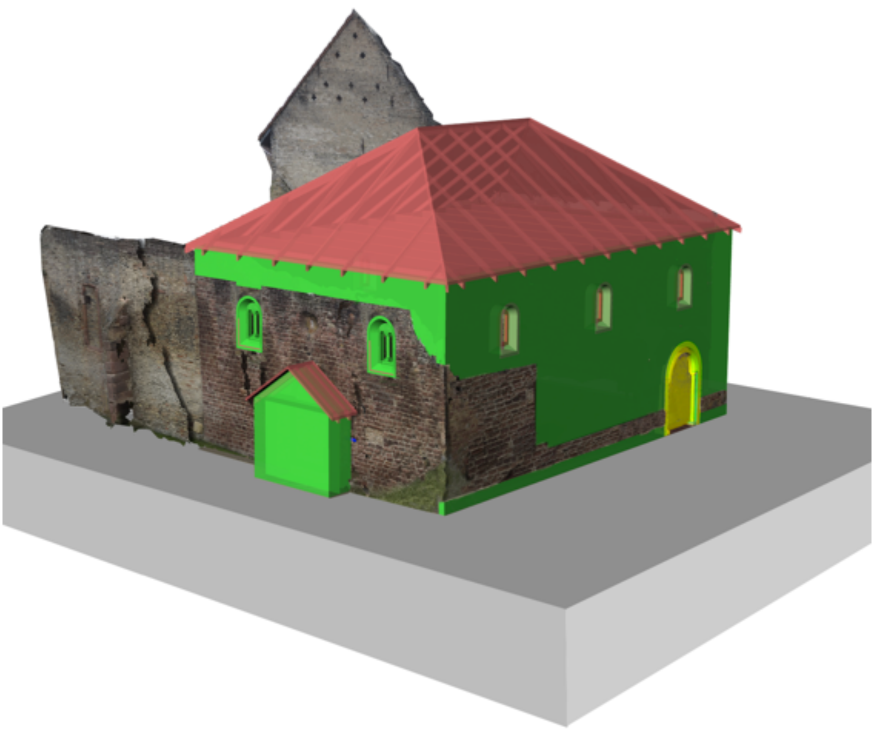


FIG. 110: In this case, the mesh has been used to visualise the still existing parts of the building, whereas a non-photorealistic model with colours indicating the different degrees of uncertainty (according to the scale seen before) represent all the source-based reconstructed elements. Author's visualisation based on the previous figure.

G.
MAKING UNCERTAINTY DATA INTEROPERABLE

We have two problems at this point:

(1) How do we share data about uncertainty? They are only visible in a particular version of Rhinoceros;
(2) Is it possible to share uncertainty data at different levels of detail?

Interoperability is allowed by using standard exchange formats such as IFC (for constructive solid geometry software) or CityGML (for boundary representation software): it is therefore necessary to focus on these standards.

(1) City GML: the model has been imported in SketchUp, so that it was possible to work with the City Editor extension. The uncertainty values were applied at two levels: the entire model and its single parts. At the end, the GML file was saved. When opened with FZK Viewer (free viewer for IFC and City GML files) we see that the information about uncertainty remains at both levels.
(2) IFC: the same can be done starting from Archicad. The work has been done by Igor Bajena in the framework of the SpSya1250 reconstruction project. He added uncertainty values according to the scale here discussed and saved the file in IFC format. Even in this case, when the file is opened with Open IFC Viewer, we can see that uncertainty data remain.

Here is an example of workflow that can be applied to SketchUp using the extension City Editor, allowing to add attributes and to export the file in .gml format.

The screenshots of the operations made on the various elements are shown in the next pages.

G.1.
Romanesque synagogue (1250)

We start the process by attributing, for all the walls, the boundary surface type “wall surface”.

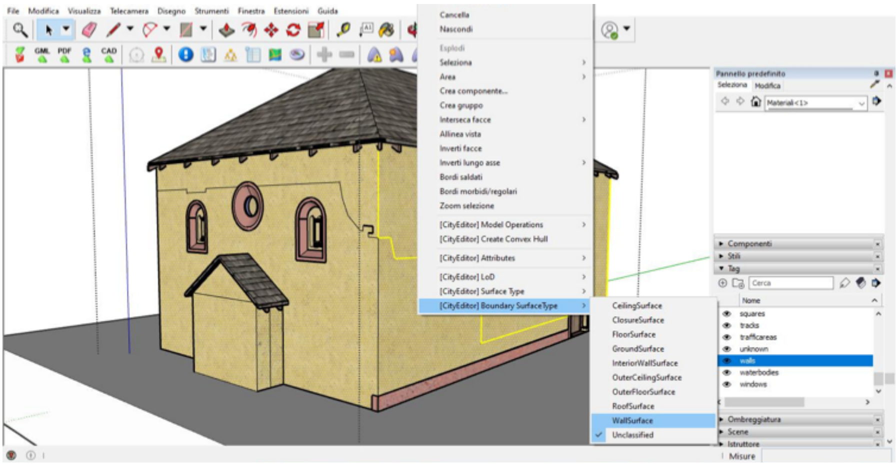


FIG. 111: Attribution of “wall surface” as boundary surface type. Author's visualisation.

Wall 1, which is the still existing part of the wall, has been then specifically identified. The standard attributes “id”, “name”, “date” are added, as well as a generic attribute called “uncertainty level”.

In the field “value”, a value in the range 0-4, according to our uncertainty scale, is entered. In the case of this wall, it corresponds to “4-still existing”.

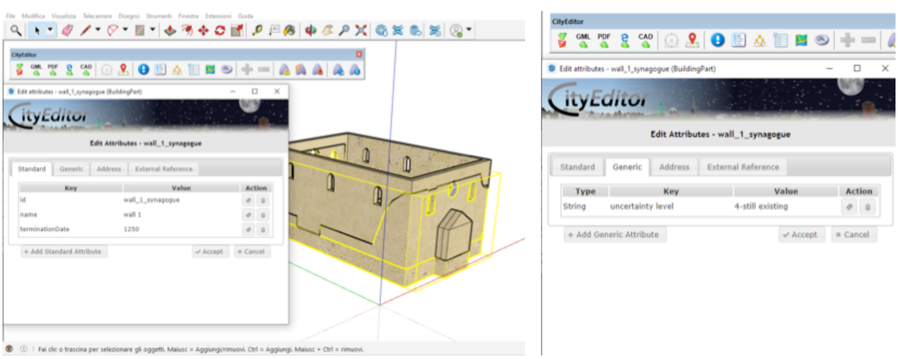


FIG. 112: The attributes related to the still existing part of the wall are added; as a generic attribute, the uncertainty level is also included. Author's visualisation.

The same has been done for all the other elements. Here we can see *Wall 2*, which is the part of the wall that no longer exists. In this case, the uncertainty value is "3-deduction".

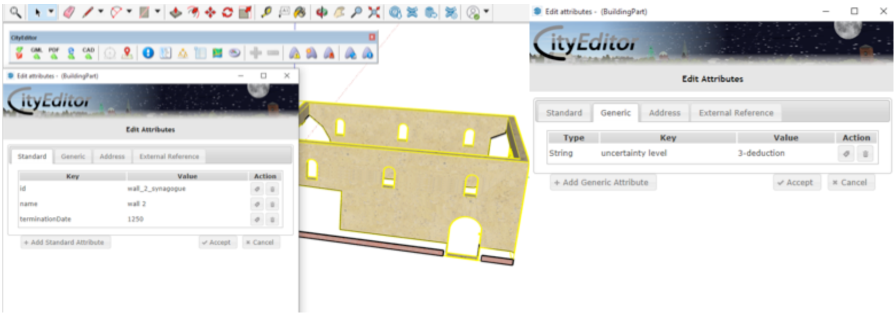


FIG. 113: The same has been done for Wall 2, whose uncertainty level is 3-deduction. Author's visualisation.

The element Roof, as the first thing, was assigned to the boundary surface type "Roof surface". Then, the usual attributes were added. The uncertainty level is "1-hypothesis".

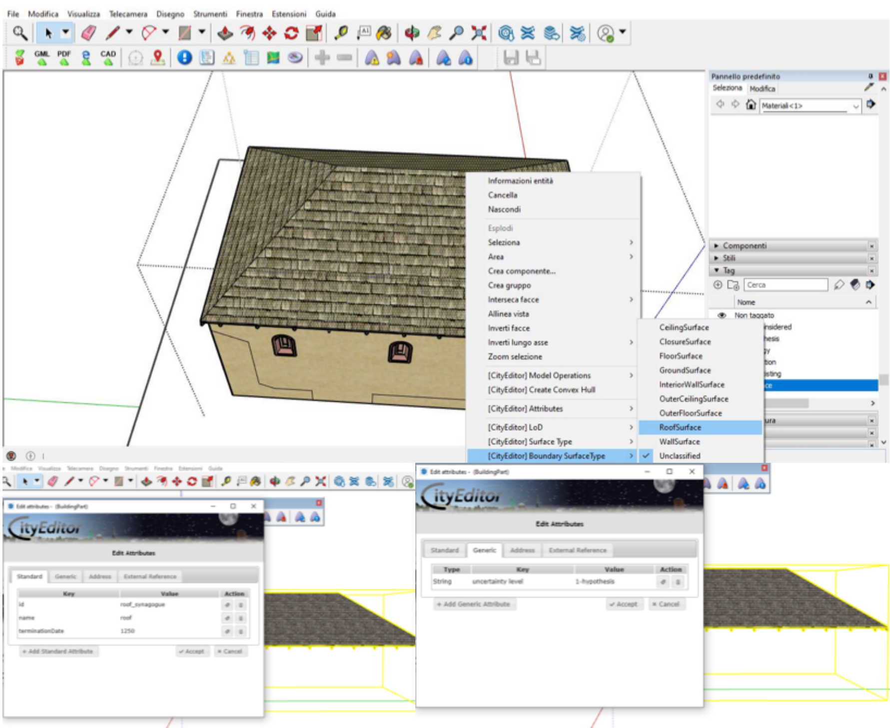


FIG. 114: Attributes were added to the roof in the same way. Here the uncertainty level is "1-hypothesis". Author's visualisation.

The *windows*, together with the portal, have been selected and identified as “closure surface”. The attributes were then added. Here the uncertainty levels are multiple: “4-still existing” for the oculi, “3-deduction” for the windows on the eastern and western façades, “2-analogy” for the portal, “1-hypothesis” for the windows on the northern and southern façades. For all the other elements of the reconstruction the process has been repeated. We show here just some other examples.

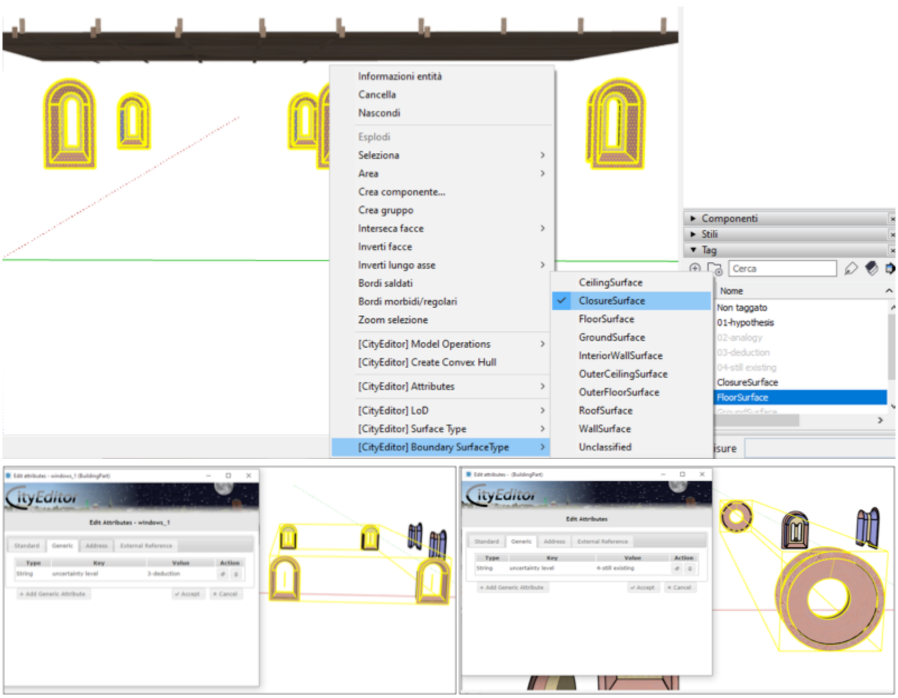


FIG. 115: Attributes are added to closure surfaces. Author's visualisation.

The same operations have also been performed on the variant with circular windows. The type of window is the same as the two oculi in the eastern and western façades.

The land on which the building is situated has been identified and the uncertainty level “0-not considered” has been attributed to it.

At the end, the entire model has been identified as a “building” (the elements seen before were indicated as “building parts”).

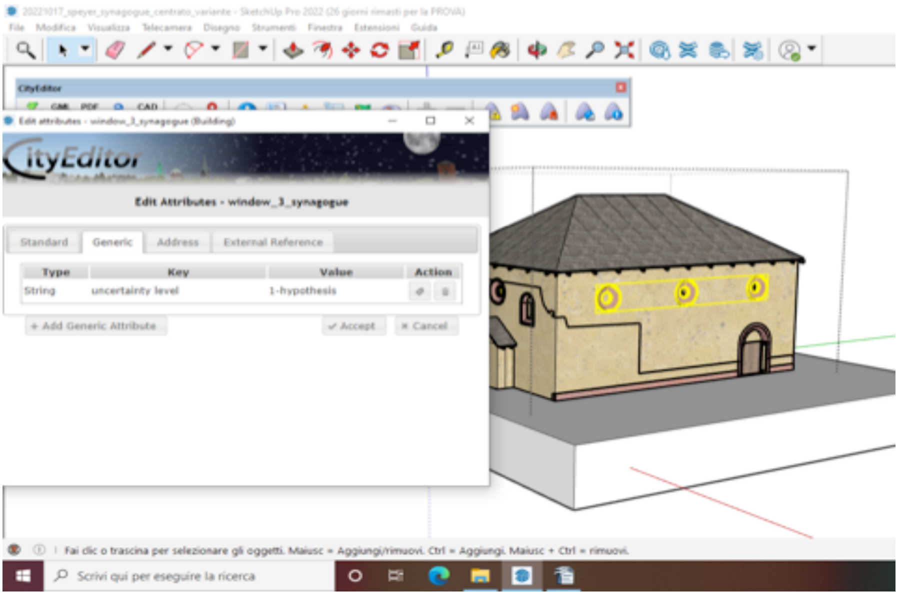


FIG. 116: Attributes are added to the variant with circular windows. Author's visualisation.

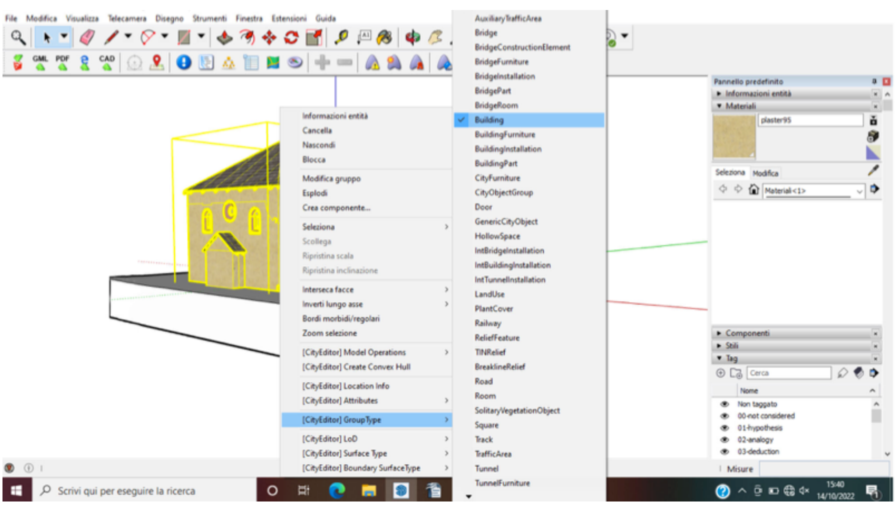


FIG. 117: The attributes are applied to the entire building, at another level of the hierarchy. Author's visualisation.

Similarly to building parts, standard attributes have been added to the whole building.

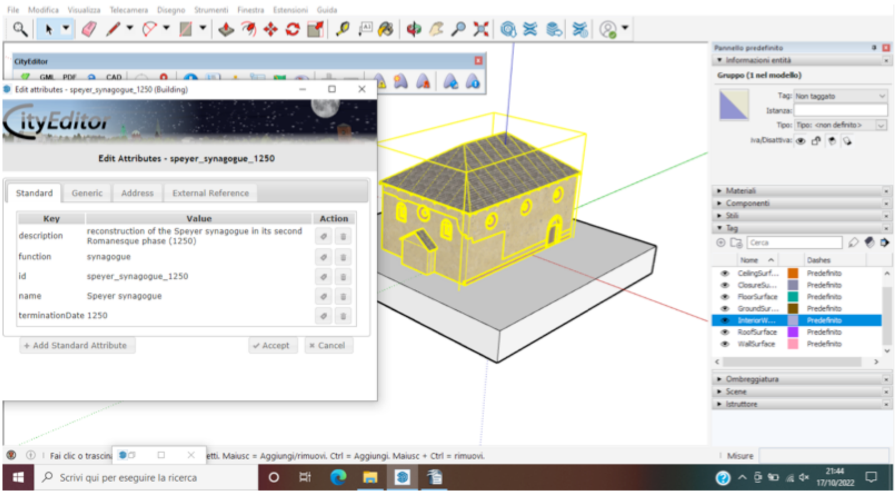


FIG. 118: The attributes are applied to the entire building, at another level of the hierarchy. Author's visualisation.

The average uncertainty level referring to the entire building has been added too, thus we have the information about uncertainty at two levels of the hierarchy.

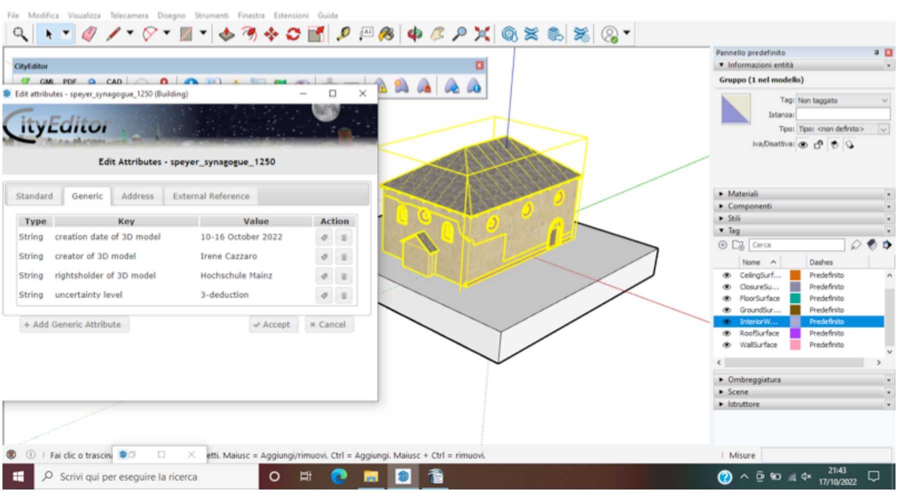


FIG. 119: The attributes are applied to the entire building, at another level of the hierarchy. Author's visualisation.

The model has been finally exported in CityGML format.

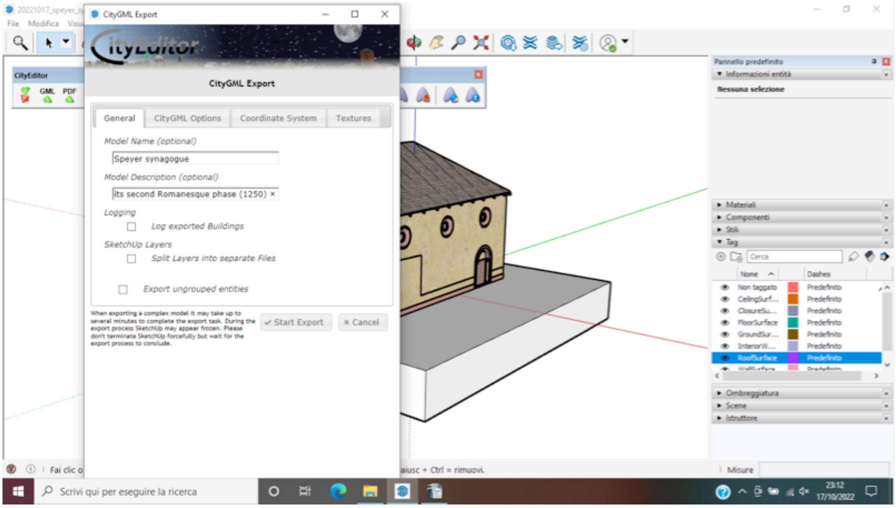


FIG. 120: The CityGML export. Author's visualisation.

When opened with FZK Viewer, a free viewer for IFC and CityGML files, we can observe that all the added properties are preserved, at both levels of the hierarchy: the entire building and the single elements. Some examples are shown here below.

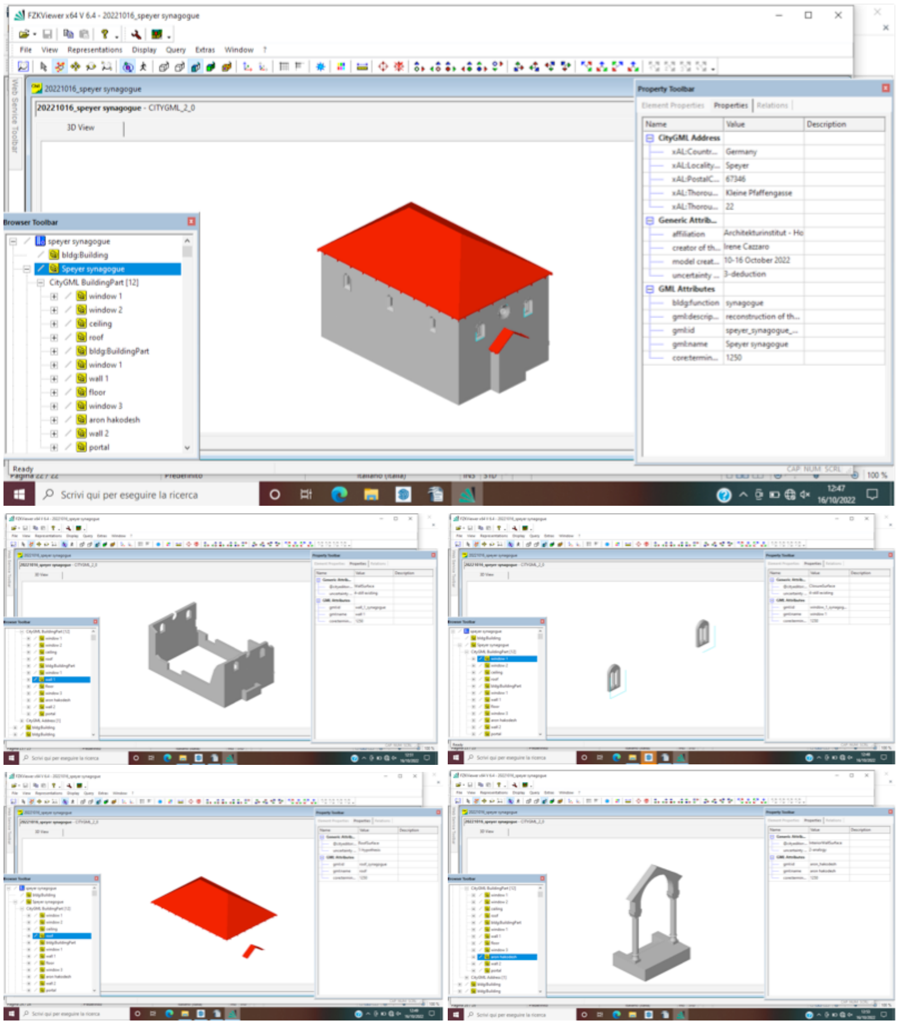


FIG. 121: Visualisation of the model and of some elements that compose it, together with the assigned attributes, in FZK Viewer. Author's visualisation.

The variant with circular windows has also been saved in GML format and opened with FZK Viewer, confirming that all the data added with CityEditor are accessible.

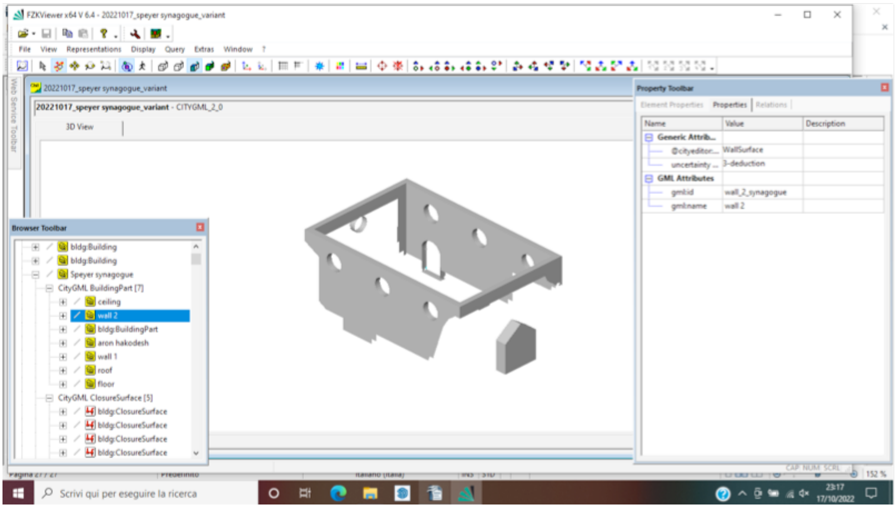


FIG. 122: Visualisation of the variant with circular windows and its related attributes in FZK Viewer: the deduced wall. Author's visualisation.

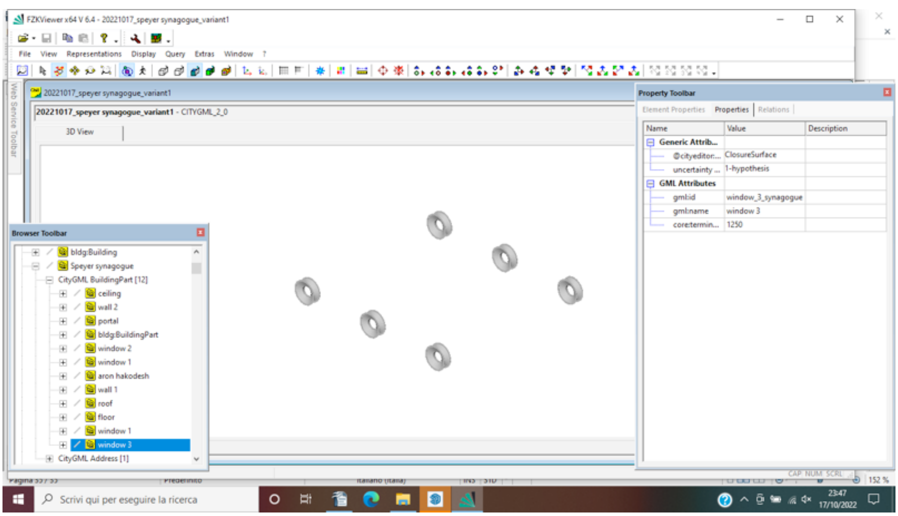


FIG. 123: Visualisation of the variant with circular windows and its related attributes in FZK Viewer: the circular windows. Author's visualisation.

G.2. Gothic synagogue (1350)

The same process has also been applied to the Gothic variant of the synagogue. A new type of window – *Window 5-Gothic* – has been created, with level of uncertainty "3-deduction" since the structure is partly visible on the eastern façade.

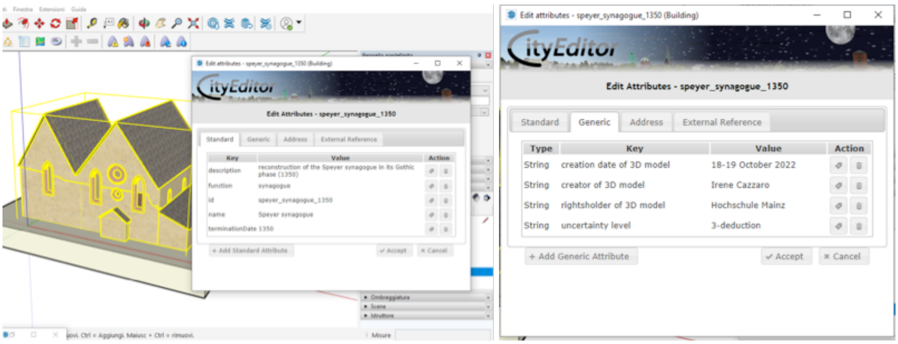


FIG. 124: Gothic variant: the attributes are added to the entire building. Author's visualisation.

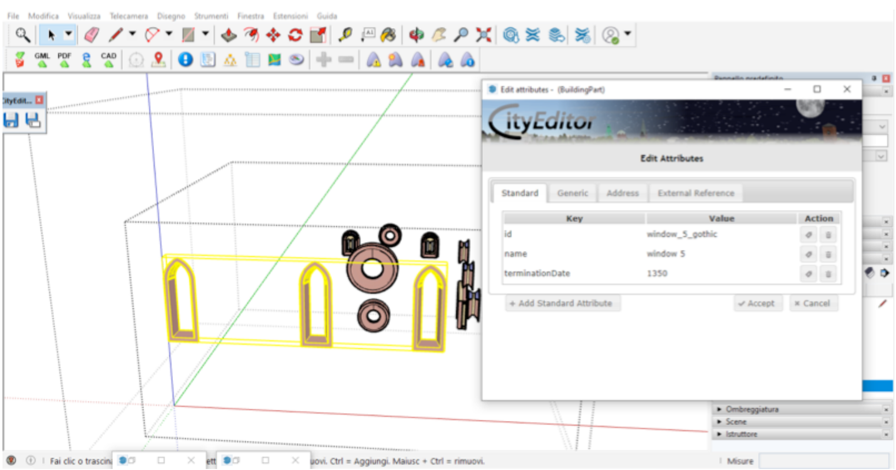


FIG. 125: Gothic variant: the attributes are added to every single element. This is only an example concerning the windows that have been transformed in the passage from the Romanesque to the Gothic synagogue. Author's visualisation.

The structure of the model can be navigated with the "model explorer" tool of CityEditor to check that everything is correct.

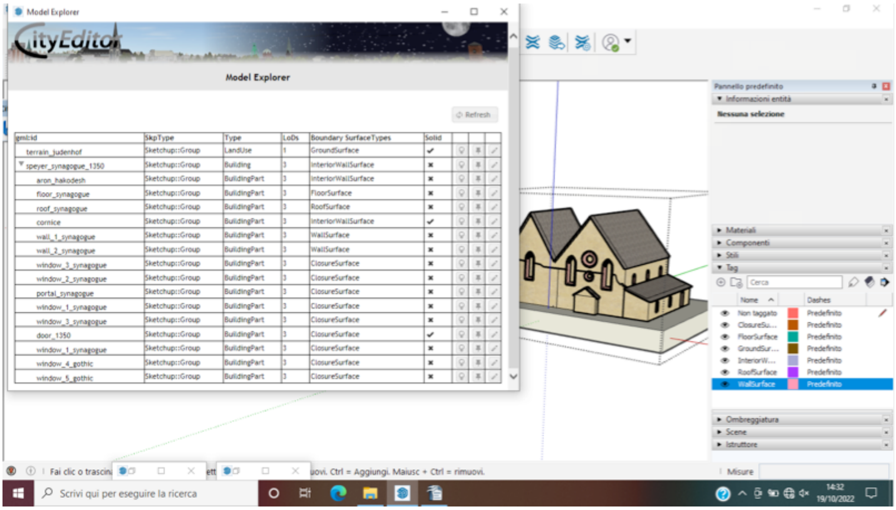


FIG. 126: The structure of the model in CityEditor. Author's visualisation.

Again, the model was saved in CityGML and opened with FZK Viewer, showing all the entered properties.

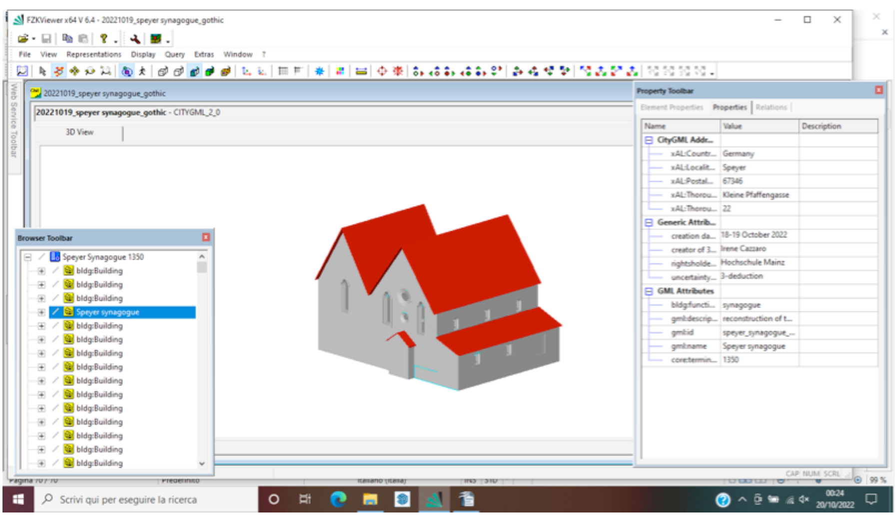


FIG. 127: The visualisation of the Gothic variant and its attributes in FZK Viewer: here the entire building can be seen. Author's visualisation.

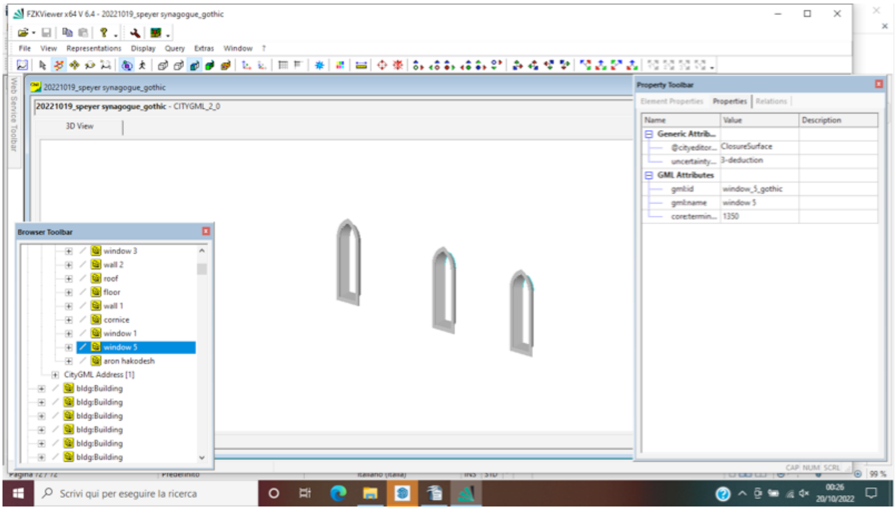


FIG. 128: The visualisation of the Gothic variant and its attributes in FZK Viewer: Gothic windows. Author's visualisation.

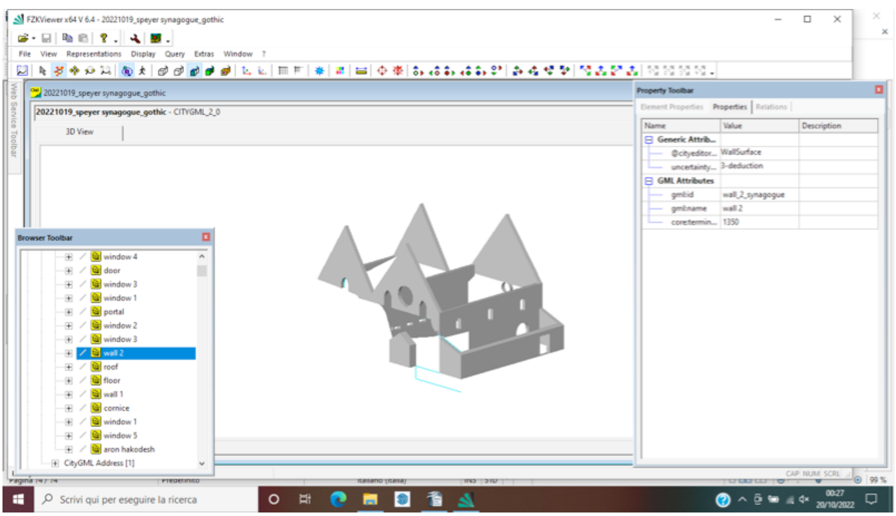


FIG. 129: The visualisation of the Gothic variant and its attributes in FZK Viewer: deduced part of the wall. Author's visualisation.

G.3.
Using Archicad / exporting in IFC format

Of particular interest, still in the context of the SpSya1250 project, is the model made by Igor Bajena using Archicad.

In this case, it could be exported in IFC format and opened with Open IFC Viewer: here, as well, we can see that all the properties, also the ones related to uncertainty documentation, are preserved. The steps are illustrated here below.

A new parameter, which can be potentially attributed to all the objects, is added by means of the Property Manager tool.

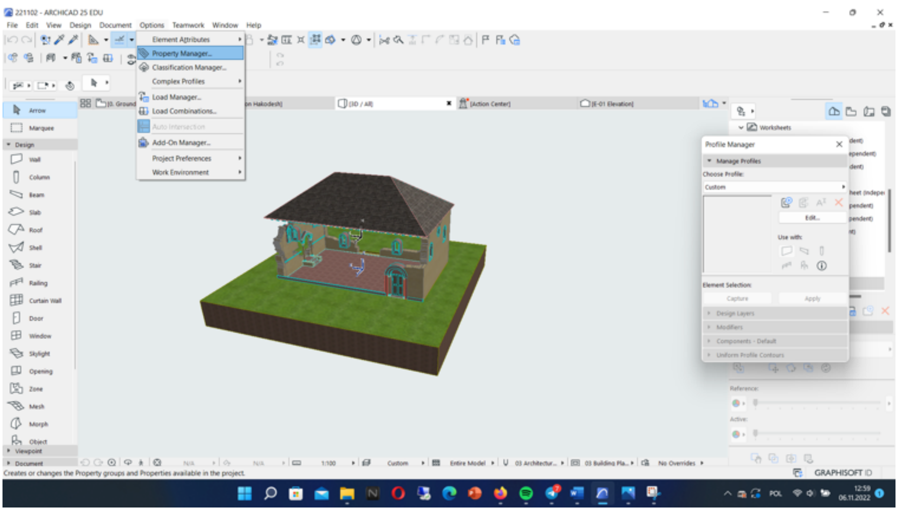


FIG. 130: Adding the uncertainty property in Archicad. Step 1. Visualisation by Igor Bajena.

This is actually a group or properties called "Uncertainty", to which the property "Level" is associated. In this way, a level, with the desired value, can be assigned to uncertainty.

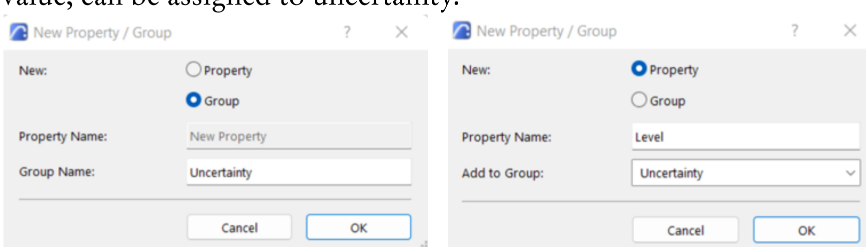


FIG. 131: Adding the uncertainty property in Archicad. Step 2. Visualisation by Igor Bajena.

Once created the new group and property, a description of the parameter is entered. “Option set” is selected as the data type: at this point, the list of the possible values is added. The value for each element will be selected from this list.

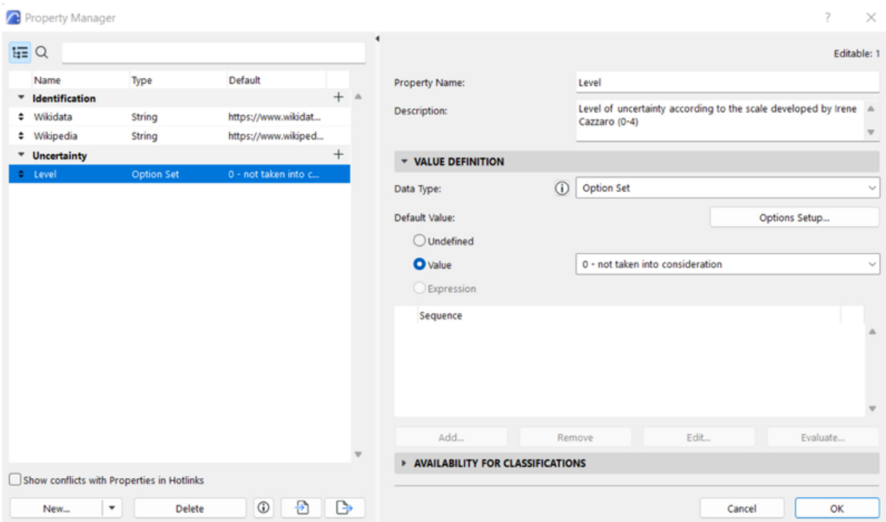


FIG. 132: Adding the uncertainty property in Archicad. Step 3. Visualisation by Igor Bajena.

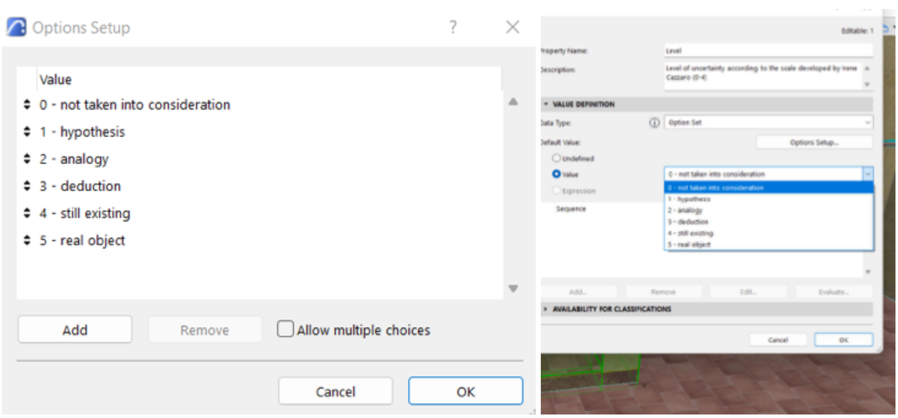


FIG. 133: Adding the uncertainty property in Archicad. Step 4. Visualisation by Igor Bajena.

Complex objects are created by connecting several components and saving them as a single object in the internal project library.

Only for the wall the division between still existing parts and missing ones has been kept.

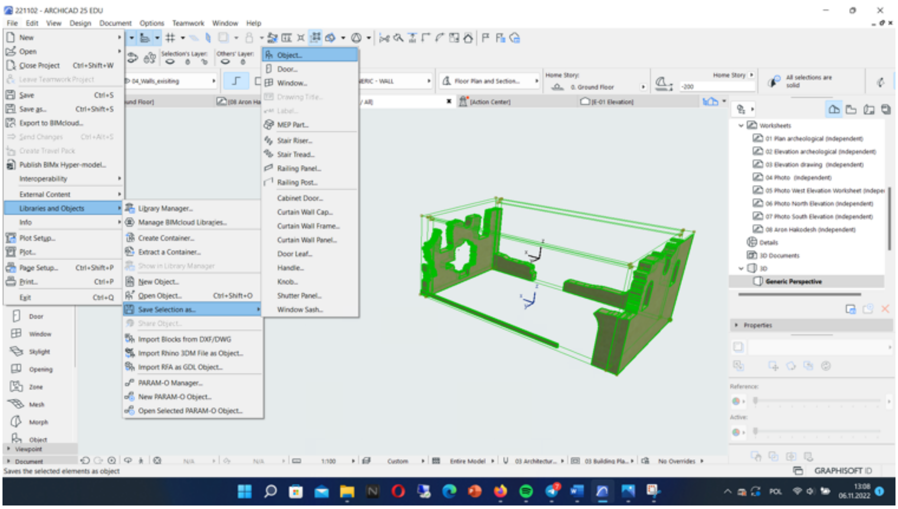


FIG. 134: Adding the uncertainty property in Archicad. Step 5. Visualisation by Igor Bajena.

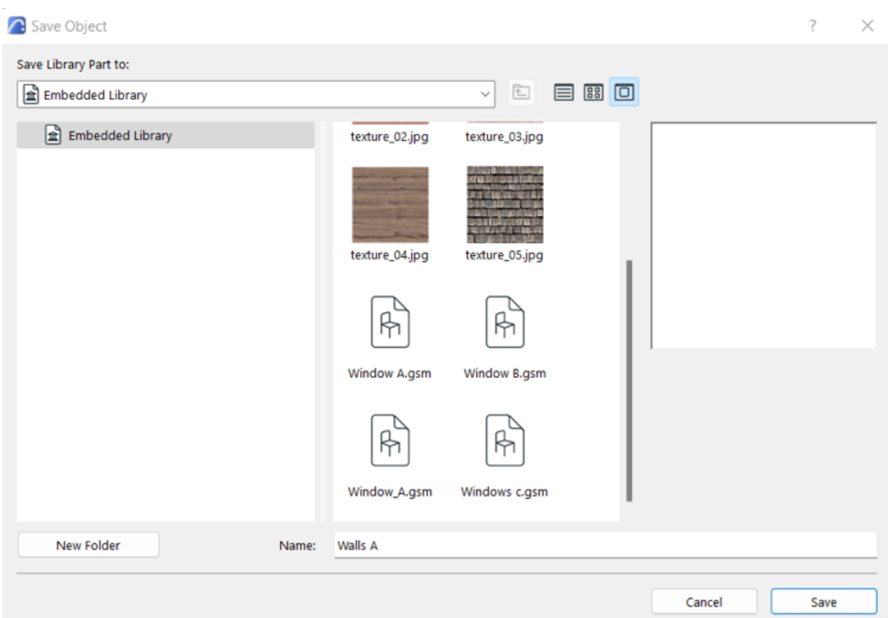


FIG. 135: Adding the uncertainty property in Archicad. Step 6. Visualisation by Igor Bajena.

The still existing wall (Wall 1) is selected and its properties are adjusted in the Object Selection Settings. Under the "classification and properties" section, the hierarchy prepared for the project "SpSya1250" is picked, as well as the class "wall".

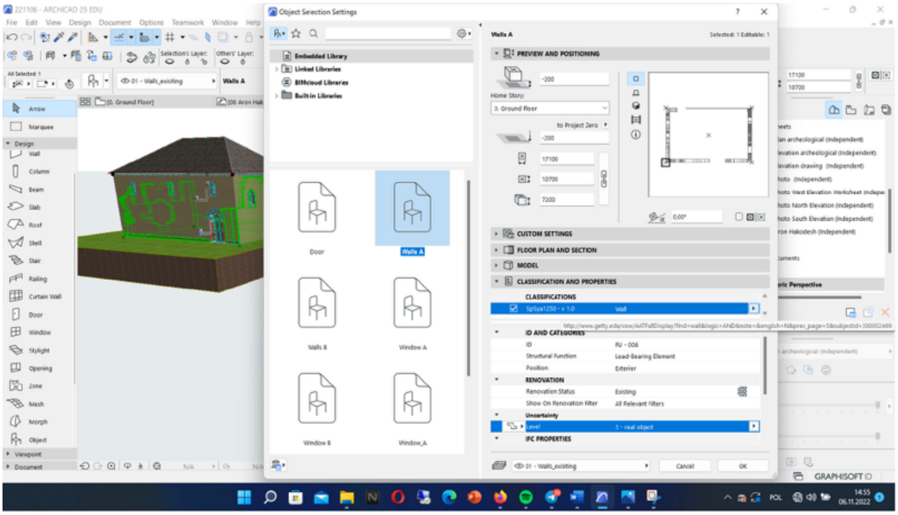


FIG. 136: Adding the uncertainty property in Archicad. Step 7. Visualisation by Igor Bajena.

Then, in the "uncertainty" section, the corresponding level is chosen (in this case, level "4-still existing").

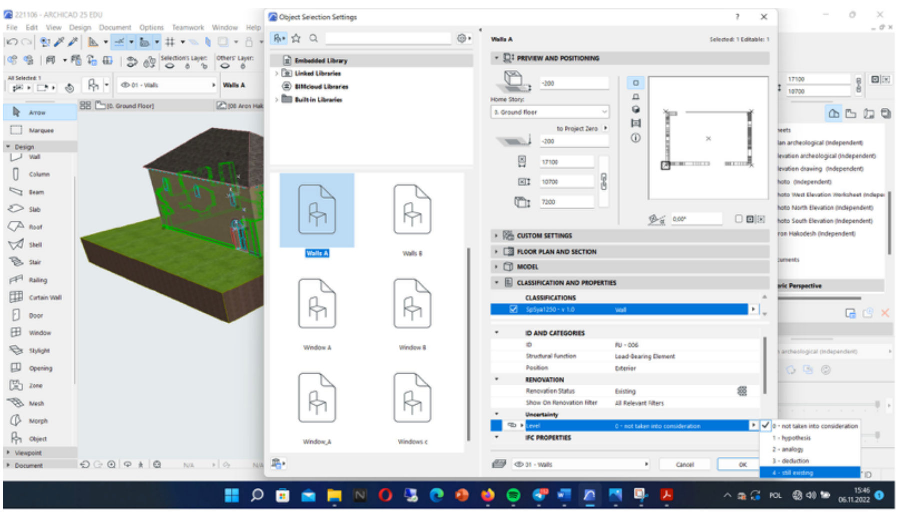


FIG. 137: Adding the uncertainty property in Archicad. Step 8. Visualisation by Igor Bajena.

The IFC export information has been adjusted in the "IFC properties" section by changing the "name" attribute to "Wall 1" and the "tag" attribute to "4 – still existing".

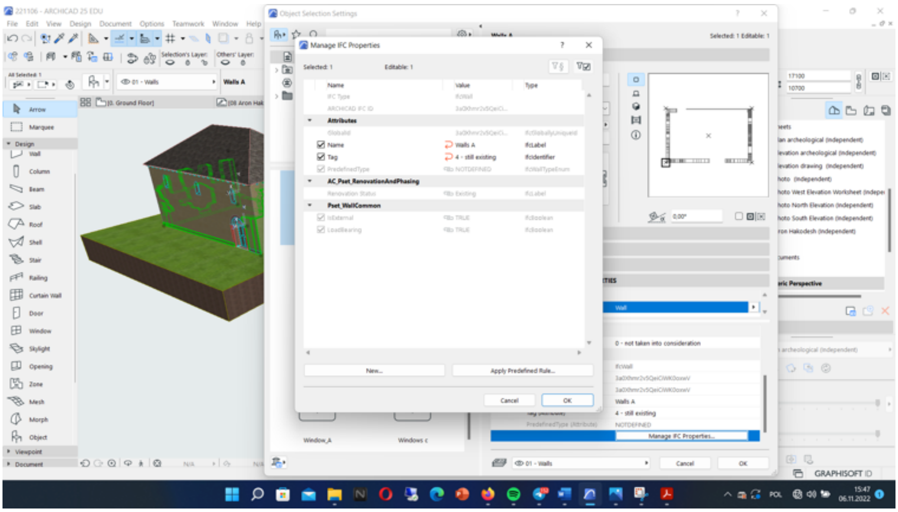


FIG. 138: Adding the uncertainty property in Archicad. Step 9. Visualisation by Igor Bajena.

After opening the IFC export in Open IFC Viewer, we can see that the uncertainty parameter is still accessible.

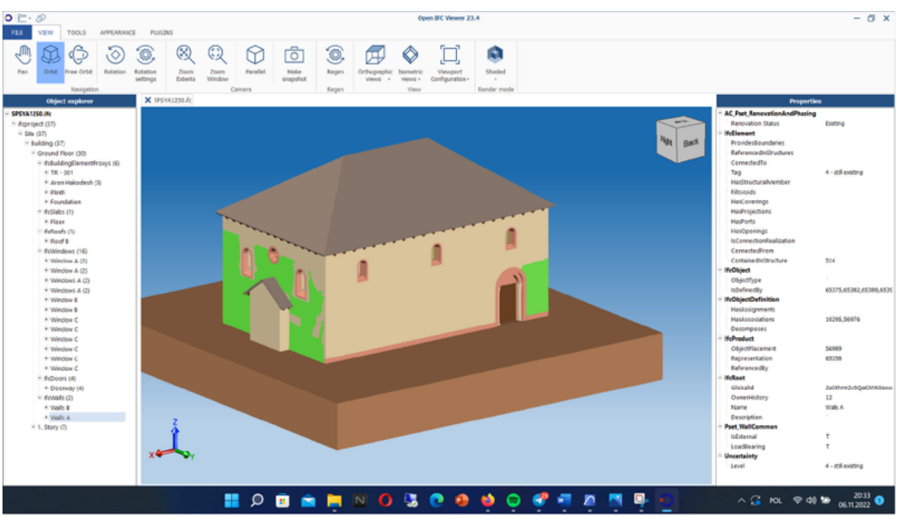


FIG. 139: Adding the uncertainty property in Archicad. Step 10. Visualisation by Igor Bajena.

H.
APPLYING THE SCALE TO OTHER MODELS

The same uncertainty scale should be applied to other reconstructions in order to be validated.

First of all, since our scale comes, to a large extent, from previous studies and applications, such as the one on Villa Pisani in Bagnolo by Andrea Palladio (Apollonio, Fallavollita, and Foschi 2021), the models shown here are actually a confirmation and validation of processes already presented, discussed[12] and in use, with the aim of standardising them and making them interoperable as far as possible.

The uncertainty scale will continue to be tested in upcoming projects; by now, we know that it has been applied in some reconstructions. In this regard, we show here the model of the Wołpa synagogue (Poland), elaborated by Katarzyna Prokopiuk, student at the University of Warsaw, who has attached the documentation of the choices she made and the uncertainty level of all the elements according to the handout for the digital 3D reconstructions that we provided.

The model was uploaded to the DFG Viewer.

By downloading it and consulting the related documentation, the uncertainty data could be integrated to the Sketchup model by means of the CityEditor extension, similarly to the previous cases, and then exported in CityGML format.

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12 Especially during *DFG* and *CoVHer* international meetings.

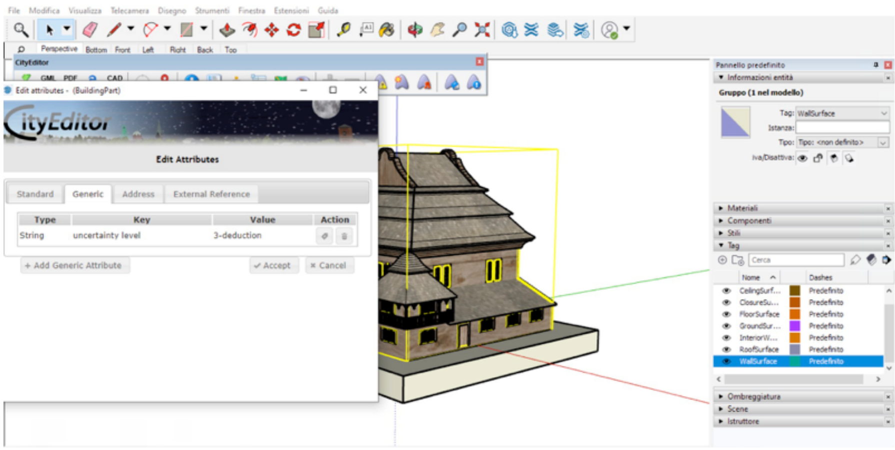

FIG. 140: Application of the average uncertainty level “3-deduction” to the entire building. Author's visualisation based on the model by Katarzyna Prokopiuk.

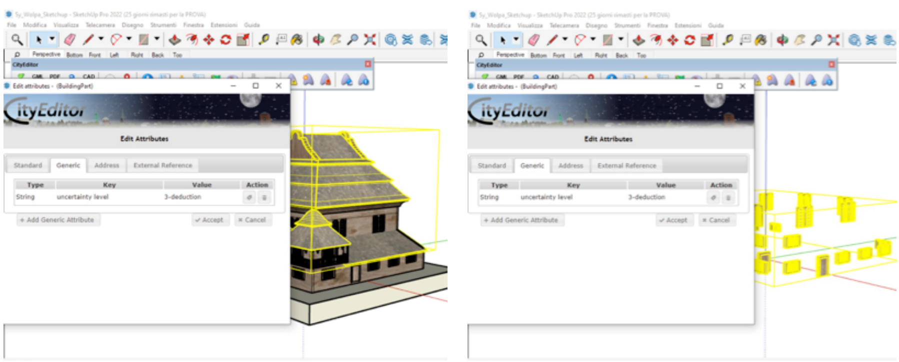

FIG. 141: Application of the uncertainty level “3-deduction” to walls, doors and windows. Author's visualisation based on the model by Katarzyna Prokopiuk.

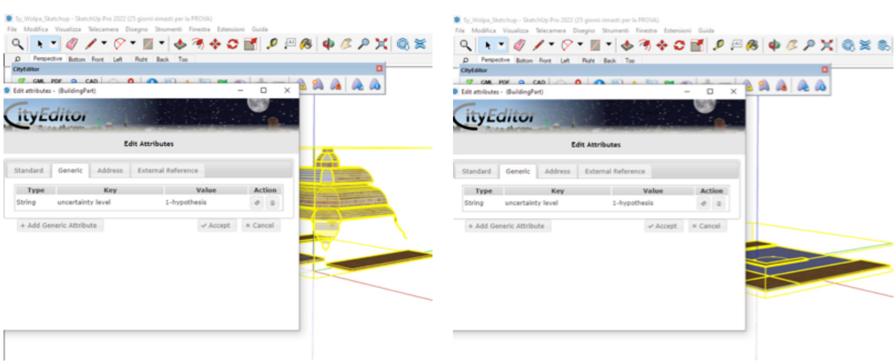

FIG. 142: Application of the uncertainty level “1-hypothesis” to the ceiling and the floor. Author's visualisation based on the model by Katarzyna Prokopiuk.

Once again, when exported in CityGML format and opened with FZK Viewer, the information about uncertainty is still accessible.

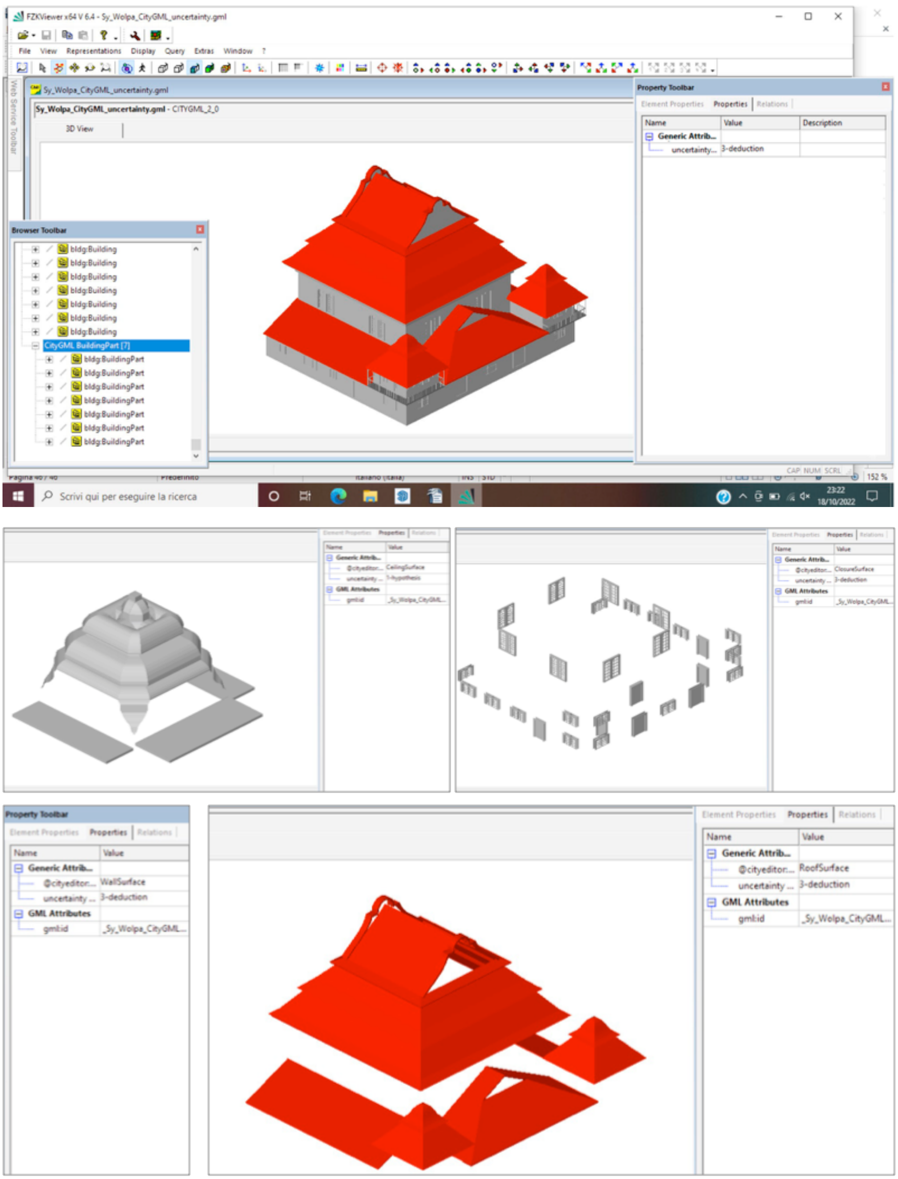

FIG. 143: The uncertainty parameter is still accessible once the CityGML file has been exported and opened with FZK Viewer. Author's visualisation based on the model by Katarzyna Prokopiuk.

IV conclusions

The proposed uncertainty scale offers differentiation and adaptability, promising wider application in various fields, with plans for further implementation in upcoming projects. Future goals include visualising uncertainty data directly in online viewers and integrating uncertainty into the CIDOC CRM ontology.

Addressing both cultural and technical challenges, methods for documenting and visualising uncertainty are outlined, together with the use of standard exchange formats like IFC and CityGML, aiming to establish it as a standard in 3D digital reconstructions for cultural heritage.

IV

conclusions

The uncertainty scale with different granularity proposed by Fabrizio Apollonio's research group, of which the one here adopted is a slight variation, seems to have a huge potential in the application in different fields: it contains as few ambiguities as possible and every level is accurately defined and differentiated, in order to avoid overlapping.

It may also be adapted to the users' needs and allow different degrees of complexity, always keeping a scientific dimension. Further applications of the scale to other projects are planned over the next few months.

We conclude with two goals for the future:

(1) The visualisation of uncertainty data directly on the online viewer;
(2) The integration of uncertainty data into the CIDOC CRM ontology for the exchange of CH information.

These two aspects should be taken in consideration for further developments, as explained here below.

Uncertainty is indeed just a part of a wider problem that we have tried to describe in the introduction: how to obtain scientific models to be used in the Cultural Heritage field.

We have seen that uncertainty issues are connected to visualisation and documentation, fields where a lot of effort is still needed in order to arrive to standardisation, in the form of guidelines with the definition of a workflow.

With our handout for the Speyer synagogue, which has also been adapted to other models, we have tried to identify the main critical issues and to solve them in the simplest way, so that the method can be taken into account by a wide audience (and we have proven this by testing it on both experts and students): the same reasons have led to the proposal of a very simplified uncertainty scale, which can nevertheless be transformed in a more complex matrix if needed.

Apart from this cultural challenge, we have also mentioned a technical one.

At this moment, there is no 3D viewer that directly visualises uncertainty. Anyway, some of them use colours to visualise other parameters.

We can thus imagine that our simple colour scale will be applied to a viewer in the near future. In this context, the IT expert of the DFG repository has been contacted. The integration of the uncertainty data directly on the displayed model seems to be possible, but will be hopefully developed at a more advanced stage of the project.

By now, we can keep trace of it in the following ways:

(1) Documentation tables downloadable from the DFG Repository as .doc or .pdf files. Actually, for the example of the Speyer synagogue, there are two different files: one for the reconstruction process for each element and one for the workflow in a particular type of software;
(2) Original file: depending on the software, uncertainty is differently embedded: as a layer, as a property of an element, etc. This can be seen in the original file, downloadable from the DFG Repository as well, although the native software is usually needed to visualise it;
(3) To avoid this problem, we should rely – and have relied – on standards to spread the models, such as IFC and City GML, which can be opened with free viewers such as FZK Viewer and Open IFC Viewer;

These three methods can be used alone or together as they deal with different ways of documenting uncertainty. We can also think of a single number (and colour) to assess the entire reconstruction.

In this case, this would be obtained as the weighted average.

Besides this, an implementation of uncertainty in a human- and machine-readable system would help solve the problem of communicating it. As we said before, a new attribute in CIDOC CRM can be created. This would be a property with a numerical value, in order to store the information about the uncertainty level.

We have seen that some attempts to incorporate data about uncertainty and critical reasoning in CIDOC CRM have been made during the last years, but a standard property to incorporate this data has not been established so far: the process is quite long and many debates are taking place inside the related community.

By now, through this work, we have made some proposals and attempts, hoping that in the future the classification and visualisation of uncertainty, a topic that cannot be ignored, can easily be considered a standard in 3D digital reconstructions in the field of cultural heritage.

V appendix

Chronology of definitions;
Some metadata schemes;
Handout for the reconstruction of the Speyer synagogue;
Documentation and workflow of the reconstruction of the Speyer synagogue.

V

appendix

A.
APPENDIX 1. CHRONOLOGY OF DEFINITIONS

DIGITAL HERITAGE STUDIES

3D modeling In 3D computer graphics, 3D modeling is the process of developing a mathematical representation of any surface of an object (inanimate or living) in three dimensions via specialized software. The product is called a 3D model. Someone who works with 3D models may be referred to as a 3D artist or a 3D modeler. A 3D Model can also be displayed as a two-dimensional image through a process called 3D rendering or used in a computer simulation of physical phenomena. The 3D model can be physically created using 3D printing devices that form 2D layers of the model with three-dimensional material, one layer at a time. In terms of game development, 3D modeling is merely a stage in the entire development process.
3D Models may be created automatically or manually. The manual modeling process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting.
3D modeling software is a class of 3D computer graphics software used to produce 3D models. Individual programs of this class are called modeling applications.
<https://en.wikipedia.org/wiki/3D_modeling>

Photogrammetry is the science and technology of obtaining reliable information about physical objects and the environment through the process of recording, measuring and interpreting photographic images and patterns of electromagnetic radiant imagery and other phenomena.[1]
Photogrammetry appeared in the middle of the 19th century, almost simultaneously with the appearance of photography itself. The use of photographs to create topographic maps was first proposed by the French surveyor Dominique F. Arago in about 1840.

The term photogrammetry was coined by the Prussian architect Albrecht Meydenbauer,[2] which appeared in his 1867 article „Die Photometrographie.“[3]
There are many variants of photogrammetry. One example is the extraction of three-dimensional measurements from two-dimensional data (i.e. images); for example, the distance between two points that lie on a plane parallel to the photographic image plane can be determined by measuring their distance on the image, if the scale of the image is known. Another is the extraction of accurate color ranges and values representing such quantities as albedo, specular reflection, metallicity, or ambient occlusion from photographs of materials for the purposes of physically based rendering.
Close-range photogrammetry refers to the collection of photography from a lesser distance than traditional aerial (or orbital) photogrammetry. Photogrammetric analysis may be applied to one photograph, or may use high-speed photography and remote sensing to detect, measure and record complex 2D and 3D motion fields by feeding measurements and imagery analysis into computational models in an attempt to successively estimate, with increasing accuracy, the actual, 3D relative motions. From its beginning with the stereoplotters used to plot contour lines on topographic maps, it now has a very wide range of uses such as sonar, radar, and lidar.
<https://en.wikipedia.org/wiki/Photogrammetry>

GIS (geographic information system) is a conceptualized framework that provides the ability to capture and analyze spatial and geographic data. GIS applications (or GIS apps) are computer-based tools that allow the user to create interactive queries (user-created searches), store and edit spatial and non-spatial data, analyze spatial information output, and visually share the results of these operations by presenting them as maps. [1][2][3]
Geographic information science (or, GIScience)—the scientific study of geographic concepts, applications, and systems—is commonly initialized as GIS, as well.[4]
Geographic information systems are utilized in multiple technologies, processes, techniques and methods. It is attached to various operations and numerous applications, that relate to: engineering, planning, management, transport/logistics, insurance, telecommunications, and business.[2] For this reason, GIS and location intelligence applications are at the foundation of location-enabled services, that rely on geographic analysis and visualization.
<https://en.wikipedia.org/wiki/Geographic_information_system>

Laser Scanning is the controlled deflection of laser beams, visible or invisible.[1] Scanned laser beams are used in some 3-D printers, in rapid prototyping, in machines for material processing, in laser engraving machines, in ophthalmological laser systems for the treatment of presbyopia, in confocal microscopy, in laser printers, in laser shows, in Laser TV, and in barcode scanners. […] Within the field of 3D object scanning, laser scanning (also known as lidar) combines controlled steering of laser beams with a laser rangefinder. By taking a distance measurement at every direction the scanner rapidly captures the surface shape of objects, buildings and landscapes. Construction of a full 3D model involves combining multiple surface models obtained from different viewing angles, or the admixing of other known constraints. Small objects can be placed on a revolving pedestal, in a technique akin to photogrammetry.
<https://en.wikipedia.org/wiki/Laser_scanning>

Interviews An interview is essentially a structured conversation where one participant asks questions, and the other provides answers.[1] In common parlance, the word „interview“ refers to a one-on-one conversation between an interviewer and an interviewee. The interviewer asks questions to which the interviewee responds, usually providing information. That information may be used or provided to other audiences immediately or later. This feature is common to many types of interviews – a job interview or interview with a witness to an event may have no other audience present at the time, but the answers will be later provided to others in the employment or investigative process. An interview may also transfer information in both directions.
<https://en.wikipedia.org/wiki/Interview>

Usability Testing is a technique used in user-centered interaction design to evaluate a product by testing it on users. This can be seen as an irreplaceable usability practice, since it gives direct input on how real users use the system.[1] It is more concerned with the design intuitiveness of the product and tested with users who have no prior exposure to it. Such testing is paramount to the success of an end product as a fully functioning application that creates confusion amongst its users will not last for long.[2] This is in contrast with usability inspection methods where experts use different methods to evaluate a user interface without involving users.
Usability testing focuses on measuring a human-made product‘s capacity to meet its intended purpose/s. Examples of products that commonly benefit from usability testing are food, consumer products, websites or web applications, computer interfaces, documents, and devices. Usabi-

lity testing measures the usability, or ease of use, of a specific object or set of objects, whereas general human–computer interaction studies attempt to formulate universal principles.
<https://en.wikipedia.org/wiki/Usability_testing>

Statistical analysis = related to machine learning. Statistical analysis is the collection and interpretation of data in order to uncover patterns and trends. It is a component of data analytics. Statistical analysis can be used in situations like gathering research interpretations, statistical modeling or designing surveys and studies. It can also be useful for business intelligence organizations that have to work with large data volumes.
In the context of business intelligence (BI), statistical analysis involves collecting and scrutinizing every data sample in a set of items from which samples can be drawn. A sample, in statistics, is a representative selection drawn from a total population.
The goal of statistical analysis is to identify trends.
<https://whatis.techtarget.com/definition/statistical-analysis#:~:text=Statistical%20analysis%20is%20the%20collection,or%20designing%20surveys%20and%20studies>

Computer vision is an interdisciplinary scientific field that deals with how computers can gain high-level understanding from digital images or videos. From the perspective of engineering, it seeks to understand and automate tasks that the human visual system can do.
Computer vision tasks include methods for acquiring, processing, analyzing and understanding digital images, and extraction of high-dimensional data from the real world in order to produce numerical or symbolic information, e.g. in the forms of decisions. Understanding in this context means the transformation of visual images (the input of the retina) into descriptions of the world that make sense to thought processes and can elicit appropriate action. This image understanding can be seen as the disentangling of symbolic information from image data using models constructed with the aid of geometry, physics, statistics, and learning theory.[8]
The scientific discipline of computer vision is concerned with the theory behind artificial systems that extract information from images. The image data can take many forms, such as video sequences, views from multiple cameras, multi-dimensional data from a 3D scanner, or medical scanning device. The technological discipline of computer vision seeks to apply its theories and models to the construction of computer vision systems. Sub-domains of computer vision include scene reconstruction, event detection, video tracking, object recognition, 3D pose estimation,

learning, indexing, motion estimation, visual servoing, 3D scene modeling, and image restoration.
<https://en.wikipedia.org/wiki/Computer_vision>

Surveying or land surveying is the technique, profession, art, and science of determining the terrestrial or three-dimensional positions of points and the distances and angles between them. A land surveying professional is called a land surveyor. These points are usually on the surface of the Earth, and they are often used to establish maps and boundaries for ownership, locations, such as the designed positions of structural components for construction or the surface location of subsurface features, or other purposes required by government or civil law, such as property sales.
Surveyors work with elements of geometry, trigonometry, regression analysis, physics, engineering, metrology, programming languages, and the law. They use equipment, such as total stations, robotic total stations, theodolites, GNSS receivers, retroreflectors, 3D scanners, radios, inclinometer, handheld tablets, optical and digital levels, subsurface locators, drones, GIS, and surveying software.
Surveying has been an element in the development of the human environment since the beginning of recorded history. The planning and execution of most forms of construction require it. It is also used in transport, communications, mapping, and the definition of legal boundaries for land ownership, and is an important tool for research in many other scientific disciplines.
https://en.wikipedia.org/wiki/Surveying3D Scanning is the process of analyzing a real-world object or environment to collect data on its shape and possibly its appearance (e.g. colour). The collected data can then be used to construct digital 3D models.
A 3D scanner can be based on many different technologies, each with its own limitations, advantages and costs. Many limitations in the kind of objects that can be digitised are still present. For example, optical technology may encounter many difficulties with shiny, reflective or transparent objects. For example, industrial computed tomography scanning and structured-light 3D scanners can be used to construct digital 3D models, without destructive testing.
Collected 3D data is useful for a wide variety of applications. These devices are used extensively by the entertainment industry in the production of movies and video games, including virtual reality.
Other common applications of this technology include augmented reality,[1] motion capture,[2][3] gesture recognition,[4] robotic mapping,[5] industrial design, orthotics and prosthetics,[6] reverse enginee-

ring and prototyping, quality control/inspection and the digitization of cultural artifacts.[7]
<https://en.wikipedia.org/wiki/3D_scanning>

Machine Learning (ML) is the study of computer algorithms that improve automatically through experience.[1] It is seen as a subset of artificial intelligence. Machine learning algorithms build a model based on sample data, known as „training data", in order to make predictions or decisions without being explicitly programmed to do so.[2] Machine learning algorithms are used in a wide variety of applications, such as email filtering and computer vision, where it is difficult or infeasible to develop conventional algorithms to perform the needed tasks.
A subset of machine learning is closely related to computational statistics, which focuses on making predictions using computers; but not all machine learning is statistical learning. The study of mathematical optimization delivers methods, theory and application domains to the field of machine learning. Data mining is a related field of study, focusing on exploratory data analysis through unsupervised learning.[4][5] In its application across business problems, machine learning is also referred to as predictive analytics.
<https://en.wikipedia.org/wiki/Machine_learning>

LiDAR is a method for measuring distances (ranging) by illuminating the target with laser light and measuring the time the reflection of the light takes to return to the sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. It has terrestrial, airborne, and mobile applications.
The term lidar was originally a portmanteau of light and radar.[1][2] It is now also used as an acronym of „light detection and ranging"[3] and „laser imaging, detection, and ranging".[4][5] Lidar sometimes is called 3-D laser scanning, a special combination of a 3-D scanning and laser scanning. Lidar is commonly used to make high-resolution maps, with applications in surveying, geodesy, geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, atmospheric physics,[6] laser guidance, airborne laser swath mapping (ALSM), and laser altimetry. The technology is also used in control and navigation for some autonomous cars.[7][8] <https://en.wikipedia.org/wiki/Lidar>

Remote Sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircraft). Special cameras collect remotely sensed images, which help researchers "sense" things about the Earth. Some examples are:

- Cameras on satellites and airplanes take images of large areas on the Earth's surface, allowing us to see much more than we can see when standing on the ground.
- Sonar systems on ships can be used to create images of the ocean floor without needing to travel to the bottom of the ocean.
- Cameras on satellites can be used to make images of temperature changes in the oceans.

Some specific uses of remotely sensed images of the Earth include:

- Large forest fires can be mapped from space, allowing rangers to see a much larger area than from the ground.
- Tracking clouds to help predict the weather or watching erupting volcanoes, and help watching for dust storms.
- Tracking the growth of a city and changes in farmland or forests over several years or decades.
- Discovery and mapping of the rugged topography of the ocean floor (e.g., huge mountain ranges, deep canyons, and the "magnetic striping" on the ocean floor).

<https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used?qt-news_science_products=0#qt-news_science_products>

Simulation approximate imitation of the operation of a process or system that represents its operation over time.[1]

Simulation is used in many contexts, such as simulation of technology for performance tuning or optimizing, safety engineering, testing, training, education,[2] and video games. Often, computer experiments are used to study simulation models. Simulation is also used with scientific modelling of natural systems[2] or human systems to gain insight into their functioning,[3] as in economics. Simulation can be used to show the eventual real effects of alternative conditions and courses of action. Simulation is also used when the real system cannot be engaged, because it may not be accessible, or it may be dangerous or unacceptable to engage, or it is being designed but not yet built, or it may simply not exist.[4]

Key issues in simulation include the acquisition of valid sources of information about the relevant selection of key characteristics and behaviors, the use of simplifying approximations and assumptions within the simulation, and fidelity and validity of the simulation outcomes. Procedures and protocols for model verification and validation are an ongoing field of academic study, refinement, research and development in simulations

technology or practice, particularly in the work of computer simulation.
<https://en.wikipedia.org/wiki/Simulation>

Image Processing = related to computer vision. Digital image processing is the use of a digital computer to process digital images through an algorithm.[1][2] As a subcategory or field of digital signal processing, digital image processing has many advantages over analog image processing. It allows a much wider range of algorithms to be applied to the input data and can avoid problems such as the build-up of noise and distortion during processing. Since images are defined over two dimensions (perhaps more) digital image processing may be modeled in the form of multidimensional systems. The generation and development of digital image processing are mainly affected by three factors: first, the development of computers; second, the development of mathematics (especially the creation and improvement of discrete mathematics theory); third, the demand for a wide range of applications in environment, agriculture, military, industry and medical science has increased.
<https://en.wikipedia.org/wiki/Digital_image_processing>

Literature review discusses published information in a particular subject area, and sometimes information in a particular subject area within a certain time period.
A literature review can be just a simple summary of the sources, but it usually has an organizational pattern and combines both summary and synthesis. A summary is a recap of the important information of the source, but a synthesis is a re-organization, or a reshuffling, of that information. It might give a new interpretation of old material or combine new with old interpretations. Or it might trace the intellectual progression of the field, including major debates. And depending on the situation, the literature review may evaluate the sources and advise the reader on the most pertinent or relevant.
<https://writingcenter.unc.edu/tips-and-tools/literature-reviews/#:~:text=A%20literature%20review%20discusses%20published,combines%20both%20summary%20and%20synthesis>

Spatial Analysis is a type of geographical analysis which seeks to explain patterns of human behavior and its spatial expression in terms of mathematics and geometry, that is, locational analysis. Examples include nearest neighbor analysis and Thiessen polygons.
<https://researchguides.dartmouth.edu/gis/spatialanalysis#:~:text=Spatial%20analysis%20is%20a%20type,neighbor%20analysis%20and%20Thiessen%20polygons>

Field Survey is a type of field research by which archaeologists (often landscape archaeologists) search for archaeological sites and collect information about the location, distribution and organization of past human cultures across a large area (e.g. typically in excess of one hectare, and often in excess of many km2). Archaeologists conduct surveys to search for particular archaeological sites or kinds of sites, to detect patterns in the distribution of material culture over regions, to make generalizations or test hypotheses about past cultures, and to assess the risks that development projects will have adverse impacts on archaeological heritage.
<https://en.wikipedia.org/wiki/Survey_(archaeology)>

Database is an organized collection of data, generally stored and accessed electronically from a computer system. Where databases are more complex they are often developed using formal design and modeling techniques.
The database management system (DBMS) is the software that interacts with end users, applications, and the database itself to capture and analyze the data. The DBMS software additionally encompasses the core facilities provided to administer the database. The sum total of the database, the DBMS and the associated applications can be referred to as a "database system". Often the term "database" is also used to loosely refer to any of the DBMS, the database system or an application associated with the database.
Computer scientists may classify database-management systems according to the database models that they support. Relational databases became dominant in the 1980s. These model data as rows and columns in a series of tables, and the vast majority use SQL for writing and querying data. In the 2000s, non-relational databases became popular, referred to as NoSQL because they use different query languages.
<https://en.wikipedia.org/wiki/Database>

Software Development is the process of conceiving, specifying, designing, programming, documenting, testing, and bug fixing involved in creating and maintaining applications, frameworks, or other software components. Software development is a process of writing and maintaining the source code, but in a broader sense, it includes all that is involved between the conception of the desired software through to the final manifestation of the software, sometimes in a planned and structured process.
Therefore, software development may include research, new development, prototyping, modification, reuse, re-engineering, maintenance, or

any other activities that result in software products.
<https://en.wikipedia.org/wiki/Software_development>

(archaeological) Excavation the exposure, processing and recording of archaeological remains.[1] An excavation site or "dig" is the area being studied. These locations range from one to several areas at a time during a project and can be conducted over a few weeks to several years.
Excavation involves the recovery of several types of data from a site. This data includes artifacts (portable objects made or modified by humans), features (non-portable modifications to the site itself such as post molds, burials, and hearths), ecofacts (evidence of human activity through organic remains such as animal bones, pollen, or charcoal), and archaeological context (relationships among the other types of data).[2][3][4][5]
Before excavating, the presence or absence of archaeological remains can often be suggested by, non-intrusive remote sensing, such as ground-penetrating radar.[6] Basic information about the development of the site may be drawn from this work, but to understand finer details of a site, excavation via augering can be used.
During excavation, archaeologists often use stratigraphic excavation to remove phases of the site one layer at a time. This keeps the timeline of the material remains consistent with one another.[7] This is done usually though mechanical means where artifacts can be spot dated and processed through methods such as sieving or flotation. Afterwards, digital methods are then used record the excavation process and its results. Ideally, data from the excavation should suffice to reconstruct the site completely in three-dimensional space.
<https://en.wikipedia.org/wiki/Archaeological_excavation>

Modelling
A model is an informative representation of an object, person or system. The term originally denoted the plans of a building in late 16th-century English, and derived via French and Italian ultimately from Latin modulus, a measure.
<https://en.wikipedia.org/wiki/Model>

Modeling and simulation (M&S) is the use of models (e.g., physical, mathematical, or logical representation of a system, entity, phenomenon, or process) as a basis for simulations to develop data utilized for managerial or technical decision-making.[1][2]
In the computer application of modeling and simulation a computer is used to build a mathematical model which contains key parameters of

the physical model. The mathematical model represents the physical model in virtual form, and conditions are applied that set up the experiment of interest. The simulation starts – i.e., the computer calculates the results of those conditions on the mathematical model – and outputs results in a format that is either machine- or human-readable, depending upon the implementation.
<https://en.wikipedia.org/wiki/Modeling_and_simulation>

(computer) Programming the process of designing and building an executable computer program to accomplish a specific computing result or to perform a specific task. Programming involves tasks such as: analysis, generating algorithms, profiling algorithms' accuracy and resource consumption, and the implementation of algorithms in a chosen programming language (commonly referred to as coding).[1][2] The source code of a program is written in one or more languages that are intelligible to programmers, rather than machine code, which is directly executed by the central processing unit. The purpose of programming is to find a sequence of instructions that will automate the performance of a task (which can be as complex as an operating system) on a computer, often for solving a given problem. Proficient programming thus often requires expertise in several different subjects, including knowledge of the application domain, specialized algorithms, and formal logic.
Tasks accompanying and related to programming include: testing, debugging, source code maintenance, implementation of build systems, and management of derived artifacts, such as the machine code of computer programs. These might be considered part of the programming process, but often the term software development is used for this larger process with the term programming, implementation, or coding reserved for the actual writing of code. Software engineering combines engineering techniques with software development practices. Reverse engineering is a related process used by designers, analysts and programmers to understand and re-create/re-implement.[3]:3
<https://en.wikipedia.org/wiki/Computer_programming>

User-centered design (UCD) is an iterative design process in which designers focus on the users and their needs in each phase of the design process. In UCD, design teams involve users throughout the design process via a variety of research and design techniques, to create highly usable and accessible products for them.
<https://www.interaction-design.org/literature/topics/user-centered-design#:~:text=User%2Dcentered%20design%20(UCD),and%20accessible%20products%20for%20them>

Network Analysis (NA) is a set of integrated techniques to depict relations among actors and to analyze the social structures that emerge from the recurrence of these relations. The basic assumption is that better explanations of social phenomena are yielded by analysis of the relations among entities.
<https://www.sciencedirect.com/topics/social-sciences/network-analysis#:~:text=Network%20analysis%20(NA)%20is%20a,of%20the%20relations%20among%20entities>

Topographic surveying accurate depiction of a site (property, area of land, defined boundary) which is scaled and detailed according to the spatial considerations and is the summary of the on-site data capture processes. This type of topographical survey is a detailed process which requires the insight of topological professionals to ensure the accuracy of all of the reports provided.
<https://indigosurveys.co.uk/what-is-a-topographical-survey/>

Data Modelling […] in software engineering is the process of creating a data model for an information system by applying certain formal techniques. [It] is a process used to define and analyze data requirements needed to support the business processes within the scope of corresponding information systems in organizations. Therefore, the process of data modeling involves professional data modelers working closely with business stakeholders, as well as potential users of the information system.
There are three different types of data models produced while progressing from requirements to the actual database to be used for the information system.[2] The data requirements are initially recorded as a conceptual data model which is essentially a set of technology independent specifications about the data and is used to discuss initial requirements with the business stakeholders. The conceptual model is then translated into a logical data model, which documents structures of the data that can be implemented in databases. Implementation of one conceptual data model may require multiple logical data models. The last step in data modeling is transforming the logical data model to a physical data model that organizes the data into tables, and accounts for access, performance and storage details. Data modeling defines not just data elements, but also their structures and the relationships between them.
<https://en.wikipedia.org/wiki/Data_modeling>
Archaeological fieldwork a body of scientific method for the responsible investigation and management of a limited and endangered resource
<http://www.eolss.net/sample-chapters/c04/E6-21-01-03.pdf>

Visualization any technique for creating images, diagrams, or animations to communicate a message. Visualization through visual imagery has been an effective way to communicate both abstract and concrete ideas since the dawn of humanity. Examples from history include cave paintings, Egyptian hieroglyphs, Greek geometry, and Leonardo da Vinci's revolutionary methods of technical drawing for engineering and scientific purposes.
Visualization today has ever-expanding applications in science, education, engineering (e.g., product visualization), interactive multimedia, medicine, etc. Typical of a visualization application is the field of computer graphics. The invention of computer graphics (and 3D computer graphics) may be the most important development in visualization since the invention of central perspective in the Renaissance period. The development of animation also helped advance visualization.
<https://en.wikipedia.org/wiki/Visualization_(graphics)>

Geophysics is a subject of natural science concerned with the physical processes and physical properties of the Earth and its surrounding space environment, and the use of quantitative methods for their analysis.
<https://en.wikipedia.org/wiki/Geophysics>

DIGITAL HUMANITIES

Text Analysis (TA) aims to extract machine-readable information from unstructured text in order to enable data-driven approaches towards managing content. To overcome the ambiguity of human language and achieve high accuracy for a specific domain, TA requires the development of customized text mining pipelines.
<https://www.ontotext.com/knowledgehub/fundamentals/text-analysis/#:~:text=Text%20Analysis%20is%20about%20parsing,manage%20and%20interpret%20data%20pieces>

Historical Studies connected to media studies, interdisciplinarity, digitization and processes of data modeling and information retrieval in digital humanities. <https://dhhistory.hypotheses.org/>

Data [/Text] Mining is a process of discovering patterns in large data sets involving methods at the intersection of machine learning, statistics, and database systems. Data mining is an interdisciplinary subfield of computer science and statistics with an overall goal to extract information (with intelligent methods) from a data set and transform the information into a comprehensible structure for further use.[1][2][3][4] Data mining is the analysis step of the „knowledge discovery in databases“ process, or KDD.[5] Aside from the raw analysis step, it also involves database and data management aspects, data pre-processing, model and inference considerations, interestingness metrics, complexity considerations, post-processing of discovered structures, visualization, and online updating.

<https://en.wikipedia.org/wiki/Data_mining>

Archives, Repositories, Sustainability As public investment in archiving research data grows, there has been increasing attention to the longevity or sustainability of the data repositories that curate such data. While there have been many conceptual frameworks developed and case reports of individual archives and digital repositories, there have been few empirical studies of how such archives persist over time. In this paper, we draw upon organizational studies theories to approach the issue of sustainability from an organizational perspective, focusing specifically on the organizational histories of three social science data archives (SSDA): ICPSR, UKDA, and LIS. Using a framework of organizational resilience to understand how archives perceive crisis, respond to it, and learn from experience, this article reports on an empirical study of sustainability in these long-lived SSDAs. The study draws from archival documents and interviews to examine how sustainability can and should be conceptualized as on-going processes over time and not as a quality at a single moment. Implications for research and practice in data archive sustainability are discussed. (Eschenfelder and Shankar 2016)
<https://datascience.codata.org/articles/10.5334/dsj-2017-012/print/>

Literary Studies -> see media studies

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<https://en.wikipedia.org/wiki/Visualization_(graphics)>

Corpora and Corpus Activities -> Corpus-assisted discourse studies, or CADS, is related historically and methodologically to the discipline of corpus linguistics. The principal endeavor of corpus-assisted discourse studies is the investigation, and comparison of features of particular discourse types, integrating into the analysis the techniques and tools developed within corpus linguistics. These include the compilation of specialised corpora and analyses of word and word-cluster frequency lists, comparative keyword lists and, above all, concordances.
A broader conceptualisation of corpus-assisted discourse studies would include any study that aims to bring together corpus linguistics and discourse analysis. Such research is often labelled as corpus-based or corpus-assisted discourse analysis, with the term CADS coined by a research group in Italy for a specific type of corpus-based discourse analysis (see the section ‚in different countries' below).
<https://en.wikipedia.org/wiki/Corpus-assisted_discourse_studies>

see also
Corpus linguistics is the study of language as expressed in corpora (samples) of „real world" text. Corpus linguistics proposes that reliable language analysis is more feasible with corpora collected in the field in its natural context („realia"), and with minimal experimental-interference.
The field of corpus linguistics features divergent views about the value of corpus annotation. These views range from John McHardy Sinclair, who advocates minimal annotation so texts speak for themselves,[1] to the Survey of English Usage team (University College, London), who advocate annotation as allowing greater linguistic understanding through rigorous recording.[2]
The text-corpus method is a digestive approach that derives a set of abstract rules that govern a natural language from texts in that language, and explores how that language relates to other languages. Originally derived manually, corpora now are automatically derived from source texts.
<https://en.wikipedia.org/wiki/Corpus_linguistics>

Interdisciplinary Cooperation -> Interdisciplinarity (or interdisciplinary studies) involves the combination of two or more academic disciplines into one activity (e.g., a research project).[1] It draws knowledge from several other fields like sociology, anthropology, psychology, economics etc. It is about creating something by thinking across boundaries. It is related to an interdiscipline or an interdisciplinary field, which is an organizational unit that crosses traditional boundaries between academic disciplines or schools of thought, as new needs and professions emerge. Large engineering teams are usually interdisciplinary, as a power station or mobile phone or other project requires the melding of several specialties. However, the term „interdisciplinary" is sometimes confined to academic settings.

<https://en.wikipedia.org/wiki/Interdisciplinarity>

Digitization, Resource Creation and Discovery Digitization is the process of converting information into a digital (i.e. computer-readable) format. The result is the representation of an object, image, sound, document or signal (usually an analog signal) by generating a series of numbers that describe a discrete set of points or samples. The result is called digital representation or, more specifically, a digital image, for the object, and digital form, for the signal. In modern practice, the digitized data is in the form of binary numbers, which facilitate processing by digital computers and other operations, but, strictly speaking, digitizing simply means the conversion of analog source material into a numerical format; the decimal or any other number system that can be used instead.

Digitization is of crucial importance to data processing, storage and transmission, because it „allows information of all kinds in all formats to be carried with the same efficiency and also intermingled". Though analog data is typically more stable, digital data can more easily be shared and accessed and can, in theory, be propagated indefinitely, without generation loss, provided it is migrated to new, stable formats as needed. This is why it is a favored way of preserving information for many organizations around the world.
<https://en.wikipedia.org/wiki/Digitization>

Content Analysis [see also Text Analysis, Text Mining, Data Mining, Machine Learning] is the study of documents and communication artifacts, which might be texts of various formats, pictures, audio or video. Social scientists use content analysis to examine patterns in communication in a replicable and systematic manner.[1] One of the key advantages of using content analysis to analyse social phenomena is its non-invasive nature, in contrast to simulating social experiences or collecting survey answers.

Practices and philosophies of content analysis vary between academic disciplines. They all involve systematic reading or observation of texts or artifacts which are assigned labels (sometimes called codes) to indicate the presence of interesting, meaningful pieces of content.[2][3] By systematically labeling the content of a set of texts, researchers can analyse patterns of content quantitatively using statistical methods, or use qualitative methods to analyse meanings of content within texts. Computers are increasingly used in content analysis to automate the labeling (or coding) of documents. Simple computational techniques can provide descriptive data such as word frequencies and document lengths. Machine learning classifiers can greatly increase the number of texts that can be labeled, but the scientific utility of doing so is a matter of debate. Further, numerous computer-aided text analysis (CATA) computer programs are available that analyze text for pre-determined linguistic, semantic, and psychological characteristics.
<https://en.wikipedia.org/wiki/Content_analysis>

Cultural Studies is a field of theoretically, politically, and empirically engaged cultural analysis that concentrates upon the political dynamics of contemporary culture, its historical foundations, defining traits, conflicts, and contingencies. Cultural studies researchers generally investigate how cultural practices relate to wider systems of power associated with or operating through social phenomena, such as ideology, class structures, national formations, ethnicity, sexual orientation, gender, and generation. Cultural studies views cultures not as fixed, bounded, stable, and discrete entities, but rather as constantly interacting and changing sets of practices and processes.[1] The field of cultural studies encompasses a range of theoretical and methodological perspectives and practices. Although distinct from the discipline of cultural anthropology and the interdisciplinary field of ethnic studies, cultural studies draws upon and has contributed to each of these fields.[2]
<https://en.wikipedia.org/wiki/Cultural_studies>

Knowledge Representation and reasoning (KR², KR&R) is the field of artificial intelligence (AI) dedicated to representing information about the world in a form that a computer system can utilize to solve complex tasks such as diagnosing a medical condition or having a dialog in a natural language.
Knowledge representation incorporates findings from psychology[1] about how humans solve problems and represent knowledge in order to design formalisms that will make complex systems easier to design and build. Knowledge representation and reasoning also incor-

porates findings from logic to automate various kinds of reasoning, such as the application of rules or the relations of sets and subsets.
Examples of knowledge representation formalisms include semantic nets, systems architecture, frames, rules, and ontologies. Examples of automated reasoning engines include inference engines, theorem provers, and classifiers.
<https://en.wikipedia.org/wiki/Knowledge_representation_and_reasoning>

NaturaI Language Processing (NLP) is a subfield of linguistics, computer science, and artificial intelligence concerned with the interactions between computers and human language, in particular how to program computers to process and analyze large amounts of natural language data.
Challenges in natural language processing frequently involve speech recognition, natural language understanding, and natural-language generation.
<https://en.wikipedia.org/wiki/Natural_language_processing>

Linking and Annotation Linguistic annotation is one of the core interfaces between linguistics and computational linguistics. It has also become a central interface between computational linguistics (CL) and digital humanities (DH). Texts are preprocessed and annotated, e.g. with parts of speech, for distant reading and other visualization applications, topic and network analyses, text mining and question answering for humanist research questions.
<https://anndh18.github.io/>

lnterface and User Experience Design is the process of supporting user behavior through usability, usefulness, and desirability provided in the interaction with a product. User experience design encompasses traditional human–computer interaction (HCI) design and extends it by addressing all aspects of a product or service as perceived by users. Experience design (XD) is the practice of designing products, processes, services, events, omnichannel journeys, and environments with a focus placed on the quality of the user experience and culturally relevant solutions. Experience design is not driven by a single design discipline. Instead, it requires a cross-discipline perspective that considers multiple aspects of the brand/ business/ environment/ experience from product, packaging, and retail environment to the clothing and attitude of employees. Experience design seeks to develop the experience of a product, service, or event along any or all of the following dimensions:

- Duration (initiation, immersion, conclusion, and continuation)
- Intensity (reflex, habit, engagement)
- Breadth (products, services, brands, nomenclatures, channels/environment/promotion, and price)
- Interaction (passive - active - interactive)
- Triggers (all human senses, concepts, and symbols)
- Significance (meaning, status, emotion, price, and function)

<https://en.wikipedia.org/wiki/User_experience_design>

Linguistics -> see Corpus Linguistics

Networks, Relationships, Graphs -> see Knowledge Representation

Metadata (connected to data modeling) is „data that provides information about other data".
In other words, it is „data about data". Many distinct types of metadata exist, including descriptive metadata, structural metadata, administrative metadata, reference metadata and statistical metadata.
Descriptive metadata is descriptive information about a resource. It is used for discovery and identification. It includes elements such as title, abstract, author, and keywords.
Structural metadata is metadata about containers of data and indicates how compound objects are put together, for example, how pages are ordered to form chapters. It describes the types, versions, relationships and other characteristics of digital materials.
Administrative metadata is information to help manage a resource, like resource type, permissions, and when and how it was created.
Reference metadata is information about the contents and quality of statistical data.
Statistical metadata, also called process data, may describe processes that collect, process, or produce statistical data.
<https://en.wikipedia.org/wiki/Metadata>

Databases connected to data modeling (already defined in the "digital heritage studies" section): a database is an organized collection of data, generally stored and accessed electronically from a computer system. Where databases are more complex they are often developed using formal design and modeling techniques.
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<https://en.wikipedia.org/wiki/Software_development>

Digital Humanities - Pedagogy and Curriculum Academic institutions are starting to recognize the growing public interest in digital humanities research, and there is an increasing demand from students for formal training in its methods. Despite the pressure on practitioners to develop innovative courses, scholarship in this area has tended to focus on research methods, theories and results rather than critical pedagogy and the actual practice of teaching.
The essays in this collection offer a timely intervention in digital humanities scholarship, bringing together established and emerging scholars from a variety of humanities disciplines across the world. The first section offers views on the practical realities of teaching digital humanities at undergraduate and graduate levels, presenting case studies and snapshots of the authors' experiences alongside models for future courses and reflections on pedagogical successes and failures. The next section proposes strategies for teaching foundational digital humanities methods across a variety of scholarly disciplines, and the book concludes with wider debates about the place of digital humanities in the academy, from the

field's cultural assumptions and social obligations to its political visions. Digital Humanities pedagogy broadens the ways in which both scholars and practitioners can think about this emerging discipline, ensuring its ongoing development, vitality and long-term sustainability.
"Digital humanities pedagogy", Brett D. Hirsch (dir.), 2012
<https://books.openedition.org/obp/1605>

Digital Humanities – Diversity Digital humanities has grown and changed over the years; we have moved away from expecting technology to be a tool to make humanities research easier and faster into one where we are now equal partners. Our collaborative projects drive forward the research agendas of both humanists and technologists. There have been other changes too. The focus of our scholarly interest has moved away from its historical origins in text-based scholarship, although that now has many more possibilities, and we are seeing an interest in exploring culture and heritage more widely. Where the progress is slower is in our moves towards openness and inclusivity, and this is to some extent hampered by a lack of linguistic diversity. This is being addressed with specialist groups within the major DH organizations on a national and a global level. DH has grown rapidly in China, and the anglophone world could do more to engage with practitioners and potential colleagues in this new vibrant and emerging area. There are certainly Western centres that specialize, particularly in Chinese texts and historical documents, but this needs to be extended further if we are not to impose limits on the conversations, synergies and collaborations that can result (Mahony 2018).
<https://link.springer.com/article/10.1007/s40647-018-0216-0>

Audio, Video, Multimedia Multimedia is a form of communication that combines different content forms such as text, audio, images, animations, or video into a single presentation, in contrast to traditional mass media, such as printed material or audio recordings. Popular examples of multimedia include video podcasts, audio slideshows, animated shows, and movies.
Multimedia can be recorded for playback on computers, laptops, smartphones, and other electronic devices, either on demand or in real time (streaming). In the early years of multimedia, the term „rich media" was synonymous with interactive multimedia. Over time, hypermedia extensions brought multimedia to the World Wide Web.
<https://en.wikipedia.org/wiki/Multimedia>

Maps and Mapping -> see Knowledge Representation

Glam - Galleries, Libraries, Archives, Museums connected to databases refers to cultural institutions with a mission to provide access to knowledge. GLAMs collect and maintain cultural heritage materials in the public interest. As collecting institutions, GLAMs preserve and make accessible primary sources valuable for researchers.

Versions of the acronym include GLAMR, which specifies „records“ management,[3] and the earlier form LAM, which did not specify „galleries“ (whether seen as a subset of museums, or else potentially confused with commercial establishments where art is bought and sold).[4][5][6]

As an abbreviation, LAM has been in use since the 1990s;[7] it emerged as these institutions saw their missions overlapping, creating the need for a wider industry sector grouping. This became apparent as they placed their collections online—artworks, books, documents, and artifacts all effectively becoming „information resources.“ The work to get GLAM sector collections online is supported by GLAM Peak in Australia[8] and the National Digital Forum in New Zealand.[9]

Proponents of greater collaboration argue that the present convergence is actually a return to traditional unity. These institutions share epistemological links dating from the „Museum“ of Alexandria and continuing through the cabinets of curiosities gathered in early modern Europe. Over time as collections expanded, they became more specialized and their housing was separated according to the form of information and kinds of users. Furthermore, during the nineteenth and twentieth centuries distinct professional societies and educational programs developed for each kind of institution.

<https://en.wikipedia.org/wiki/GLAM_(industry)>

Media Studies is a discipline and field of study that deals with the content, history, and effects of various media; in particular, the mass media. Media Studies may draw on traditions from both the social sciences and the humanities, but mostly from its core disciplines of mass communication, communication, communication sciences, and communication studies.

Researchers may also develop and employ theories and methods from disciplines including cultural studies, rhetoric (including digital rhetoric), philosophy, literary theory, psychology, political science, political economy, economics, sociology, anthropology, social theory, art history and criticism, film theory, and information theory.

<https://en.wikipedia.org/wiki/Media_studies>

Information Retrieval (IR) is the activity of obtaining information system resources that are relevant to an information need from a collection of those resources. Searches can be based on full-text or other content-based indexing. Information retrieval is the science of searching for information in a document, searching for documents themselves, and also searching for the metadata that describes data, and for databases of texts, images or sounds.
Automated information retrieval systems are used to reduce what has been called information overload. An IR system is a software system that provides access to books, journals and other documents; stores and manages those documents. Web search engines are the most visible IR applications.
<https://en.wikipedia.org/wiki/Information_retrieval>

Data Modeling (already defined in the "digital heritage studies" section): in software engineering is the process of creating a data model for an information system by applying certain formal techniques. [It] is a process used to define and analyze data requirements needed to support the business processes within the scope of corresponding information systems in organizations. Therefore, the process of data modeling involves professional data modelers working closely with business stakeholders, as well as potential users of the information system.
There are three different types of data models produced while progressing from requirements to the actual database to be used for the information system.[2] The data requirements are initially recorded as a conceptual data model which is essentially a set of technology independent specifications about the data and is used to discuss initial requirements with the business stakeholders. The conceptual model is then translated into a logical data model, which documents structures of the data that can be implemented in databases. Implementation of one conceptual data model may require multiple logical data models. The last step in data modeling is transforming the logical data model to a physical data model that organizes the data into tables, and accounts for access, performance and storage details. Data modeling defines not just data elements, but also their structures and the relationships between them.
<https://en.wikipedia.org/wiki/Data_modeling>

Semantic Web -> see Knowledge Representation
The Semantic Web is an extension of the World Wide Web through standards set by the World Wide Web Consortium (W3C). The goal of the Semantic Web is to make Internet data machine-readable.
To enable the encoding of semantics with the data, technologies such

as Resource Description Framework (RDF) and Web Ontology Language (OWL) are used. These technologies are used to formally represent metadata. For example, ontology can describe concepts, relationships between entities, and categories of things. These embedded semantics offer significant advantages such as reasoning over data and operating with heterogeneous data sources.
These standards promote common data formats and exchange protocols on the Web, fundamentally the RDF. According to the W3C, „The Semantic Web provides a common framework that allows data to be shared and reused across application, enterprise, and community boundaries".The Semantic Web is therefore regarded as an integrator across different content and information applications and systems. The term was coined by Tim Berners-Lee for a web of data (or data web) that can be processed by machines—that is, one in which much of the meaning is machine-readable. While its critics have questioned its feasibility, proponents argue that applications in library and information science, industry, biology and human sciences research have already proven the validity of the original concept.
<https://en.wikipedia.org/wiki/Semantic_Web>

Ontologies -> see Knowledge Representation
In computer science and information science, an ontology encompasses a representation, formal naming and definition of the categories, properties and relations between the concepts, data and entities that substantiate one, many, or all domains of discourse. More simply, an ontology is a way of showing the properties of a subject area and how they are related, by defining a set of concepts and categories that represent the subject.
Every academic discipline or field creates ontologies to limit complexity and organize data into information and knowledge. New ontologies improve problem solving within that domain. Translating research papers within every field is a problem made easier when experts from different countries maintain a controlled vocabulary of jargon between each of their languages.
<https://en.wikipedia.org/wiki/Ontology_(information_science)>

The full definitions of the words contained in the 27 analysed papers (see **CHAPTER I**) are presented below in chronological order and divided by thematic area according to this key:

- ● Virtual Archaeology
- ● Model / Visualisation
- ● Documentation
- ● Authenticity
- ● Uncertainty
- ● Cultural Heritage

Some papers have been attributed to more than one thematic area (represented by the coloured circles on the left); the main one is indicated in the colour of the title.

Duranti (Berners-Lee 2006) ●

Legally authentic documents are those which bear witness on their own because of the intervention, during or after their creation, of a representative of a public authority guaranteeing their genuineness. **Diplomatically authentic** documents are those which were written according to the practice of the time and place indicated in the text, and signed with the name(s) of the person(s) competent to create them. **Historically authentic** documents are those which attest to events that actually took place or to information that is true. The three types of authenticity are totally inde- pendent of one another.

Document de Nara sur l'authenticité (1994) ●●●

French / *English* versions of the document

Conservation: comprend toutes les opérations qui visent à comprendre une œuvre, à connaître son histoire et sa signification, à assurer sa sauvegarde matérielle et, éventuellement sa restauration et sa mise en valeur. (Le patrimoine culturel comprend les monuments, les ensembles bâtis et les sites tels que les définit l'article 1 de la Convention du patrimoine mondial) / ***Conservation**: all efforts designed to understand cultural heritage, know its history and meaning, ensure its material safeguard and, as required, its presentation, restoration and enhancement.*

(Cultural heritage is understood to include monuments, groups of buildings and sites of cultural value as defined in article one of the World Heritage Convention).

Sources d'information: ensemble des sources monumentales, écrites, orales, figurées, permettant de connaître la nature, les spécificités, la signification et l'histoire d'une œuvre / ***Information sources****: all material, written, oral and figurative sources which make it possible to know the nature, specifications, meaning and history of the cultural heritage.*

Taylor and Kuyatt (1989)

The **uncertainty** of the result of a measurement generally consists of several components which, in the CIPM[1] approach, may be grouped into two categories according to the method used to estimate their numerical values:

A. those which are evaluated by statistical methods

B. those which are evaluated by other means.

In general, the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement, that is, the measurand, and thus the result is complete only when accompanied by a quantitative statement of its uncertainty.

Goodchild et al. (1994)

Information on validity affects the reliability of all aspects of analysis, spatial inference and reasoning. It also affects the **credibility** attached to decisions [...]. The term '**validity**' encompasses concepts related to measurable validity, including, but not limited to, measurement by deductive estimates, inferential evidence, or comparison with independent sources. [...] Validity can thus encompass both the accuracy of data and of the procedures applied to those data.

The term '**data quality**' encompasses more than testable elements subsumed here under validity, incorporating aspects of lineage that are often monitored or tracked in database operations. Trackable elements

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1 Comité International des Poids et Mesures (International Committee for Weights and Measures).

include chronological reporting of data collection and processing, algorithms used to process the data, and tests applied to the evaluation.

The types of validity that may be discovered or measured in geographical data most commonly include error and accuracy.

Accuracy measures the discrepancy from a modelled or an assumed value, while error measures discrepancy from the true value.

Although data validity may be measurable, data quality has been defined as a point in the three-dimensional space of data goodness, application and purpose.

Hunter and Goodchild (1994)

In the context of geographic data, it is argued there is a clear distinction between '**error**' and '**uncertainty**', since the former implies that some degree of knowledge has been attained about differences (and the reasons for their occurrence) between the results or observations and the truth to which they pertain. On the other hand, 'uncertainty' conveys the fact that it is the lack of such knowledge which is responsible for hesitancy in accepting those same results or observations without caution, and often the term 'error' is used when it would be more appropriate to use 'uncertainty'.

JCGM 100:2008 GUM 1995 with minor corrections[2]

The word "**uncertainty**" means doubt, and thus in its broadest sense "uncertainty of measurement" means doubt about the validity of the result of a measurement. Because of the lack of different words for this general concept of uncertainty and the specific quantities that provide quantitative measures of the concept, for example, the standard deviation, it is necessary to use the word "uncertainty" in these two different senses.

2 A working group of the Joint Committee for Guides in Metrology (JCGM), convened by the Bureau International des Poids et Mesures, has developed these guidelines starting from the Recommendation 1 (CI-1981) of the Comité International des Poids et Mesures (CIPM) and Recommendation INC-1 (1980) of the Working Group on the Statement of Uncertainties. "GUM" stands for "Guides for the expression of Uncertainty in Measurement".

2.2.2 In this Guide, the word "uncertainty" without adjectives refers both to the general concept of uncertainty and to any or all quantitative measures of that concept. When a specific measure is intended, appropriate adjectives are used.

NOTE The result of a measurement (after correction) can unknowably be very close to the value of the measurand (and hence have a negligible error) even though it may have a large uncertainty. Thus the uncertainty of the result of a measurement should not be confused with the remaining unknown error.

3.3.2 In practice, there are many possible sources of uncertainty in a measurement, including:

a) Incomplete definition of the measurand;

b) Imperfect realization of the definition of the measurand;

c) Nonrepresentative sampling – the sample measured may not represent the defined measurand;

d) Inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions;

e) Personal bias in reading analogue instruments;

f) Finite instrument resolution or discrimination threshold;

g) Inexact values of measurement standards and reference materials;

h) Inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm;

i) Approximations and assumptions incorporated in the measurement method and procedure;

j) Variations in repeated observations of the measurand under apparently identical conditions.

ICOMOS Principles for the recording of monuments, groups of buildings and sites 1996

Cultural Heritage refers to monuments, groups of buildings and sites of heritage value, constituting the historic or built environment.

Recording is the capture of information which describes the physical configuration, condition and use of monuments, groups of buildings and sites, at points in time, and it is an essential part of the conservation process.

Records of monuments, groups of buildings and sites may include tangible as well as intangible evidence, and constitute a part of the documentation that can contribute to an understanding of the heritage and its related values.

Pang et al. (1995)

We define **uncertainty** to include statistical variations or spread, errors and differences, minimum-maximum range values, noisy, or missing data. This broad umbrella is intended to capture most if not all the possible types and sources of uncertainty in data. NIST [Taylor and Kuyatt 1993, author's note] has written a standards report which identifies four ways of expressing uncertainty. For the discussion in this paper, we consider three types of uncertainty: **statistical** – either given by the estimated mean and standard deviation, which can be used to calculate a confidence interval, or an actual distribution of the data; **error** – a difference, or an absolute valued error among estimates of the data, or between a known correct datum and an estimate; and **range** – an interval in which the data must exist, but which cannot be quantified into either the statistical or error definitions. Note that the term **data quality has an inverse relationship with data uncertainty** and hence can also take advantage of the techniques presented in this paper.

Smets (1996)

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.

We use imperfection as the most general label. Information is perfect when it is precise and certain. Imperfection can be due to imprecision, inconsistency and uncertainty, the major aspects of imperfect data.

Imprecision and inconsistency are properties related to the content of the statement: either more than one world or no world is compatible with the available information, respectively. **Uncertainty** is a property that results from a lack of information about the world for deciding if the statement is true or false. **Imprecision** and **inconsistency** are essentially properties of the information itself whereas uncertainty is a property of the relation between the information and our knowledge about the world. Imprecision can be characterized by the presence of absence of an error component.

When several statements are combined, new aspects of imperfection can appear, in which cases some kind of error is always involved. An information can be **conflicting**: 'marital status = bachelor', 'spouse name = Joan'. The conflict in the data leads to an incoherence in the conclusions. Indeed the conclusion drawn from the data is that John is a 'married bachelor' as he has a spouse.

Logicians used **inconsistency** to define the **incoherence** that results from a conflicting information, like when you learn that at 3 p.m. the eggs were boiled and at 3.15 p.m. the same eggs were fresh.

The third aspect of informational imperfection, uncertainty, concerns the state of knowledge of an agent (denoted You, but the agent could even be a computer) about the relation between the world and the statement about the world. The statement is either true or false, but Your knowledge about the world does not allow You to decide if the statement is true or false. Certainty is full knowledge of the true value of the data. Uncertainty is partial knowledge of the true value of the data. Uncertainty results in **ignorance** (etymologically not knowing). It is essentially, if not always, an epistemic property induced by a lack of information. A major cause of uncertainty is imprecision in the data. Whether uncertainty is an objective or a subjective property is a still debated philosophical question left aside here.

Imperfect: Something is imperfect if it is incomplete, faulty.

Negligent: Someone who is negligent fails to deal with something or someone with the right amount of care or concern, or fails to do something which they ought to do. A lack of proper care or attention.

Imprecise: Something that is imprecise is not clear, accurate, or precise, not accurately expressed, not scrupulous in being inexact.

Vague: Vague is used to describe things that people say or write that are not clearly explained or expressed, so that they can be understood in different ways. It results in uncertain or ill-defined meaning.

Ambiguous: Something that is ambiguous is unclear or confusing because it can have more than one possible meaning. It can be due to vagueness.

Amphibologic: Synonymous to ambiguous.

Approximate: An approximate number, amount, time, position, etc. is close correct number, amount, etc., but is probably slightly different from it because it has been calculated quickly rather than exactly. An idea or description of something that is approximate provides some indication of what it is like but is not intended to be absolutely precise or accurate.

Fuzzy: If your thoughts are fuzzy or what you are thinking about is fuzzy, you are confused and cannot see an idea clearly or make a decision. You also describe something as fuzzy when it is not clearly defined and is indistinct or vague .

Missing: If something is missing, it is not in its place, it is lost, not present. You say that something is missing from a statement, report, etc. when it has not been included in it and you think that it should have been.

Incomplete: Something that is incomplete does not have all the parts that it should have, Not entered, not filled in.

Deficient: If someone or something is deficient in a particular thing, they do not have the full amount of it that they need in order to function normally or work properly. Someone or something that is deficient is not good enough for a particular purpose or standard.

Incomplete or insufficient in some essential respect.

Erroneous: Beliefs, opinions, methods etc. that are erroneous are incorrect or only partly correct.

Incorrect: Something that is incorrect is wrong, untrue , inaccurate .

Inaccurate: Something that is inaccurate is not correct, not precise and not conforming exactly to a standard or to truth.

Invalid: If an argument, conclusion, result, is invalid, it is not acceptable, because it is based on a mistake. Not sound logically.

Distorted: If an argument or a statement is distorted, its meaning becomes different and misrepresenting of what it should be.

Biased: Subject to a constant error.

Nonsensical: That do not make sense, absurd, foolish, stupid, ridiculous, untrue.

Meaningless: Without any meaning, but also: without importance or relevance.

Conflicting: If two or more things are in conflict, they are very different and not compatible. It seems impossible for each of them to be true, impossible for them to exist together, or for each of them to be believed by the same person.

Incoherent: If something is incoherent, it is unclear and difficult to understand, rambling in speech or reasoning.

Inconsistent: Someone who is inconsistent is unpredictable and behaves differently is a particular situation each time it happens, rather than doing or saying the same thing each time. Not compatible or not in harmony. Not constant to the same principles of thought or action.

Confused: Something is confused if it does not have any order or pattern and is difficult to understand because of this.

Random: Something that is random happens or is chosen without a definite plan, pattern, or purpose. Made or done without method or conscious choice.

Likely: Indicates that something is probably the case or will probably happen in a particular situation.

Believable: Something you think is likely.

Doubtful: That seems unlikely or uncertain.

Unreliable: If people, machines, or methods are unreliable, you cannot trust them or rely on them. That may be not relied on.

Irrelevant: An irrelevant fact, remark, is not connected with what you are focusing or dealing with, and is therefore not important. Not related to the matter in hand.

Ignorance: Lack of knowledge.

Undecidable: Which validity or truth cannot be decided, is questionable, or on which you cannot make your mind.

Gershon (1996)

Sources of **imperfection**:

- Corrupt data and information: analogous to errors in physics and engineering. Examples include errors in the location of targets reported by sensors.
- **Incomplete** data and information: quite frequent (most of the time, actually) in the real world.
- **Inconsistency**: pieces of data and information not consistent with each other or with what we already know.

- **Difficulty** in **understanding**: information itself is too complicated to understand.
- **Uncertainty**: data and information known, but the user is not sure about their existence or accuracy. The data and information could be exact, though. For example, "the information about the target flying around at 1,000 feet" is old and thus uncertain.
- **Imperfect presentation**: data and information could be exact, but a suboptimal presentation means the user cannot get the information in the allocated time or perceive the information wrongly. Examples include the poor choice of colors creating visual artifacts, or too fast a presentation creating information overload.

Strothotte et al. (1998) ●

Uncertainty describes the absence of information due to some reason. One simply does not know what something was like in the past or (for that matter) what it will be like in the future. In our context, uncertainty can arise for two reasons as defined – in general – by Kruse et al.:

Imprecision: this describes the fact that "one cannot measure or observe with an arbitrary degree of accuracy", this means that the existence of a certain feature can be safely assumed, but not its dimensions.

Incompleteness: this refers to the fact that certain information is unavailable, for example the answer to the question, "Did a given tower have windows, or not"?

Barceló (1999) ●

A **model** is a representation of some (not necessarily all) features of a concrete or abstract entity. It is a representation of a system showing not only the system components, but also the relationships between those components. Better than a mere analogy with the real world, we should imagine a model as a projection from a theory, that means one of the possible valid results from this theory.

Visual models are those that use graphical means for creating and editing the model, to obtain values for its parameters, and to understand its behaviour and structure.

Consequently, "**visualization**" can be defined as the process of creating a geometric representation of the regularity present in a data set:

joining points with lines, fitting surfaces to lines, or “solidifying” connected surfaces[3].

Unesco operational guidelines for the implementation of the world heritage convention - 2005 version[4]

Authenticity: the ability to understand the value attributed to the heritage depends on the degree to which information sources about this value may be understood as credible or truthful. Knowledge and understanding of these sources of information, in relation to original and subsequent characteristics of the cultural heritage, and their meaning as accumulated over time, are the requisite bases for assessing all aspects of authenticity.

Integrity is a measure of the wholeness and intactness of the natural and/or cultural heritage and its attributes.

Examining the conditions of integrity, therefore requires assessing the extent to which the property:

a) Includes all elements necessary to express its Outstanding Universal Value;

b) Is of adequate size to ensure the complete representation of the features and processes which convey the property’s significance;

c) Suffers from adverse effects of development and/or neglect.

Hermon et al. (2001)

Incompleteness is a concept implicit in archaeological studies. Archaeology, and any other discipline that integrates archaeological data aiming at creating a virtual model, de facto do not provide enough data to establish a scientifically unquestionable model.To a certain point, all reconstructions remain “speculative”.

We should therefore consider as **scientifically valid** a model that al-

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3 The author quotes Gershon (López-Menchero Bendicho and Grande 2011).

4 The World Heritage Convention dates back to 1972; the first version of the operational guidelines was adopted by the Unesco World Heritage Committee in 1978. Authenticity and integrity are clearly defined starting from the version published in February 2005. Before that date, conditions of authenticity and integrity were listed without giving a definition of the two terms. For a history of the document with all its versions, see: <https://whc.unesco.org/en/guidelines/> (accessed 04.11.2024) lows us to quantify the "degree of speculation" and express it through established rules.

London Charter (2006-2009)

English / *Italian* versions of the document

Computer-based visualisation: the process of representing information visually with the aid of computer technologies / ***Visualizzazione/ rappresentazione digitale****: il processo di rappresentazione grafica digitale dell'informazione elaborata o creata con l'aiuto di tecnologie informatiche.*

Computer-based visualisation method: the systematic application, usually in a research context, of computer-based visualisation in order to address identified aim / ***Metodo di visualizzazione/ rappresentazione digitale****: l'applicazione sistematica, solitamente in un contesto di ricerca, della rappresentazione digitale per affrontare scopi identificati.*

Computer-based visualisation outcome: an outcome of computer-based visualisation, including but not limited to digital models, still images, animations and physical models / ***Prodotto della visualizzazione / rappresentazione digitale****: il prodotto della visualizzazione digitale, che include (ma non si limita a) modelli, immagini ferme e animazioni.*

Cultural heritage: the Charter adopts a wide definition of this term, encompassing all domains of human activity which are concerned with the understanding of communication of the material and intellectual culture. Such domains include, but are not limited to, museums, art galleries, heritage sites, interpretative centres, cultural heritage research institutes, arts and humanities subjects within higher education institutions, the broader educational sector, and tourism / ***Patrimonio culturale****: la Carta adotta una definizione ampia di questo termine, che racchiude tutti i settori dell'attività umana legati alla conoscenza della comunicazione della cultura materiale ed intellettuale. Tali settori comprendono (ma non si limitano a) musei, gallerie d'arte, siti culturali, centri interpretativi, istituti di ricerca sui beni culturali, materie artistiche e umanistiche all'interno degli istituti di educazione superiore, oltre al più ampio settore educativo ed al turismo.*

Dependency relationship: a dependent relationship between the properties of elements within digital models, such that a change in one property will necessitate change in the dependent properties. (For instance, a change in the height of a door will necessitate a corresponding change in the height of the doorframe.) / ***Relazione di dipendenza**: relazione fra le proprietà degli elementi all'interno dei modelli tridimensionali tale che il cambiamento di una proprietà implica il cambiamento di altre – dette dipendenti (ad esempio, la modifica dell'altezza di una porta determinerà necessariamente la modifica dell'altezza dell'intelaiatura).*

Intellectual transparency: the provision of information, presented in any medium or format, to allow users to understand the nature and scope of "knowledge claim" made by a computer-based visualisation outcome / ***Informazione sulla trasparenza**: l'informazione, attuata in qualsiasi mezzo o formato, che permette agli utenti di capire la natura e gli scopi del prodotto di una rappresentazione digitale e l'asserzione di conoscenza che porta.*

Paradata: information about human processes of understanding and interpretation of data objects. Examples of paradata include descriptions stored within a structured dataset of how evidence was used to interpret an artefact, or a comment on methodological premises within a research publication. It is closely related, but somewhat different in emphasis, to "contextual metadata", which tend to communicate interpretations of an artefact or collection, rather than the process through which one or more artefacts were processed or interpreted / ***Paradata**: la Carta definisce "paradata" come le informazioni riguardanti i procedimenti umani del capire ed interpretare i dati stessi (i paradata vengono in tal modo continuamente creati senza essere sistematicamente registrati o divulgati.) Esempi di paradata includono metodi di registrazione di note in un rapporto di laboratorio, descrizioni immagazzinate all'interno di un archivio strutturato che dimostra come l'evidenza sia stata usata per interpretare un manufatto, oppure un commento sulle premesse metodologiche all'interno di una ricerca pubblicata. È molto simile (ma in qualche modo diverso quanto all'enfasi) a "metadati contestuali", i quali tendono a comunicare interpretazione di un artefatto o di una collezione, piuttosto che il processo attraverso il quale uno o più artefatti sono processati o interpretati.*

Research sources: all information, digital and non-digital, considered during, or directly influencing, the creation of the computer-based visualisation outcomes / ***Fonti della ricerca****: tutte le informazioni, digitali e non, prese in considerazione durante la creazione di risultati per mezzo della visualizzazione digitale o che vi abbiano influito direttamente.*

Subject community: a group of researchers generally defined by a discipline (e.g. Archaeology, Classics, Sinology, Egyptology) and sharing a broadly- defined understanding of what constitute valid research questions, methods and outputs within their subject area / ***Comunità di soggetti****: un gruppo di ricercatori generalmente definiti da una disciplina (ad esempio, Archeologia, Egittologia) e che condividono un ampio e definito contesto nel quale vengono effettuate valide ricerche, poste domande, applicati metodi e divulgati risultati all'interno del campo di studi.*

Sustainability strategy: a strategy to ensure that some meaningful record of computer-based visualisation processes and outcomes is preserved for future generations / ***Strategia di sostenibilità****: una strategia per garantire che significative testimonianze della procedura di rappresentazione digitale e dei suoi risultati venga conservata per le generazioni future.*

Icomos Ename (2008) ●●

Cultural Heritage Site refers to a place, locality, natural landscape, settlement area, architectural complex, archaeological site, or standing structure that is recognized and often legally protected as a place of historical and cultural significance.

The two main concepts that emerge from this document are **interpretation** and **presentation**.

Interpretation refers to the full range of potential activities intended to heighten public awareness and enhance understanding of cultural heritage site. These can include print and electronic publications, public lectures, on-site and directly related off-site installations, educational programmes, community activities, and ongoing research, training, and evaluation of the interpretation process itself.

Presentation more specifically denotes the carefully planned communication of interpretive content through the arrangement of interpretive information, physical access, and interpretive infrastructure at a cultural heritage site. It can be conveyed through a variety of technical means, including, yet not requiring, such elements as informational panels, museum-type displays, formalized walking tours, lectures and guided tours, and multimedia applications and websites.

Interpretation is also related to:

Interpretive infrastructure refers to physical installations, facilities, and areas at, or connected with a cultural heritage site that may be specifically utilised for the purposes of interpretation and presentation including those supporting interpretation via new and existing technologies.

Site interpreters refers to staff or volunteers at a cultural heritage site who are permanently or temporarily engaged in the public communication of information relating to the values and significance of the site.

Adam (2006) ●

The term **authenticity** has different definitions depending on the context of its use. Duranti (1998) writes, "diplomatically authentic documents are those which were written according to the practice of the time and place indicated in the text, and signed with the name(s) of the person(s) competent to create them. Historically authentic documents are those, which attest to events that actually took place or to information that is true".

Clark (2010) ●

"It is the contention of this paper that the notion of "**reconstructing**" the past is not only a misnomer but one that has been detrimental to the discipline. This holds true for conventional archaeology as well as virtual. We should only be talking about "**constructions**" of the past and rarely, if ever, about reconstructions. We are always constructing models, whether visual, verbal, or some other type, which are tools for understanding, not statements of reality. The criticisms that have often been leveled against virtual visualizations have been largely due to calling, and thinking about, visualizations as reconstructions of some aspect of the past rather than regarding them for what they are—models. Calling these models reconstructions is not only fallacious but has hindered the acceptance and use of virtual archaeology by the larger professional community".

He discusses two apparently contrasting ideas: 1) no matter what name we give to something, it does not change the essential character of it; 2) terminology does matter: "There is indeed power in words. Words, including and perhaps especially names and terminology, reflect as well as shape what we think about things. Those terms convey meaning to others whose perceptions are then influenced, subtly or profoundly".

Thoomu (2010)

Uncertainties in the **input** due to:

- Missing components or errors in the data.
- Variability in the data because of imperfect observations.
- Random sampling errors.
- Inaccuracy in measurement.

Uncertainties in **models** due to:

- Unfamiliar functional relationship among the components even if the functions of individual components are known.
- Inherent performance of the system and effects of the surroundings.
- Ambiguity in predicting the final outcome. Qualms introduced by approximation techniques used to solve a set of equations that characterize some model.

Other sources of uncertainty:

- Vaguely defined concepts and terminology.
- Lack of communication.

Though there are many sources of uncertainty, as described by researchers from different fields, the main reasons behind it are:

- **Variability**

Variability is a characteristic of being subjected to changes. The variation could be in input, system, or performance of the system, etc.

- **Lack of knowledge**

Lack of knowledge about the system, inadequate awareness of component interactions in a system, insufficient and non reliable information, contribute for the occurrence of uncertainty.

Beacham (2010)

Realism:

1) Treatment of forms, colours, space, etc., in such a manner as to

emphasize their correspondence to actuality or to ordinary visual experience[5].

2) Fidelity to nature or to real life; representation without idealization, and making no appeal to the imagination; adherence to the actual fact[6].

Paradata according to the London Charter (employing the term coined by my CVL colleague, Drew Baker) is "Information about human processes of understanding and interpretation of data objects. Examples of paradata include descriptions stored within a structured dataset of how evidence was used to interpret an artefact, or a comment on methodological premises within a research publication. It is closely related, but somewhat different in emphasis, to 'contextual metadata', which tend to communicate interpretations of an artefact or collection, rather than the process through which one or more artefacts were processed or interpreted".

Beacham et al. (2011)

Archaeological reconstructions of ancient houses and villas: they typically limit themselves to the precise structural and decorative evidence available;

Social and art historians' point of view: the whole architectural and decorative ensemble is necessary for an understanding of the dynamic use of space in antiquity as a complex system of signification.

Rocheleau (2011)

Original French version / *translation by Irene Cazzaro*

Il est donc peu étonnant de constater qu'une analyse des vingt dernières années au sujet de l'évolution de la 3D et de la réalité virtuelle en sciences historiques fasse ressortir des principes directeurs essentiellement liés aux deux mêmes domaines, l'archéologie et les études patrimoniales, au point où il est courant aujourd'hui de parler de virtual archaeology ou de virtual heritage. / *It is therefore hardly surprising to note that an analysis of the last twenty years on the subject of the evolution of 3D and virtual*

5 See <http://dictionary.reference.com/browse/realism>.
6 See <https://www.webster-dictionary.org/definition/realism>.

reality in historical sciences reveals guiding principles essentially linked to the same two domains, archaeology and heritage studies, to the point that it is common today to speak of virtual archaeology or virtual heritage.

Par **scientifique**, nous entendons un modèle 3D qui résulte d'un programme de recherche conduit de manière traditionnelle: accessibilité aux sources employées, confrontation de ces dernières, explication des méthodes utilisées et du processus pour en arriver à la modélisation finale, etc. En clair, tout ce qui permet au chercheur de comprendre le raisonnement derrière la réalisation d'un modèle (et qui peut se comparer à l'appareillage critique d'un texte). Tout le contraire d'un modèle créé par un studio multimédia dont il serait impossible de valider l'authenticité historique parce que le processus décisionnel de restitution n'est pas documenté. / *By* ***scientific****, we mean a 3D model resulting from a research program carried out in a traditional way: accessibility to the sources used, comparison of the latter, explanation of the methods used and the process to arrive to the final modeling, etc. Clearly, anything that allows the researcher to understand the reasoning behind the realization of a model (and which can be compared to the critical apparatus of a text). Quite the opposite of a model created by a multimedia studio whose historical authenticity would be impossible to validate because the restitution decision-making process is not documented.*

5 points based on rules that have been laid down:

Le **réalisme** est le thème le plus ancien et, dans une certaine mesure, le plus évident. Cette course effrénée vers le réalisme visuel provient, en partie, de l'objectif initial des restitutions et des reconstitutions virtuelles, qui a été la diffusion de l'histoire pour le grand public et la volonté de faire voir le passé / ***Realism*** *is the most ancient theme and, to some extent, the most evident one. This frantic rush towards visual realism partly comes from the initial aim of virtual renditions and reconstructions, which was the dissemination of history for the general public and the desire of showing the past.*

Transparence: Vers la fin des années 1990, lorsque des chercheurs universitaires ont commencé à s'intéresser aux modélisations virtuelles en 3D pour leur travail, l'objectif principal est devenu, avec raison, la **crédibilité scientifique** du procédé de restitution virtuelle. Ce principe a rapidement rejoint une des considérations qui, depuis longtemps, anime une grande partie des chercheurs des sciences historiques: 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. Ce concept, transposé dans le monde des technologies, se nomme la transparence. Cela consiste à rendre les étapes du processus de création d'un modèle 3D accessibles par l'intermédiaire de ce que nous appelons des métadonnées et des paradonnées / ***Transparency***: *Towards the end of the 1990s, once university researchers started focusing on 3D virtual reconstructions for their work, the main purpose became, with good reason, the* ***scientific credibility*** *of the virtual reconstruction process. This principle has rapidly reached one of the considerations that, for a long time, has guided a large part of researchers in historical sciences: 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. This concept, transposed in the world of technologies, is called transparency. It consists in making the steps of the creation process of a 3D model accessible by means of what we call metadata and paradata.*

Le problème de l'**incertitude**, dans son acception la plus large, concerne l'ensemble des modèles 3D virtuels, car même le scientifique le plus aguerri ne peut être absolument certain que ce qu'il réalise ou construit reproduit parfaitement l'ancienne réalité. Faire état des incertitudes entourant la restitution renforce ainsi la transparence et exprime une forme d'honnêteté intellectuelle / *The problem of* ***uncertainty***, *it its widest meaning, involves all 3D virtual models, because even the most seasoned scientist cannot be absolutely sure that what he creates or constructs perfectly reproduces ancient reality. Reporting the uncertainties surrounding the rendition thus reinforces transparency and expresses a form of intellectual honesty.*

Toutefois, pour qu'ils aient un réel impact, les modèles 3D doivent également être **pérennes**, comme les articles scientifiques d'aujourd'hui ou les maquettes **de** l'époque. Il est en effet primordial de prévoir la sauvegarde à long terme de ces réalisations virtuelles, au même titre que n'importe quel autre patrimoine historique, comme le demande notamment la Charte de l'UNESCO sur la conservation du patrimoine numérique[7] / *However, in order to ensure they have a significant impact, 3D models should also be **sustainable**, such as the modern scientific articles or the ancient models. It is indeed essential to foresee the long-term preservation of these virtual realisations, as well as any other example of historical heritage, as called in the UNESCO Charter on the preservation of digital heritage.*

Enfin, il devient de plus en plus courant de suivre des **standards internationaux** et d'utiliser une **méthode** dite **scientifique** pour la création d'un modèle 3D. Il s'agit simplement de mettre en pratique les principes que nous venons d'évoquer. Quelques initiatives internationales proposent leurs standards et leur méthode de travail qui permettent d'encadrer la création de modèles 3D numériques à caractère historique et patrimonial / *Finally, it becomes increasingly common to follow **international standards** and to use a so-called **scientific method** for the creation of a 3D model. It is simply a question of putting the principles that we just mentioned into practice. Some international initiatives propose their standards and their working method that provide a framework for the creation of 3D digital models for history and cultural heritage.*

Seville Principles (2011)[8]

English / *Spanish* versions of the document

Virtual archaeology: the scientific discipline that seeks to research and develop ways of using computer-based visualisation for the comprehensive management of archaeological heritage / ***Arqueología Virtual**: es la disciplina científica que tiene por objeto la investigación y el desarrollo de formas de aplicación de la visualización asistida por ordenador a la gestión integral del patrimonio arqueológico.*

Archaeological heritage: the set of tangible assets, both movable and immovable, irrespective of whether they have been extracted or not and

7 Unesco Charter on the Preservation of Digital Heritage, Paris, 29 September to 17 October 2003.
<http://portal.unesco.org/en/ev.php-URL_ID=17721&URL_DO=DO_TOPIC&URL_SECTION=201.html> (accessed 23/09/2020)

8 See also: Hacia una Carta Internacional de Arqueología Virtual. El Borrador SEAV by Víctor Manuel López-Menchero Bendicho and Alfredo Grande.

whether they are on the surface or underground, on land or in water, which together with their context, which will also be considered a part of archaeological heritage, serve as a historical source of knowledge on the history of humankind. The distinguishing feature of these elements, which were or have been abandoned by the cultures that produced them, is that they may be studied, recovered or located using archaeological methodology as the primary method of research, using mainly excavation and surveying or prospection techniques, without compromising the possibility of using other complementary methods for knowledge / ***Patrimonio arqueológico****: es el conjunto de elementos materiales, tanto muebles como inmuebles, hayan sido o no extraídos y tanto si se encuentran en la superficie o en el subsuelo, en la tierra o en el agua, que junto con su contexto, que será considerado también como formante del patrimonio arqueológico, sirven como fuente histórica para el conocimiento del pasado de la humanidad. Estos elementos, que fueron o han sido abandonados por las culturas que los fabricaron, tienen como sello distintivo el poder ser estudiados, recuperados o localizados usando la metodología arqueológica como método principal de investigación, cuyas técnicas principales son la excavación y la prospección, sin menoscabo de la posibilidad de usar otros métodos complementarios para su conocimiento.*

Comprehensive management: this includes inventories, surveys, excavation work, documentation, research, maintenance, conservation, preservation, restoration, interpretation, presentation, access and public use of the material remains of the past / ***Gestión integral****: comprende las labores de inventario, prospección, excavación, documentación, investigación, mantenimiento, conservación, preservación, restitución, interpretación, presentación, acceso y uso público de los restos materiales del pasado.*

Virtual restoration: this involves using a virtual model to reorder available material remains in order to visually recreate something that existed in the past. Thus, virtual restoration includes virtual anastylosis / ***Restauración virtual****: comprende la reordenación, a partir de un modelo virtual, de los restos materiales existentes con objeto de recuperar visualmente lo que existió en algún momento anterior al presente. La restauración virtual comprende por tanto la anastilosis virtual.*

Virtual anastylosis: this involves restructuring existing but dismembered parts in a virtual model / ***Anastilosis virtual:*** *recomposición de las partes existentes pero desmembradas en un modelo virtual.*

Virtual reconstruction: this involves using a virtual model to visually recover a building or object made by humans at a given moment in the past from available physical evidence of these buildings or objects, scientifically-reasonable comparative inferences and in general all studies carried out by archaeologists and other experts in relation to archaeological and historical science / ***Reconstrucción virtual:*** *comprende el intento de recuperación visual, a partir de un modelo virtual, en un momento determinado de una construcción u objeto fabricado por el ser humano en el pasado a partir de las evidencias físicas existentes sobre dicha construcción u objeto, las inferencias comparativas científicamente razonables y en general todos los estudios llevados a cabo por los arqueólogos y demás expertos vinculados con el patrimonio arqueológico y la ciencia histórica.*

Virtual recreation: this involves using a virtual model to visually recover an archaeological site at a given moment in the past, including material culture (movable and immovable heritage), environment, landscape, customs, and general cultural significance / ***Recreación virtual:*** *comprende el intento de recuperación visual, a partir de un modelo virtual, del pasado en un momento determinado de un sitio arqueológico, incluyendo cultura material (patrimonio mueble e inmueble), entorno, paisaje, usos, y en general significación cultural.*

Favre-Brun (2011)

Original French version / *translation by Irene Cazzaro*

Le concept d'incertitude possède un champ sémantique très large pour lequel aucun consensus sur ses multiples significations n'a pu être trouvé. Les terminologies utilisées pour exprimer l'**incertitude** sont vagues et aussi nombreuses que le disciplines qui l'étudient ou les modes de perception. […] En archéologie, l'interprétation des données, fondée sur des données lacunaires, ambigües, imprécises, hétérogènes et issues de séries discontinues, appartient au domaine du plausible / *The concept of* ***uncertainty*** *has a huge semantic field for which no consensus on its various meanings has been found. The terminologies used to express uncertainty are vague and as numerous as the disciplines that study it or the perception modes. […] In archaeology, the interpretation of data, based* *on data that are incomplete, ambiguous, imprecise, heterogeneous and originated from discontinuous series, belongs to the domain of plausible*[9].

L'usage de nombreux synonymes révèle le «caractère multi-facettes» de l'incertitude et souligne sa nature objective ou subjective, quantifiable ou non, et réductible ou irréductible / *The use of several synonyms reveals the «multi-faceted character» of uncertainty and underlines its objective or subjective nature, quantifiable or not, and reducible or irreducible10.*

Les **nuances** recensées à travers la littérature expriment la confusion générale lorsqu'il s'agit de qualifier l'incertitude, souvent confondues avec les sources et les types d'incertitude / *The* ***nuances*** *examined through literature express the general confusion when it comes to qualifying uncertainty, often confused with the sources and types of uncertainty.*

Classifications de l'incertitude: il existe plusieurs classifications de l'incertitude. La première répartit neuf types d'incertitude en trois catégories relatives à la qualité de l'information, à sa cohérence et à son objectivité / ***Classifications of uncertainty****: there are many classifications of uncertainty. The first one assigns nine types of uncertainty to three categories related to the quality of information its coherence and its objectivity.*

9 Bertoncello 2013
10 Dungan, Gao, Pang 2002; Thoomu 2010

Qualité / *Quality*	Cohérence / *Coherence*	Objectivité / *Objectivity*
Exactitude/erreur: difference entre l'observation et la réalité Exactitude de la collecte Erreurs de traitement Tromperie ***Exactness/error:*** *difference between observation and reality* - *Exactness of the collection* - *Treatment errors* - *Deception*	**Cohérence:** Concordance entre les composants de l'information - Conflits - Modèle/observation - Cohérence ***Coherence:*** *harmony between the components of information* - *Conflicts* - *Model/observation* - *Coherence*	**Crédibilité:** Fiabilité des sources - Fiabilité - Proximité - Justesse - Motivation de la source ***Credibility:*** *reliability of sources* - *Reliability* - *Proximity* - *Accuracy* - *Motivation of the source*
Précision: exactitude de la mesure - Précision de la collecte ***Precision:*** *exactness of the measure* - *- Precision of the collection*	**Lignage:** Conduit à travers lequel est passée l'information - Traduction - Transformation - Interprétation ***Lineage:*** *channel through which information passes* - *Translation* - *Transformation* - *Interpretation*	**Subjectivité:** Niveau d'interprétation ou de jugement - Jugement analytique ***Subjectivity:*** *level of interpretation or judgement* *- Analytical judgement*
Exhaustivité: Niveau de complétude de l'information - Exhaustivité composite - Exhaustivité des informations - Séquence incomplete ***Exhaustiveness:*** *Level of completeness of information* - *Composite exhaustiveness* - *Exhaustiveness of information* - *Incomplete sequence*	**Actualité:** Lacunes temporelles entre l'apparition de l'information, sa collecte et son utilisation - Lacunes temporelles - Versions ***Topicality:*** *temporal gaps between the appearance of information, its collection and its use* - *Temporal gaps* - *Versions*	**Corrélation/dépendance:** Indépendance de la source par rapport à d'autres informations - Indépendance de la source ***Correlation/dependence:*** *Independence of the source in relation to other information* - *– Independence of the source*

Perlinska (2013)

There has been many articles written concerned with the issue of the adequacy of the word "**reconstruction**" in archaeology. I will use the words ***model*** or ***virtual simulation*** instead, as proposed by Jeffrey Clark. "Reconstruction", as pointed out by many authors, assumes that we know precisely how the things were in the past and that we are reproducing an exact image of the past. It is hard to uproot this concept, as there has not been any convincing replacements proposed. Model and virtual simulation might still be too ambiguous, but it is not in the scope of this thesis to define a new technical terminology. In this work, model or virtual simulation will be used alternatively to denominate a 3D virtual construct done on the basis of the remains of the ancient Pompeian house V 1,7. In some instances, where those words can cause the confusion or may seem unclear, I will continue to use the word "reconstruction".

Virtual Reality (in short VR) can be defined as a cyber space environment (sometimes called a computer simulation), resembling the real world or not, that can be explored by people, and, in some cases, interacted with. It should give the viewer a sense of telepresence, which is a feeling of being physically present in this environment through a medium (like 3D glasses). For each visitor, the sensual perception (sometimes also other senses than vision are stimulated) will be slightly different, depending on each individuals physical and mental condition.

The VR environment enables its users (depending on the level of accessibility) to perceive the model and to freely move around in it, but also to interact with it in a variety of ways. This creates interesting possibilities for archaeological research which have not been completely explored yet and – looking at the intense pace at which technology develops today – might never be fully researched.

The definition of **probability** assumes that the number of all possible cases is known. Unfortunately, we cannot hope for that in our discipline. Thus, probability is not a word we should use. In some cases, words such as uncertainty and confidence were used instead. ***Uncertainty*** is a misleading word: an uncertainty map shows the level of our certitude, or incertitude. This is very confusing, whereas ***confidence***, in my opinion, is too close to actually believe and have faith in something (probably in the archaeological knowledge of the archaeologist).

The most suitable word could be plausibility. It is a more "humanistic" equivalent of the word probability. It states the possibility of an event to occur, but the chance for it is not calculated by any mathematical formula. I think that in future implementation plausibility map should be forced as a standard nomenclature.

However, as I stated before, the introduction of a new terminology is not within the scope of this thesis. Under those circumstances, I would like to use this unfortunate probability map, but to do so, the term requires proper definition.

Thus, a **probability map** should be understood as additional information to the virtual visualization, one that indicates the level of the researchers certitude in his knowledge about how each of the individual features looked like. It has not much to do with the "objective" past Roman world, but rather with our ideal imaginations that we have about it. The goal is not only to provide a "pretty picture" (this is something that everybody seeks, regardless of what they claim), but also to collect information about all the features and visualize it in as high a quality as technology allows us to.

Lengyel and Toulouse (2014) ●

The expression **uncertain knowledge** underlines the large and productive field between knowledge on one hand and the lack of knowledge on the other hand pointing out the other states of knowledge in between. Uncertain knowledge takes into account **incomplete knowledge**, e. g. if some parts of a structure are known while other parts are unknown, but also **contradictory knowledge**, that is if the stringent deduction of prerequisites allow contradictory yet equivalent conclusions. Incomplete and contradictory knowledge is then summarized as uncertain knowledge.

Demetrescu and Fanini (2015) ●●

Scientific process behind an archaeological reconstruction: it includes not only the specialists' hypotheses regarding a specific context in order to reconstruct its "original aspect" in a given historical time period, but also the collection and the use of the "sources".

Sources: they comprise all the physical evidence (such as discoveries made during excavation or pieces from a museum's collection), historical assumptions (i.e. in Roman times outside the city wall and along the main road there was a necropolis), and documents (drawings or writings) from the past that testify to the lost aspects of the archaeological site as well as its 3D survey and stratigraphic reading.

Lost context: a context that is no longer existent and/or has been completely or partially "lost" over time due to various causes (war, neglect, environmental factors etc…).

Extended matrix (EM): as defined in its 1.0 version (Demetrescu 2015), it is a formal language specifically designed for the reconstruction of lost contexts and operates with the same tools already in use in the archaeological domain in order to manage time sequences (matrix of Harris) and data granularity (stratigraphy). The version 1.1 of the Extended Matrix adds a complete support for 3D representation of extended matrices and scientific publication of the whole dataset behind a virtual reconstruction hypothesis. The EM is the theoretical and methodological background, usable even outside a digital environment. It is about scientific-driven content creation.

Extended matrix framework (EMF): the integration of the EM with digital tools for 3D representation of virtual reconstructions and visual inspection of extended matrices is identified with the expression Extended Matrix Framework (EMF). It is about technological-driven solutions.

Amico et al. (2017) ●

If the term '**authentic**' is used to define something original and unique, the authenticity of digital objects or their physical replicas, generated from a real object, cannot be applied because 'all digital object are copies' (Lynch 2000) and infinitely replicable and modifiable. In this case, the term 'faithful' seems to fit better.

B.
APPENDIX 2. SOME DOCUMENTATION SCHEMES

Grellert and Pfarr-Harfst (2019) "Die Rekonstruktion-Argument-Methode: minimaler Dokumentationsstandard im Kontext digitaler Rekonstruktionen": German original version and English translation.

Projekt → Projektname → Zusatzinformation für die Projektbezeichnung → Kurzbeschreibung des Projektes → Ausführliche Beschreibung des Projektes → Repräsentatives Bild der Rekonstruktion → Entstehungszeit des Bauwerks/Stadtanlage → Laufzeit des Projektes → Institution, die die Rekonstruktion durchgeführt hat → Bearbeiterinnen / Bearbeiter → Wissenschaftliche Beratung → Auftraggeber/Kooperationspartner → Sponsoren → Eingesetzte Hard-/Software → Geokoordinaten des rekonstruierten Bauwerks / Stadtanlage → Website des Projektes → Name des Ansprechpartners mit E-Mail-Adresse/Telefonnummer → Weitere Angabe zur Institution: Allgemeine E-Mail-Adresse und Telefonnummer, Website, Anschrift, Kurzname der Institution → Renderings bzw. Filme des fertiggestellten Projektes	**Project** → project name → Additional information for the project designation → Brief description of the project → Detailed description of the project → Representative image of the reconstruction → Time of construction of the building/city facility → Duration of the project → Institution that carried out the reconstruction → Editors → Scientific advice → Client/cooperation partner → sponsors → Hardware/software used → Geo-coordinates of the reconstructed building / city complex → Website of the project → Name of contact person with e-mail address/telephone number → Additional information about the institution: general e-mail address and telephone number, website, address, short name of the institution → Renderings or films of the completed project
Bereiche → Anzahl der Bereiche (1: n) → Bezeichnung	**Areas** → number of areas (1: n) → designation

→ Übersichtsbild, das den Bereich verortet, und Bildunterschrift → Anzahl der Varianten für einen einzelnen Bereich (1: n) → Wenn gewünscht, ausführlichere Beschreibung des Bereichs **Varianten** → Bezeichnung der Variante (Standardbezeichnung 1) →Bewertung der Varianten in gesichert, wahrscheinlich, möglich und hypothetisch → Angabe, ob die Variante Bestandteil der Endpräsentation des Projektes ist → Rekonstruktion–Argument–Quelle **Rekonstruktion** → Screenshot/Rendering (1: n) → Bildunterschrift **Argument** → Freie Texteingabe **Quelle** → Abbildung (1: n) → Bildunterschrift → Autorin/Autor → Entstehungszeit → Archiv → Signatur → Copyright → Direkt-URL, wenn vorhanden → Veröffentlicht von → Titel der Veröffentlichung → Herausgeber der Veröffentlichung → Titel des Sammelbands → Ort der Veröffentlichung → Jahr der Veröffentlichung → Seite → Eigener Kommentar für weitere Informationen	→ Overview image that locates the area, and caption → Number of variants for a single area (1:n) → If desired, more detailed description of the area **Variants** → Designation of the variant (standard designation 1) →Evaluation of variants in saved, probable, possible and hypothetical → Specification whether the variant is part of the final presentation of the project → Reconstruction-argument-source reconstruction **Reconstruction** → Screenshot/Rendering (1:n) → Caption **Argument** → Free text entry **Source** → Figure(1:n) → Caption → Author → Time of origin → Archive → Signature → Copyright → Direct URL, if available → Published by → Title of publication → Publisher of the publication → Title of the anthology → Place of publication → Year of publication → Page → Own comment for further information

→ Art (3D-Laser-Scan, SFM-Bauaufnahme, Befundzeichnung, Befund- skizze, Foto der archäologischen / architektonischen Reste, Fotos des bestehenden Bauwerks, Bauplan, Entwurfsplan, zeichnerische Bauaufnahme, haptisches Rekonstruktionsmodell, Rekonstruktionszeichnung, Textquelle, historische Zeichnung, historisches Gemälde, historische Filmaufnahme).	→ Type (3D laser scan, SFM building survey, finding drawing, finding sketch, photo of the archaeological/architectural remains, photos of the existing structure, building plan, draft plan, drawing of the building survey, haptic reconstruction model, reconstruction drawing, text source, historical drawing, historical painting , historical film recording).

Statham (2019) "Scientific rigour of online platforms for 3D visualisation of heritage"

The proposed information package should include:

» Descriptive name
» Type of 3D visualisation
» Level of certainty of the reconstruction
» Description
» Original location
» Current location
» Date
» Author
» Team responsible for the visualisation
» Team supervisor
» Funding
» Part of project(s)
» Project description
» Related publications
» Related visualisations
» Sources
» Visualisation methodology and tools

Wacker and Bruschke (2019) "Dokumentation von Digitalen Rekonstruktionsprojekten": German original version and English translation.

[…] Dazu empfiehlt es sich, Dokumentationsstrategien zu entwickeln, die diese Aktivitäten tatkräftig verbessern und strukturieren. Im Konkreten bedeutet das die Dokumentation der → Kenntnislage: Es ist darzustellen, was die Visualisierung anstrebt, und von welcher Art und welchem Ausmaß die faktischen Unsicher- heiten sind. → Forschungsquellen: Die genutzten Quellen einschließlich ihrer Herkunft sollen aufgelistet werden. → Prozesse: Alle auswertenden, analytischen, deduktiven, interpretativen und kreativen Entscheidungen sollen so zur Verfügung stehen, dass die Beziehung zwischen Quelle, implizitem Wissen, expliziten Schlussfolgerungen und den Visualisierungsergebnissen verstanden werden kann. → Methoden: Anwendern, die mit den gewählten Visualisierungsmethoden nicht vertraut sind, sollte eine Beschreibung der Methoden zur Verfügung gestellt werden. Außerdem sollte erklärt werden, warum die gewählte Methode die geeignetste ist (in Bezug auf Leitsatz 2 der Londoner Charta Ziele und Methoden). Die Dokumentation sollte darüber hinaus bei der »Artikulation impliziten Wissens« und der »Identifizierung der verschiedenen Terminologien« (mit Blick auf interdisziplinäre Projekte) helfen. → Verknüpfung von Abhängigkeiten: »Die Art und Wichtigkeit der wesentlichen, hypothetischen Abhängigkeitsverhältnisse zwischen den Elementen [sollen] identifiziert und die zugrunde liegenden Folgerungen verstanden werden können.« → Formate und Standards: Die Dokumentation soll durch die »Nutzung der effektivsten verfügbaren Medien« und Standards in einer Form verbreitet werden, dass deren Benutzung sowie die Aufnahme in Zitationsdatenbanken vereinfacht werden.	[…] It is advisable to develop documentation strategies that actively improve and structure these activities. In concrete terms, this means the documentation of the → Knowledge: It must be shown what the visualization is aiming for and what the type and extent of the factual uncertainties are. → Research sources: The sources used, including their origin, should be listed. → Processes: All evaluating, analytical, deductive, interpretative and creative decisions should be available in such a way that the relationship between the source, implicit knowledge, explicit conclusions and the visualization results can be understood. → Methods: Users who are not familiar with the selected visualization methods should be provided with a description of the methods. It should also explain why the method chosen is the most appropriate (in relation to Principle 2 of the London Charter Objectives and Methods). The documentation should also help with the "articulation of implicit knowledge" and the "identification of the various terminologies" (with a view to interdisciplinary projects). → Linking of dependencies: "The type and importance of the essential, hypothetical dependencies between the elements [should] be identified and the underlying conclusions understood." → Formats and standards: The documentation should be disseminated through the "use of the most effective available media" and standards in a form that simplifies its use and inclusion in citation databases.

Scheme used in DFG repository

It is mainly based on the following points:

» Model representation
» Model description
» Reconstructed period (WissKi entity)
» Model copyright (WissKi entity)
» Model creation
» Object
» Project
» Native file
» Documentation
» Viewer file upload

Example of metadata related to the Speyer synagogue (1250) entry in the DFG Viewer:

Model Representation
Polygonal
Model Description
The model depicts the Speyer synagogue at around 1250 AD.
Reconstructed period
1250
Model Copyright
License
CC-BY-NC Attribution-NonCommercial
Author(s)
Name
Irene Cazzaro
Affiliation
University of Bologna
ORCID ID
https://orcid.org/0000-0002-9484-1980
Holder (Organization)
Name
Institute of Architecture, Univeristy of Applied Scinces Mainz

VIAF ID
https://viaf.org/viaf/170713989/
Website
https://architekturinstitut.hs-mainz.de/
Model Creation
Used Software
Rhino 5
SketchUp 2017
Modeling Techinque
Polygonal modeling
NURBS and curve modeling
Boolean modeling
Creation Time Span
2022-03-08 — 2022-04-11
Participant(s)
Object
Name
Synagogue in Speyer
Synagogue Speyer
Alternative Name(s)
Former Synagogue in Speyer [en]
Synagoge Speyer
Type
Synagogue
Location
City
Speyer
Geonames ID
http://www.geonames.org/2830582/speyer.html
City
Speyer
Historical Relations
City
Speyer
Wikidata
https://www.wikidata.org/wiki/Q64825449

Wikipedia
https://en.wikipedia.org/wiki/Jewish_courtyard,_Speyer
Project
Title
Case Study of the reconstruction of the Synagogue in Speyer in 800
Acronym
CaSt: SpSya1250
Outcome(s)
3d representation
3d information model
Project Time Span
2022-02 — 2022-06
Description
A case study of the reconstruction of the synagogue in Speyer to test the possibility of saturating the 3D model with scientific information in modeling programs and the preservation of this information during export to various file formats. The most popular 3D modeling software in the field of digital heritage (Blender, Maya, 3DS Max, Sketchup, Archicad, Rhino, Cinema4D, LightWave 3D, Revit, Allplan) listed in the following publications / research were selected for testing: "3D content in Europeana task force" , "Sketchfab Cultural Heritage User Survey 2019 Results", "3D Digitization in Cultural Heritage" by Emma Cieslik and "First Results of Community Survey" made as a part of 3D-DFG Viewer project.
Participant(s) (Organizations)
Name
Department of Architecture of the University of Bologna
VIAF ID
https://viaf.org/viaf/304306047
Website
https://phd.unibo.it/architettura/en
Role
Conceptor
Native File
20220526_speyer synagogue.skp

Documentation
documentation_template_01_modifiche_3.docx
documentation_template_02_1.docx
Viewer File Name
https://3d-repository.hs-mainz.de/sites/default/files/2022-05/20220526_speyer_synagogue_ZIP/gltf/20220526_speyer_synagogue.glb

Linked data technologies: URI, RDF, RDFS, OWL, ontologies, SPARQL
Four rules (or good practices) to follow in order to arrive to linked data have been identified (Chandler and Polkinghorne 2016):

(1) Use URI to identify objects;
(2) Use http URI so that the objects can be identified by humans and machines;
(3) Provide useful information about the object by using standards such as RDF (Resource Description Framework, it gives semantic structure);
(4) Include links to other URIs.

The URI identifies univocally a source, for example a name, expressed in a recognisable way.

At the following level we find XML to give structure to data and RDF to define the syntax.

These file formats support the higher level of the language to establish a non-arbitrary meaning (RDFS and OWL), the language to query data (SPARQL) and the exchange rules on the web (RIF).

This leads to a unifying logic, where new knowledge can derive from information. It can be used as a proof, being it a standard to represent evidence, based on concepts such as credibility and reliability.

1. some acronyms explained:

URI: Uniform Resource Identifier

URN: Uniform Resource Name, it can be used to create URIs.

URL: Uniform Resource Locator, it can be used to create URIs.

IRI: Internationalised Resource Identifier, it also used non-ASCII characters.

OWL: Ontology Web Language, recommended by W3C.

2.

To add syntax and semantics, we use RDF and XML.

XML format gives the structure, whereas RDF is a syntax based on triples. A triple is an oriented graph with subject, predicate, object.

A source is everything that can be described with RDF: a web page, a person, a work, a city, an animal, an event... It can be described by attributing it an URI.

In order to translate a database into graph of this kind, we need serialisation, that is the use of specific computer languages such as RDF/XML, TURTLE, N-TRIPLES, JSON_LD. The last one is the most popular, but none of these is the "best" language: it depends on what we need.

RDFS (where "s" stands for "schema") is necessary to give a meaning to the triple: it is a way to restrict the domain and range of a relation (for example, only a field "author" can be associated to a field "work of art" through a relation "is the author of").

Thus, it is a group of classes and properties to express restrictions on associations of terms and avoid statements that could be syntactically correct, but meaningless.

A *domain* limits the application of properties to individuals of one or more classes.

A *range* limits the application on the basis of what is allowed by the domain.

RDF and RDFS still have expressiveness limits: for the principles of the semantic web, sophisticated programs should reason on data, thus we need a technological infrastructure.

OWL and the ontologies are tools of semantic disambiguation: that means that objects should be univocally identifiable and software agents should recognize and associate them. The ontologies should be public and shared between users.

Ontologies are controlled vocabularies that describe in shared, formal, explicit way a given knowledge domain. They are an «explicit specification of a conceptualisation» (Gruber), they «define basic terms and relationships» (Neches), «terms of domain structured in a hierarchical way» (Swartout). The role is to give explicit meaning to the concept avoiding the arbitrary attribution of meaning so that software agents can be helped in the creation of new relationships.

OWL provides constructs: classes (instances with homogeneous features) and properties (relations to describe a source). Object property is a relationship between classes; datatype property is between classes and literal.

The ontology somehow remains a subjective property that depends on our point of view: when we create an ontology, we have to create a reference document to understand classes, properties, rules of domain.

FOAF (friend of a friend) is one of the most used vocabularies. It is an ontology that describes people, relationships between people, information about people.

We can search reference documents online. They are readable by people and the authorised connections.

If a class has particular properties, these can be applied also to sub-classes.

The aim of the semantic web is the dissemination and creation of new knowledge, also allowing the reuse and/or adaptation of vocabularies and ontologies, always keeping in mind the open world assumption: information which is not true is not false, but unknown.

Thanks to ontologies, we can generate inference and combine information to create new knowledge (for example, if two people have the same parents, they are – by inference – brothers or sisters).

SPARQL (Protocol and RDF query language) is an interrogation language to explore information in RDF graphs and extract knowledge bases distributed on the web.

The representation of the query is based on triple and graph. They are always unambiguous identifiers. The triples are conserved in a database (triple store) through endpoint SPARQL. There is a box where an interrogation can be written.

Best practices ("Data on the web best practices, W3C recommendations", 31.01.2017):

(1) Use standards
(2) Use stable URIs
(3) Provide information about licenses
(4) Produce machine-readable data
(5) Overlook local peculiarities (or declare them in the metadata)
(6) Reuse vocabularies
(7) Provide up-to-date information
(8) Specifically, the reuse of data facilitates consensus in a community
(9) Interoperability

(10) Reduction of redundancy
(11) Elimination of ambiguity

Before modelling a new ontology, it is a good practice to see if someone has already done it or, at least, connect the new ontology to the already existing (and more used) one. This operation can be useful if the main ontology is not so used and may no longer exist in the future. If our ontology has been connected to that one, it won't lose meaning.

Sometimes dates are in a "literal" field. But if at least the year were transformed in URI, we would be able to link facts happened during the same year.

Cultural heritage (archives, libraries, museums) is a field where semantic interoperability is (or should be) widely used, in order to integrate different *corpora* of information.

As a result, enrichment, decentralisation and more control will be obtained.

The advantages are:

(1) Processing: machine-readable information;
(2) Discoverability: exploring and discovering new information thanks to links;
(3) Reuse: reduction of duplicated data;
(4) Trust: institute that adopts LOD becomes a trustworthy source;
(5) Linkability: continuous enrichment through links;
(6) Accessibility: fragmentation allows the exploration from different access points;
(7) Interoperability: every system can process in an independent and decentralised way.

Linked open vocabularies (LOV) allow us to search for existing ontologies.

Here are some examples of ontologies and publication projects:

Europeana is an aggregator of sources. It doesn't directly produce contents. It was created in November 2008. It is a digital library with digitised contents. Partner institutions send metadata of digitised objects to widen the search function and access to objects through links. The providers independently manage the data and send them to the aggregator.

Data are explored based on thematic areas: art, archaeology,…

It uses EDM = Europeana Data Model. Some items are taken up from the Dublin Core. It ensures the interoperability between ontologies and used models.

Problems = very high abstraction, high granularity; the producers themselves should send data to Europeana in LOD format. At this moment, Europeana has to convert them. It would be more decentralised and controlled by producers.

The *Biblioteca Nacional de España* has formalised its model. It proposes a new approach to materials such as bibliographical data.

The search function links information of that website to external information, for example a biography from Wikipedia, declaring the source.

Data are serialised in Turtle format.

Culturalis.org (cultural institution and site ontology) and *IBC*: dataset to describe subjects producers of archives. Other linked sources are OCSA (ontology of cultural organisations, services and access 2.0), EAC_CPF (descriptions ontology for linked archival data), OAD (ontology of archival description).

Culturalis vocabulary specification: also with explanatory graphs. Developed in 2012 and used for many different projects. Updated in 2018 to separate the objects of the description and its instantiation, so that every object can be linked to multiple descriptions.

The ontology eac-cpf has also been updated in the same way.

Ontologies can be used and combined with one another.

Yale Center for British Art: their dataset is linkable to external ones.

They use CIDOC. They also provide a SPARQL endpoint. I can search a work of art and get the complete description.

Possibility to export data in RDF format, to see how they are written according to the CIDOC ontology.

They use IIIF technology = International Image Interoperability

Framework. Different software applications that allow an easy dialogue between images.

The example of CIDOC CRM

CIDOC = conceptual model of the International Committee for Documentation starting from 1990. ISO standard in 2006, updated in 2014.

It is the wider ontology for cultural heritage. Widely disseminated for a thematic conceptualisation.

Exchange of information between heterogeneous sources.

All-encompassing, but, on the other hand, it loses expressiveness.

To describe all the domain of cultural heritage, I have to make use of abstraction.

It depends on the desired level of detail.

The attempt to keep everything together is a failure, but, thanks to LOD, I can refer to a higher model (for example CIDOC) and then describe local peculiarities with other ontologies.

The LOD lifecycle: from raw data to publication

Raw data and analysis > ontology (reuse and/or new) > data cleaning, production, publication (SPARQL), data cleaning, adaptation and interlinking

Raw data and analysis

Identify the domain that I want to describe

Identify the entities that are part of it

Analysis: which data do I have?

Analysis of the sources of origin

Ontology

Understand what I have (what I can reuse) and what I have to create: discussion with the domain expert

Concepts to represent

Assessment of the ontology

Useful tools = LOV = Linked Open Vocabularies: the creator of an ontology communicates it and it is published there. I can find all the classes and properties with a given prefix, with descriptions, comments, relationships.

Modelling choices: reuse (interoperability, discoverability, consensus), customisation (expressiveness, analyticity, independence).

A balance between the two approaches is recommended.

Production: how do I create URIs?

AGID guidelines = http://[domain]/[type]/[concept]/[reference_number]

Input can be an Excel table, a text file, an XML, an Access file

Transformation: rules are applied to translate documents, but they are not fixed

Output in RDF, N-triples, Turtle…

Publication

Triplestore: database that preserves the triples.

Endpoint SPARQL. In a default query, the command "select" defines which information is asked, "limit" limits the number of results, "where" defines a criterion of selection by specifying one or more triple patterns.

Adaptation and interlinking: it enhances the reuse of data.

C.
APPENDIX 3. SPEYER SYNAGOGUE RECONSTRUCTION: HANDOUT

TECHNIK
HOCHSCHULE MAINZ
UNIVERSITY OF
APPLIED SCIENCES

Handout for source-based 3D reconstruction of former synagogue in Speyer in 1250

Igor Bajena, Irene Cazzaro, Piotr Kuroczyński

2022

Introduction

The handout presents the methodology developed for the case study of the reconstruction of the former synagogue in Speyer in 1250 AD within the research project “DFG-Viewer 3D – Infrastruktur für digitale 3D-Rekonstruktionen”[11] and is a topic of interest of the Arbeitsgruppe Digitale Rekonstruktion (AG Digitale Rekonstruktion)[12] . The aim of this paper is to test scientific approach for documentation and publication of the source-based digital reconstruction.

Methodology

The proposed methodology for the digital reconstruction treats the 3D model as the result of scientific work, where all the choices that have been made during the process are accurately documented. This allows the preservation of the information behind the model and its evaluation. The final publication in the online 3D repository is thus vital for sharing the results and giving access to the scientific content carried by the model.
The different steps of the proposed methodology will be explained in the next chapters. They mainly include:

- The identification of the object;
- The collection of sources;
- Their classification according to their nature (photos in the location, archaeological reports and texts directly related to the synagogue, analogies with other buildings…);
- The creation of the structure of the model (identification of the hierarchy of semantical elements);
- The modelling phase;
- The documentation of the reconstructed elements;
- The publication of the results.
-

Assumptions outline

The first step is to draw up an overview of the assumptions for the reconstruction model of the object. Prepared description should

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11 <http://dfg-viewer.de/> (accessed 04.11.2024).
12 <https://digitale-rekonstruktion.info/> (accessed 04.11.2024).

contains information about objects name, location, function and presents the object during the phase, which will be reconstructed. It should also cover the outline of the requirements, scope of development or level of detail applied to the 3D model. A good starting point for object description may be to check websites such as Wikipedia[13] or Wikidata[14].
Description made by Irene Cazzaro for the Speyer Synagogue in 1250 AD is as follows:
"The object of concern is the medieval synagogue of Speyer (in today's Germany), whose remains are still visible at the Judenhof, near the Speyer Cathedral. It is one of the best-preserved synagogues of the 12th century in Europe. Consecrated in 1104, the Romanesque building was then restored approximately in 1200 – again in Romanesque style – after a fire. In the second half of the 13th century it was renovated in Gothic style and a women's synagogue was built attached to it. The synagogue was the centre of the Jewish life until the 16th century, when, after several persecutions, only a few Jews still lived in Speyer. Our digital reconstruction takes into account the synagogue in 1250, thus during the second Romanesque construction phase. Some remains dating back to that time are still visible: the external walls, for instance, are still partially standing and in the western facade we can see two windows that are copies of the original Romanesque ones preserved in the Judenhof museum. It is assumed that at that time the walls, according to some small traces found on them, were covered with plaster. A portal was situated on the northern wall, whereas on the eastern wall the remains of an arch – part of the Aron Hakodesh – are still visible. There are no traces of the roof."
Outline of requirements for the same model made by Igor Bajena is as follows:
"The building should be placed in the middle of a flat fragment of terrain with dimensions of 25 x 25 m and a depth of 3.0 m and the depth of the foundations should be about 1.5 m. Some elements of interior equipment are excluded from the study. Modellers were

13 <https://www.wikipedia.org/> (accessed 04.11.2024).
14 <https://www.wikidata.org/> (accessed 04.11.2024).

required to model an ideal version of the building, where geometry is based on the right angle, without any deformation. The main objective was to test the methodology and technical solutions rather than to imitate the illusion of realism."

The description should also consider the purpose of the model and what information it provides. It is also important to include characteristic information about the model, especially in the case when the same topic is reconstructed in several versions by different people.

Sources collection

Sources collection is fundamental for digital reconstruction. It can consist of many steps and can often evolve during the process enriching our reconstruction with new findings. Activities in this stage include photographic documentation of the location, visits to museums dedicated to the subject of reconstruction, searching for plans in archives, collecting articles, books and archaeological findings, and trying to find analogies, which can fill in the gaps caused by the lack of sources regarding particular elements of the building.

Other reconstruction projects carried out on the same object can also be an important element of the process. However, reconstruction projects are always marked by a certain level of hypothesis (uncertainty) and they should not be considered as the main source of the new research – rather they should be used to test new hypotheses. The assumptions made at the start of each project can affect its level of detail and development. This can mean that the same building, when reconstructed in different projects and with different constraints, can look very different.

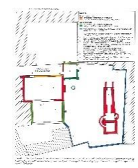
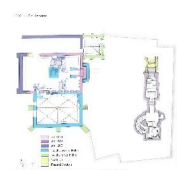
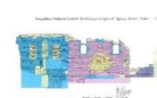
Photos

In the case of the synagogue reconstruction project, it was possible to successfully locate and prepare photographic documentation of both the remains of the building and the exhibits of the local museum (**FIG. 144**). A map with the location of each image has been prepared to make it easier for modellers to use the photographic resources (**FIG. 145**).

List of sources

The list has been elaborated during the SpSya_1250 project, together with Igor Bajena and under the supervision of Piotr Kuroczyński.

Archaeological reports

Provenance	Name of the file	Description	Preview
-	report_text.pdf	The entire text reports on the archaeological excavations carried out between 3 March and 22 June 2001 on the ruins of the medieval synagogue in Speyer by Monika Porsche.	
Archäologische Grabung 5. März 2001 – 22. Juni 2001 in der Ruine der mittelalterlichen Synagoge zu Speyer Abschlussbericht. Porsche, Monika.	report_drawing_01.jpg	Johannes Becker, Description of St. Free Roman Empire city of Speyer together with the four suburbs in 1773 [StA SP 1 aA nr, 895/1] Entry of names and dimensions in the cadastre on a scale 1:200 circumscription M. Porsche	
Information table on the site of the remains of the synagogue in Speyer	report_drawing_02.jpg	Plan of the synagogue distinguishing the different historical phases of the building by Monika Porsche and Pia Herber	
"Das mittelalterliche jüdische Erbe von Erfurt - Forschung und Vermittlung" Sczech, Karin, Stürzebecher, Maria. (2013) - In: Die SchUM-Gemeinden Speyer, Worms, Mainz S. 377-392	report_drawing_03.jpg	Drawing illustrating different construction phases of the building on the plan of the synagogue	
Archäologische Grabung 5. März 2001 – 22. Juni 2001 in der Ruine der mittelalterlichen Synagoge zu Speyer Abschlussbericht. Porsche, Monika.	report_drawing_04.jpg	Plan of the Synagogue in Speyer with	
"Das mittelalterliche jüdische Erbe von Erfurt - Forschung und Vermittlung" Sczech, Karin, Stürzebecher, Maria. (2013) - In: Die SchUM-Gemeinden Speyer, Worms, Mainz S. 377-392	report_drawing_05.jpg	Drawing illustrating different construction phases of the building on the elevation of the synagogue	

Photographs

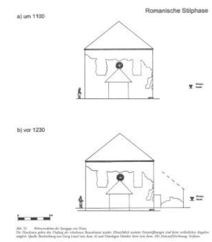
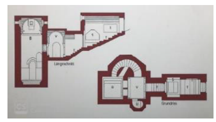
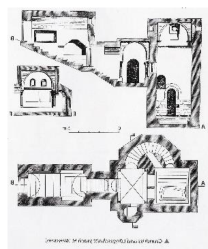
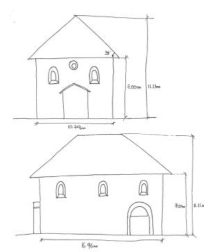
Author	Provenance	Date	Name of the file	Description	Preview
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_01.jpg	General view of the synagogue from North	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_02.jpg	General view of the synagogue from North	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_03.jpg	Synagogue – part of the external surface of the northern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_04.jpg	Outer surface of the eastern wall of the synagogue (right) and the Frauenschul (left)	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_05.jpg	Synagogue - outer surface of the eastern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_06.jpg	Synagogue - inner surface of the northern wall	

Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_07.jpg	Synagogue - part of the inner surface of the northern and eastern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_08.jpg	Synagogue - inner surface of the western wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_09.jpg	Synagogue - inner surface of the western wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_10.jpg	Synagogue - detail of the inner surface of the western wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_11.jpg	Synagogue - inner surface of the eastern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_12.jpg	Synagogue - part of the inner surface of the northern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_13.jpg	Synagogue - inner surface of the northern wall	

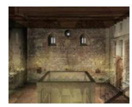
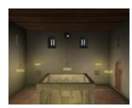
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_14.jpg	Synagogue - part of the inner surface of the southern wall (towards the Frauenschul)	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_15.jpg	Synagogue - part of the inner surface of the southern wall	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_16.jpg	Synagogue - part of the outer surface of the southern wall (from the Frauenschul)	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_17.jpg	Inner surface of the southern wall of the Frauenschul (left) and the synagogue (right)	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_18.jpg	Entrance to the Mikwa	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_19.jpg	Mikwa – detail of the vestibule	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_20.jpg	Mikwa - detail of the vestibule	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_21.jpg	Mikwa – shaft with basin from bottom to top	

Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_location_22.jpg	Mikwa – shaft with basin from bottom to top	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_museum_01.jpg	Physical remains of the western windows detached from the original structure of the synagogue and exposed in the museum.	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_museum_02.jpg	Description of the windows in "photo_museum_01"	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_museum_03.jpg	Floor tile from the Frauenschul	
Irene Cazzaro	Private collection of Irene Cazzaro	23.01.2022	photo_museum_04.jpg	Description of the three floor tiles from the Frauenschul exhibited in the museum ("photo_museum_03" is one of them)	

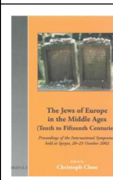
Drawings

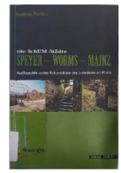
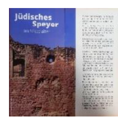
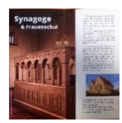
Author	Provenance	Date	Name of the file	Description	Preview
Christoph Engels	Engels, Christoph, "Gedanken zur Baugeschichte der mittelalterlichen Synagoge in Speyer", Pfälzer Heimat, 52 (2001), S. 61–72	2001	drawing_01.jpg	Sketches of the hypothetical reconstruction of the east elevation of the Synagogue in Speyer in 1100 and before 1230	
Based on the drawing by H. Weisstein, 1885	Panel found on the site	2022	drawing_02.jpeg	Section and plan of the Mikwe in Speyer	
Based on the drawing by H. Weisstein, 1885	Floss, Susanne, "Die Grabungen am Judenhof in Speyer 1965–1968: Die mittelalterlichen Befunde" (M.A. thesis, Universität Tübingen, 2005).	2005	drawing_03.jpeg	Section and plan of the Mikwe in Speyer	
Aliyah Mahmood	Archive of AI MAINZ. Sources used for the sketch are unknown!	2020	drawing_04.pdf	Sketch of the hypothetical reconstruction of the east and north elevation of the Synagogue in 1250 with dimensions	

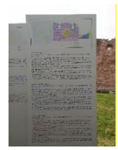
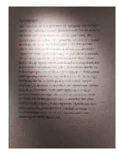
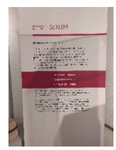
Reconstructions

Provenance	Source	Name of the file	Description	Date	Preview
"The medieval synagogue Speyer 3D computer reconstruction" by Architectura Virutalis with cooperation of the TU-Darmstadt	http://www.architectura-virtualis.de/rekonstruktion/synagogespeyer/pdf/2004_synagoge_speyer.pdf	reconstruction_01_flyer.pdf	Short presentation of the project "Die mittelalterliche Synagoge Speyer. 3D Computer Rekonstruktion".	2003	
	Private collection of Irene Cazzaro	reconstruction_01_rendering_01.jpg	Photo of the 2003 synagogue visualization banner in the building location	2003	
	http://www.architectura-virtualis.de/rekonstruktion/synagogespeyer.php?lang=de&img=0&file=0	reconstruction_01_rendering_02.jpg	Interior visualisation of the synagogue in the Romanesque phase – view 1	2003	
	http://www.architectura-virtualis.de/rekonstruktion/synagogespeyer.php?lang=de&img=9&file=7	reconstruction_01_rendering_03.jpg	Interior visualisation of the synagogue in the Romanesque phase with superimposition of a photograph of the current state of the building – view 2	2003	
	http://www.architectura-virtualis.de/rekonstruktion/synagogespeyer.php?lang=de&img=10&file=7	reconstruction_01_rendering_04.jpg	Interior visualisation of the synagogue in the Romanesque phase – view 2	2003	
	Uknown	reconstruction_01_rendering_05.jpg	Visualisations of the exterior of the synagogue in the Romanesque phase	2003	
Mainz – Worms – Speyer. Drei mittelalterliche Städte im Zentrum Europas als Linked Data	AI Mainz archive	reconstruction_02_model_01.pln	3D model of the synagogue reconstruction in Archicad format	2021	X
	23.01.2022	reconstruction_02_model_02.ifc	Model export to IFC format	2021	X
	23.01.2022	reconstruction_02_rendering_01.jpg	Screenshot of the synagogue model prepared for animation	2021	
	23.01.2022	reconstruction_02_rendering_02.jpg	Screenshot of the synagogue model prepared for 3D printing	2021	

Texts

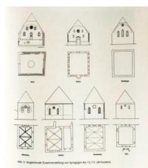
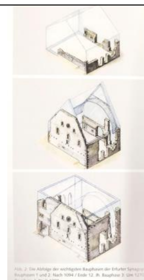
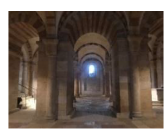
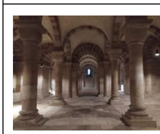
Author	Title	Publisher	Date	Name of the file	Preview
Pia Heberer	„... war gezieret an den getünchten Mauern mit Gemählden“: Die Synagoge in Speyer. In *Die jüdische Gemeinde von Erfurt und die SchUM-Gemeinden: Kulturelles Erbe und Vernetzung*	Bussert & Stadeler	2012	article_01.pdf	
Monika Porsche	Villa Spira – civitas: Zwei mittelalterliche Judensiedlungen in Speyer? In *Zeitschrift für die Gesichte des Oberrheins*		2003	article_02.pdf	
	„Jerusalem am Rhein - eine Zeitreise vom Mittelalter bis heute“: Handreichung zur Nutzung der Materialsammlung im schulischen Unterricht und für außerschulische Projekte	Schumstaedte.de guidelines	2019 or after	article_03.pdf	
Igal Aviden	Jüdische SchUM-Städte am Rhein: Speyer, Worms und Mainz sollen Weltkulturerbe werden. In *Kultur Neu Entdecken*	SWR2 Leben	31.01.2020	article_04.pdf	
Falk Nicol und Diethard Walter	Ausgrabung und präsentation eines Mittelalterlichen ritualbades in sondershausen. In *Synagogen, mikwen, siedlungen: Jüdisches alltagsleben im lichte Neuer archäologischer funde*	Schriften des Archäologischen Museums Frankfurt	2004	article_05.pdf	
Pia Heberer	Mittelalterliche Synagoge in Speyer: Forschung und Rekonstruktion. In *Europas Juden in Mittelalter*	Herausgeben vom Historischen Museum der Pfalz Speyer	2004	article_06.pdf	
Ursula Reuter	Jerusalem am Rhein: Die SchUM-Gemeinden Speyer, Worms und Mainz. In: *Beiträge zur rheinisch-jüdischen Geschichte*	Eine Schriftenreihe - Herausgegeben von der Gesellschaft zur Förderung eines Hauses und Museums der jüdischen Kultur in NRW e.V.	2013	book_01.pdf	
Ed: Christoph Cluse	The Jews of Europe in the Middle Ages (Tenth to Fifteenth Centuries) *Proceedings of the International Symposium held at Speyer, 20-25 October 2002*	Brepols Publishers n.v., Turnhout, Belgium	2004	book_02.pdf	

Eds.: Pia Heberer, Ursula Reuter	Die SchUM-Gemeinden Speyer – Worms – Mainz Auf dem Weg zum Welterbe	Schnell & Steiner	2013	book_03 (folder)	
Matthias Preißler	Die SchUM-Städte Speyer Worms Mainz: Ausflugsziele zu den Kulturstätten des Judentums am Rhein	Schnell & Steiner	2013	book_04 (folder)	
Georg Litzel	Description of the Speyer Synagogue		1759	description_01.jpg	
???	Die Ausstellung: SchUM am Rhein Von Mittelalter in die Moderne	Jüdisches Museum Worms Raschi-Haus	2021	flyer_01.pdf	
	Jüdisches in Speyer in Mittelalter	SchUM Museum Speyer		flyer_02.jpg	
	Synagoge & Frauenschul	SchUM Museum Speyer		flyer_03.jpg	
	Jewish life in medieval Speyer	SchUM Museum Speyer – at location of synagogue ruins		infoboard_01.jpg	
	The medieval “Jewish courtyard” and its buildings	SchUM Museum Speyer – at location of synagogue ruins		infoboard_02.jpg	

	The “Frauenschul” and other gothic transformations	SchUM Museum Speyer – at location of syangogue ruins		infoboard_03.jpg	
	The eastern wall of the synagogue	SchUM Museum Speyer – at location of syangogue ruins		infoboard_04.jpg	
	Eastern wall of woman’s prayer hall	SchUM Museum Speyer – at location of syangogue ruins		infoboard_05.jpg	
	Synagoge	SchUM Museum Speyer		infoboard_06.jpg	
	Ein Verbund von drei Gemeinden	SchUM Museum Speyer		infoboard_07.jpg	
	Die mittelalterliche Synagoge in Speyer	SchUM Museum Speyer		infoboard_08.jpg	
	The Jews in Speyer in middle ages; The synagogue; Double arched windows	SchUM Museum Speyer		museum_labels _01.jpg	
	Fragment of round arch; Cushion capital; Pillar base; Three floor tiles	SchUM Museum Speyer		museum_labels _02.jpg	

Analogies
Sources related to similar buildings

Object	Provenance	Name of the file	Description	Preview
Eastern portal of the Cathedral in Mainz (Germany)	https://www.1000-jahre-mainzer-dom.de/rundgang/ostbau.html	analogy_01_01.jpg	Upper part of the portal	
Eastern portal of the Cathedral in Mainz (Germany)	https://www.1000-jahre-mainzer-dom.de/rundgang/ostbau.html	analogy_01_02.jpg	Detail of column capitals	
Eastern portal of the Cathedral in Mainz (Germany)	https://www.1000-jahre-mainzer-dom.de/rundgang/ostbau.html	analogy_01_03.jpg	Picture of the entire eastern portal	
Eastern portal of the Cathedral in Mainz (Germany)	https://www.1000-jahre-mainzer-dom.de/rundgang/ostbau.html	analogy_01_description.txt	Description of the object from the source page in German	X
Portal of the St Mary's Church in Great Bradley (Great Britain)	https://greatbradley.weebly.com/romanesque-architecture.html	analogy_02_01.jpg	Picture of the entire portal	
Portal of the St Mary's Church in Great Bradley (Great Britain)	https://greatbradley.weebly.com/romanesque-architecture.html	analogy_02_02.jpg	Detail of portal column base	
Portal of the St Mary's Church in Great Bradley (Great Britain)	https://greatbradley.weebly.com/romanesque-architecture.html	analogy_02_03.jpg	Detail of column capital	

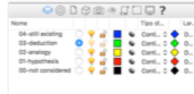
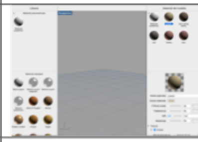
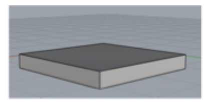
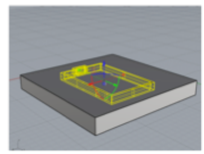
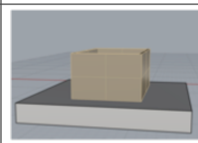
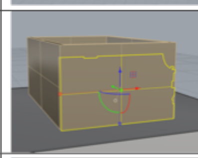
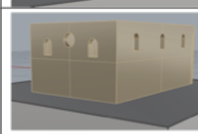
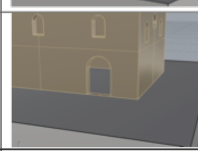
Portal of the St Mary's Church in Great Bradley (Great Britain)	https://greatbradley.weebly.com/romanesque-architecture.html	analogy_02_04.jpg	Detail of column capital on the other side of the portal	
Portal of the St Mary's Church in Great Bradley (Great Britain)	https://greatbradley.weebly.com/romanesque-architecture.html	analogy_02_description.txt	Description of the object from the source page in English	X
Portal of the Worms Synagogue (Germany)	„Perspektive Welterbe SchUM: Ein Managementplan für Speyer, Worms, Mainz - Bestandsaufnahme und Desiderate" Heberer, Pia. (2013) In: Die SchUM-Gemeinden Speyer, Worms, Mainz S. 393-446	analogy_03.jpg	Historical photo of the portal of the Worms Synagogue in 1959/61	
Synagogues in Erfurt, Rufach, Nördlingen, Miltenberg, Maribor, Korneuburg, Tulln (Germany)	„Diaspora-Architektur: Synagogen im Kontext mittelalterlicher Städte" Untermann, Matthias. (2013) - In: Die SchUM-Gemeinden Speyer, Worms, Mainz S. 283-296	analogy_04.jpg	Sketches of plans for medieval German synagogues from the late 12th and early 13th centuries. Particularly noteworthy is the shape of the roof, for which no sources are available for the Synagogue in Speyer	
Walls of the Erfurt Synagogue (Germany)	„Diaspora-Architektur: Synagogen im Kontext mittelalterlicher Städte" Untermann, Matthias. (2013) - In: Die SchUM-Gemeinden Speyer, Worms, Mainz S. 283-296	analogy_05.jpg	Sketches showing the reconstruction of the missing elements of the synagogue's masonry structure based on deduction	
Crypt of the Speyer cathedral (Germany)	Private photos taken by Irene Cazzaro	analogy_06_01.jpg	The synagogue (topic of reconstruction) and the cathedral were built at the same time and by the same craftsmen. It means that we can use some of the elements of the cathedral to the reconstruction of the synagogue.	
Crypt of the Speyer cathedral (Germany)	Private photos taken by Irene Cazzaro	analogy_06_02.jpg		
Crypt of the Speyer cathedral (Germany)	Private photos taken by Irene Cazzaro	analogy_06_03.jpg		

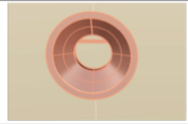
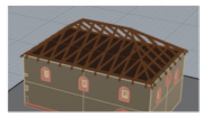
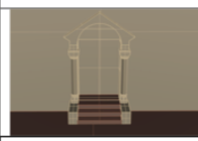
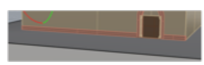
D.
APPENDIX 4. SPEYER SYNAGOGUE RECONSTRUCTION: WORKFLOW

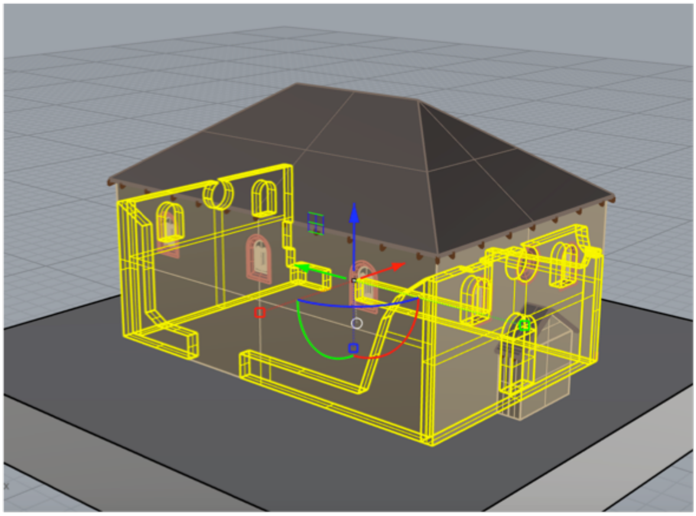
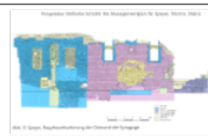
In the following pages are the documentation tables related to the reconstruction process applied to the Speyer synagogue (and, after that, to the other examples mentioned above).

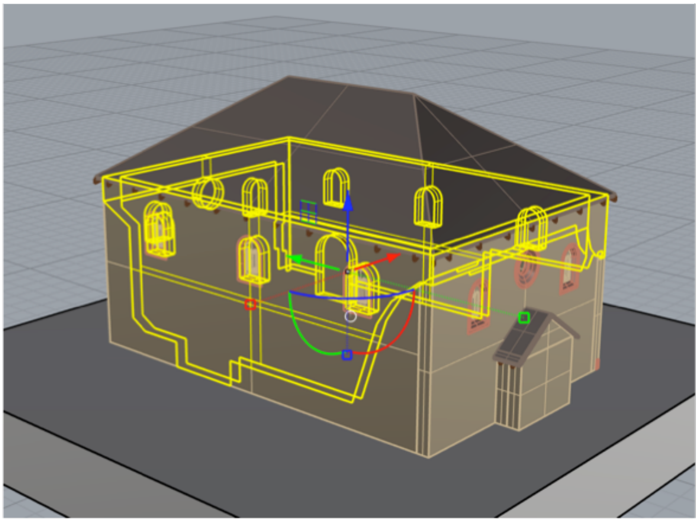
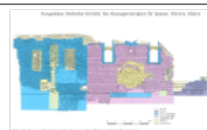
The first table traces the workflow that led to the creation of the model in Rhinoceros step by step; the other tables – one for each element as defined in the initial segmentation of the building – explain how each element has been reconstructed based on the available sources and their uncertainty level.

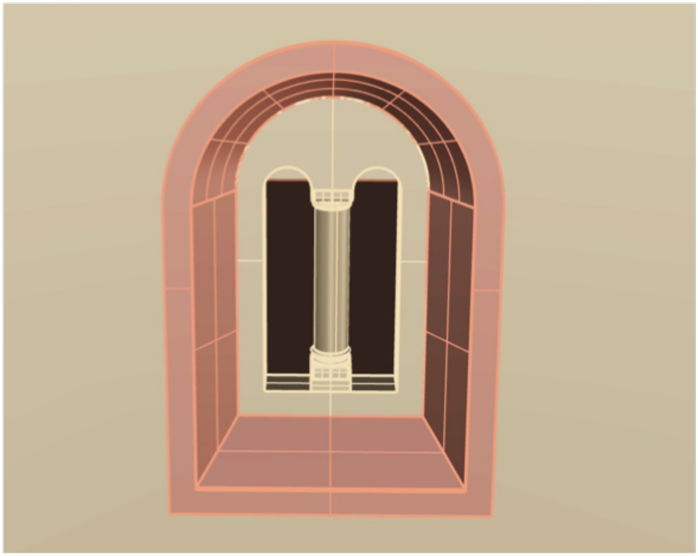
Workflow in *Rhinoceros*

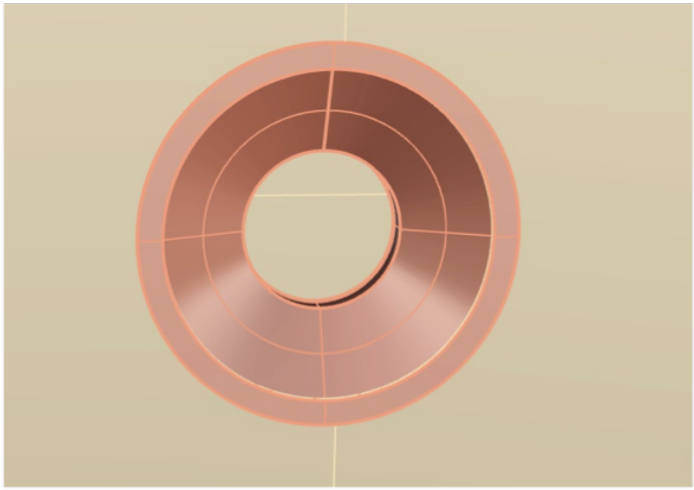
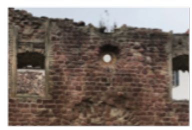
Creation of ***layers*** *for uncertainty visualisation: "04-still existing" (blue); "03-deduction" (green); "02-analogy" (yellow); "01-hypothesis" (red); "00-not considered (black)*	
Creation of ***object materials*** *and related visualisation* ***colours*** *according to the handout. The materials have been called "plaster" (texture_01); "frames" (texture_02); "floor" (texture_03); "door ceiling beams" (texture_04); "roof" (texture_05).*	
Basement *Obtained by extrusion (3 m) of a 25x25 m square* *Object name: "basement"* *Layer: "00-not considered"; colour: "by layer" (black); material: not defined.*	
Foundations *Obtained by extrusion of the related surface as in "report_03.jpg"* *Object name: "foundations"* *Layer: "04-still existing"; colour and material according to texture_01*	
Perimeter walls *Obtained by extrusion of the related surface* *Object name: "wall_2"* *Layer: "03-deduction"; colour and material according to texture_01*	
Subdivision of the eastern façade *Obtained by cutting "wall_2" according to the information in "report_05.jpg"* *Object name: "wall_1"* *Layer: "04-still existing"; colour and material according to texture_01*	
Holes for windows *Obtained by Boolean difference*	
Hole for portal *Obtained by Boolean difference*	
Floor *Obtained by extrusion of the area inside the perimeter walls.* *Object name: "floor"* *Layer: "01-hypothesis"* *Colour and material according to texture_03*	
"Bifora" windows *Obtained by extrusion and by rotation (columns)* *Frames obtained by extrusion and loft* *Object name: "window_1"* *Layer: "04-still existing" for those in the western façade; "03-deduction" for the other ones; colour and material according to texture_01 for the internal part and texture_02 for the frames*	

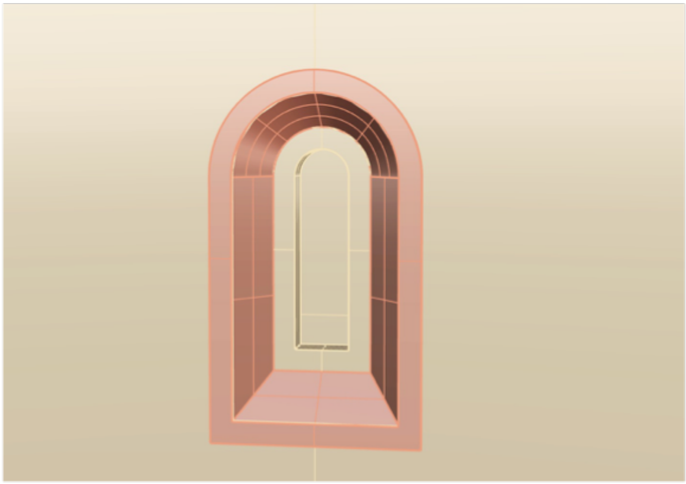
Circular windows *Frame obtained by extrusion and loft around the circular hole* *Object name: "window_2"* *Layer: "03-deduction"; colour and material according to texture_02*	
Arch windows *Obtained by extrusion* *Frames obtained by extrusion and loft* *Object name: "window_3"* *Layer: "01-hpothesis", colour and material according to texture_01 for the internal part and texture_02 for the frames*	
Portal *Some details are still needed. Mainly obtained by extrusion.* *Object name: "portal".* *Layer: "02-analogy"* *Colour and material according to texture_02 for the frames, texture_01 for columns and semi-circular wall above the door, texture_04 for the door*	
Beams *Obtained by drawing the rectangular section, extruding it for all the length of the beam that was then copied many times (some are horizontal, for the others the angle is 35°; the length varies according to the construction scheme)* *Object name: "beams"* *Layer: "01-hypothesis"; colour and material according to texture_04*	
Roof *Four surfaces with a 35° angle were created above the beams, then they were extruded* *Object name: "roof"* *Layer: "01-hypothesis"; colour and material according to texture_05*	
Aron Hakodesh – exterior *The walls were extruded according to the foundation. The roof follows the traces of the arch on the eastern façade.* *Object name: "aron hakodesh_exterior"* *Layer: "02-analogy"; colour and material according to texture_01 for the wall, texture_04 for the beams and texture_05 for the roof*	
Aron Hakodesh *Basement, stairs and upper part modelled by extrusion, columns by rotation.* *Layer: "02-analogy", colour and material according to texture_01 apart from the stairs, for which texture_03 is used*	
Plinth *Obtained by extrusion of a part of the wall.* *Layer: "03-deduction"* *Colour and material according to texture_02*	
Cornice *Obtained by extrusion of a part of the wall.* *Layer: "03-deduction"* *Colour and material according to texture_02*	

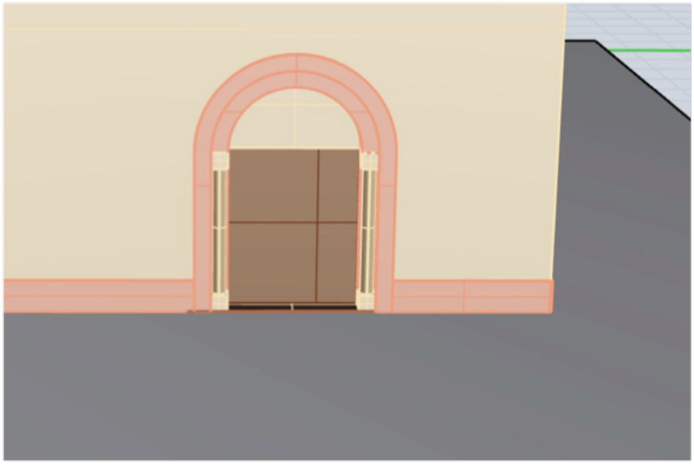
Wall type 1		
Reconstructed object		
Used sources	*report_05.jpg*	
	photo_location_01.jpg	
Argumentation and evaluation of the uncertainty	*This is the part of the wall that we can still see*	*04-still existing*

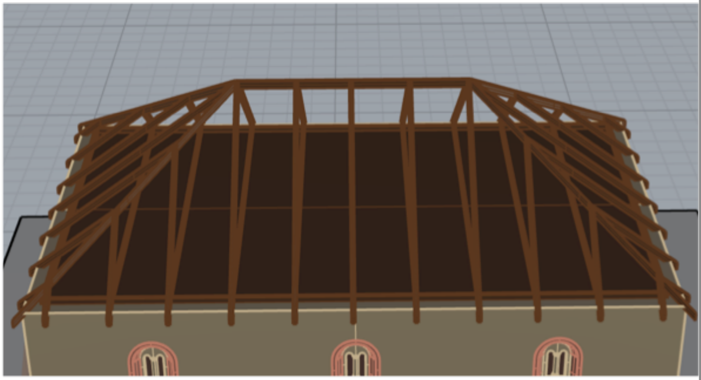
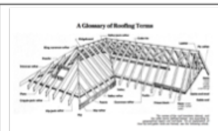
Wall type 2		
Reconstruction		
Used sources	report_05.jpg	
	photo_location_01.jpg	
Uncertainty	This part of the wall was reconstructed by deduction, assuming that it was similar to the still existing part	03-deduction

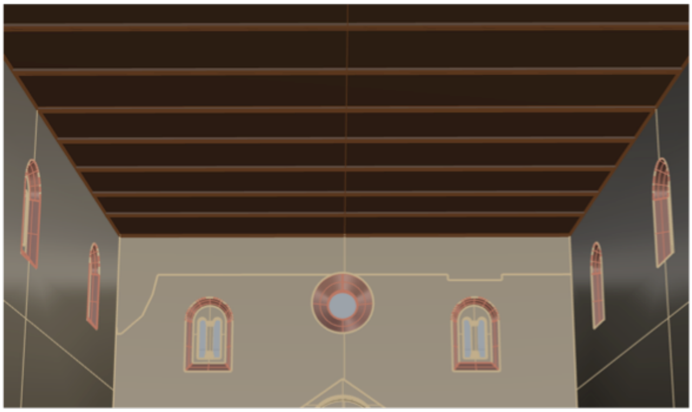
Window type 1		
Reconstruction		
Used sources	*photo_location_04.jpg*	
	photo_museum_02.jpg	
Uncertainty	*The windows on the western façade are copies of the original ones preserved in the Judenhof museum, thus in that case the uncertainty level is "04-still existing". It is assumed that the other windows were similar and can be reconstructed by deduction.*	***04-still existing*** *for those on the western façade;* ***03-deduction*** *for the other ones*

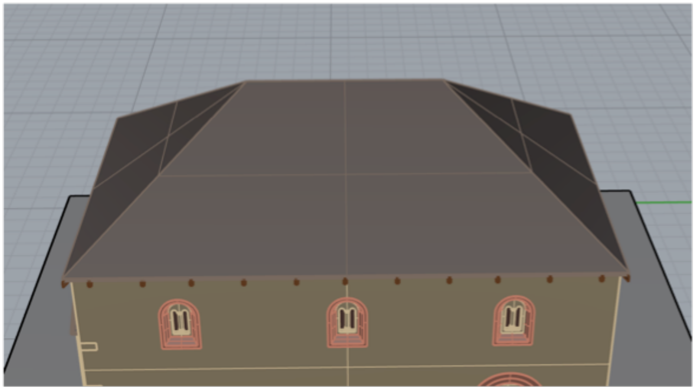
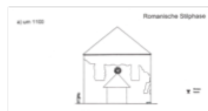
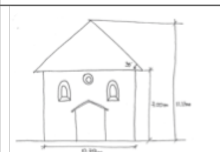
Window type 2		
Reconstruction		
Used sources	*photo_location_01.jpg*	
	photo_location_04.jpg	
Uncertainty	*We can see the complete circular hole in the still existing part of the wall*	*04-still existing*

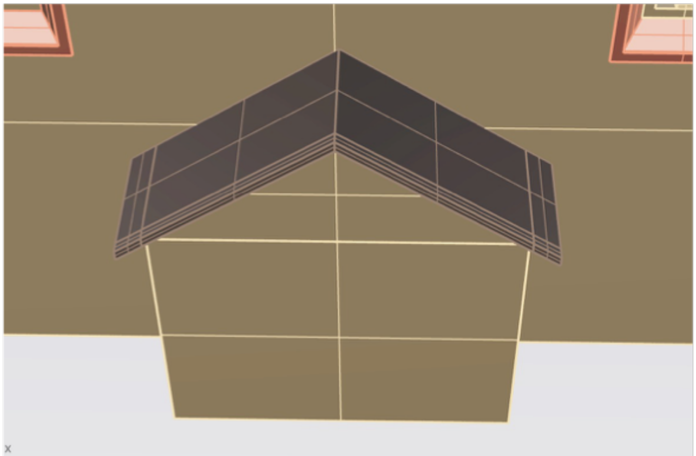
Window type 3		
Reconstruction		
Used sources	*reconstruction_01_rendering_02.jpg*	
	reconstruction_01_rendering_05.jpg	
Uncertainty	*We know nothing about the windows on the northern and southern façade, but there must be some source of natural light, maybe smaller than on the other walls.*	***01-hypothesis***

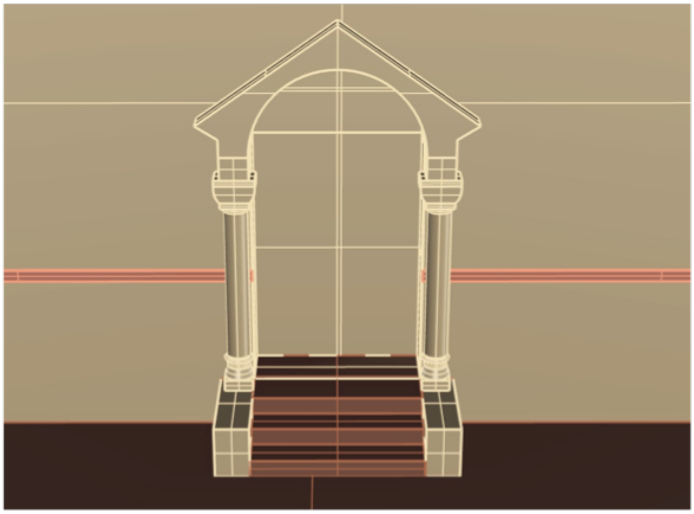
Portal		
Reconstruction		
Used sources	*analogy_02_01.jpg*	
	analogy_03.png	
Uncertainty	*We do not have traces of the portal of the Speyer synagogue, but we can reconstruct it by analogy e.g. with the portal of the medieval synagogue in Worms*	*03-analogy*

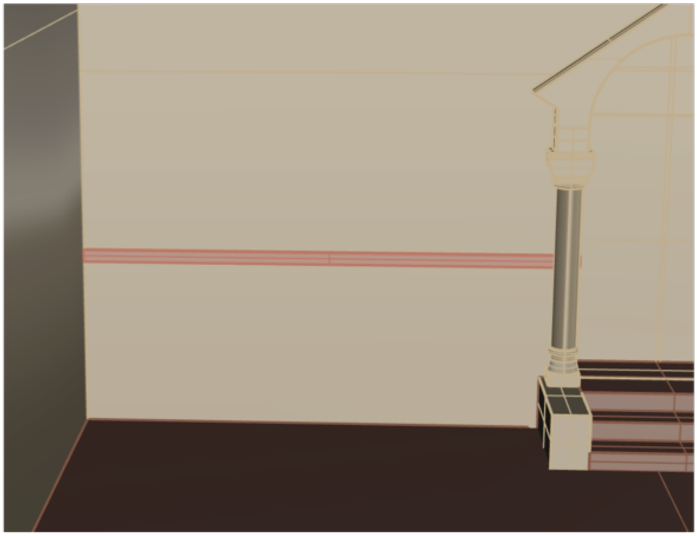
Beams		
Reconstruction		
Used sources	*https://s3.amazonaws.com/finehomebuilding.s3.tauntoncloud.com/app/uploads/1982/09/29111349/roof-framing-terms.jpg (accessed April 4th, 2022)*	
	reconstruction_01_rendering_03.jpg	
Uncertainty	*We know nothing about the structure of the roof*	***01-hypothesis***

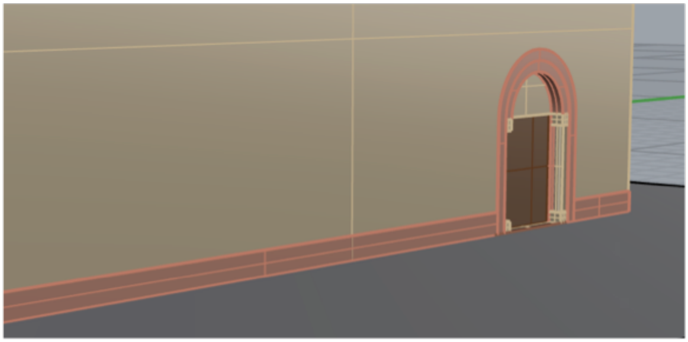
Ceiling		
Reconstruction		
Used sources	*reconstruction_01_rendering_02.png*	
Uncertainty	*We know nothing about the structure of the roof*	***01-hypothesis***

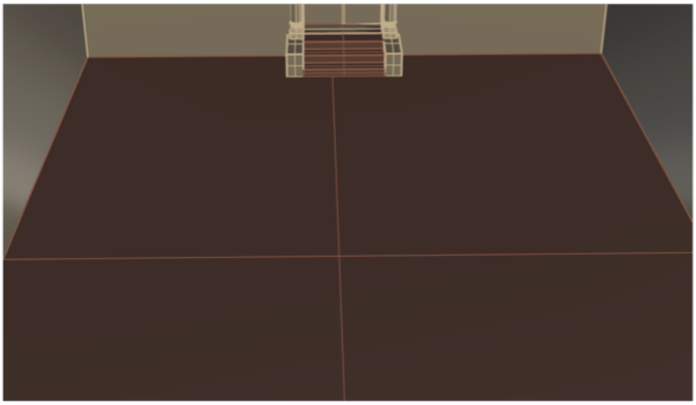
Roof type 1		
Reconstruction		
Used sources	*drawing_01.jpg*	
	drawing_04.jpg	
Uncertainty	*We know nothing about the structure of the roof*	***01-hypothesis***

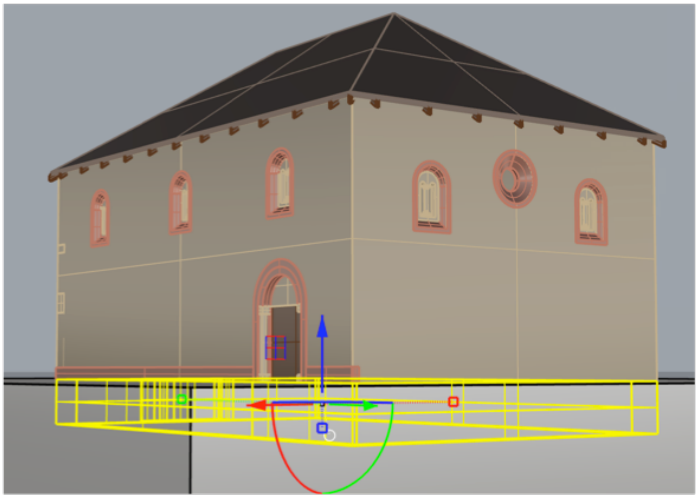
Roof type 2		
Reconstruction		
Used sources	*reconstruction_01_rendering_05.jpg*	 
Uncertainty	*We know nothing about the structure of the roof. The simplest thing to assume is that the slope of the roof is the same as the upper part of the Aron Hakodesh (this can be seen in the interior). The material is assumed to be the same as the main roof.*	*01-hypothesis*

Aron Hakodesh		
Reconstruction		
Used sources	*reconstruction_01_rendering_02.png*	
	Personal archive of Irene Cazzaro, who can make it accessible if required	
Uncertainty	*It was modelled based on similar examples of the same historical period.*	*03-analogy*

Cornice		
Reconstruction		
Used sources	*Personal archive of Irene Cazzaro, who can make it accessible if required*	
Uncertainty	*There are clear traces of it in the internal part of the wall*	*04-still existing*

Plinth		
Reconstruction		
Used sources	*reconstruction_01_rendering_01.jpg*	
Uncertainty	*There are some traces of the plinth, but they have to be mentally completed*	***03-deduction***

Floor		
Reconstruction		
Used sources	*reconstruction_01_rendering_02.png*	
Uncertainty	*There are no traces of the ancient floor*	***01-hypothesis***

Foundations		
Reconstruction		
Used sources	*report_05.jpg*	
Uncertainty	*The foundations are still there and they were analysed during the archaeological excavations*	*04-still existing*

acknowledgements

I would like to thank, first of all, the supervisor and co-supervisor of this work, respectively prof. Fabrizio Ivan Apollonio from University of Bologna and prof. Piotr Kuroczyński from Hochschule Mainz, for all the great advice and opportunities they gave me.

The research group of prof. Apollonio, with prof. Federico Fallavollita and Riccardo Foschi, was extremely important especially for the studies related to uncertainty in digital 3D reconstructions and for the elaboration of a hopefully shared uncertainty scale.

Prof. Kuroczyński hosted me at Hochschule Mainz for six months, where I had the opportunity of developing my thesis, also working on the project SpSya1250, concerning the reconstruction of the second Romanesque phase of the medieval synagogue in Speyer.

On that occasion, we set up a handout with a workflow that can be potentially applied (and has already been applied) to other reconstructions. This document, which is part of the study here presented, was also produced with the significant contribution of Igor Bajena, PhD student at University of Bologna, with whom I have largely – and with great pleasure – cooperated during these years. Stefan Wetherington, a talented student of HS Mainz, has also contributed to the SpSya1250 project. Sebastian Zanke, curator and member of the scientific committee of the Historisches Museum der Pfalz in Speyer, was determinant in the collection of documentation about the synagogue. Daniel Dworak, the IT expert who is developing the DFG repository, has been of great help not only in defining the procedures for uploading the models and data about them, but also in prefiguring the next steps of this project.

The members of the DFG group “Digitale Rekonstruktion” and of the CoVHer project were undoubtedly important for defining the topics of interest presented in this work and following the related international debate.

Finally, I would like to thank all the people who have been close to me during these years.

list of figures

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CHAPTER OPENERS

FIGURES

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. Elaboration by Irene Cazzaro based on <https://math.stackexchange.com/questions/619311/abductive-vs-inductive-reasoning>.

FIG. 2 Categories in which the terms related to a critique of source-based 3D digital models can be grouped. Visualisation by Irene Cazzaro.

FIG. 3 Connections between terms related to a critique of source-based 3D digital models from 1994 to 2019. Visualisation by Irene Cazzaro.

FIG. 4 Evolution in the definitions of terms related to the concept of „cultural heritage“. Visualisation by Irene Cazzaro.

FIG. 5 Evolution in the definitions of the term "authenticity". Visualisation by Irene Cazzaro.

FIG. 6 Evolution in the definitions of the term "uncertainty". Visualisation by Irene Cazzaro.

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. Visualisation by Irene Cazzaro.

FIG. 8 Workflow for reality- and source-based 3D digital models (visualisation by Irene Cazzaro 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.

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).

FIG. 10 An example of "uncertainty" evaluation based on fuzzy logic (Niccolucci and Hermon 2004). For each element in which the model is segmented, a calculation of fuzziness is performed by means of coefficients according to fuzziness diagrams such as the one shown here in the bottom right. For some elements, the creation of more variants may be necessary. Courtesy of the authors.

FIG. 11 An example of extended matrix in which, to the stratigraphic units found on site, some virtual stratigraphic units are added according to deductions and analogies. In the diagrams, they correspond to the cells with black background (Demetrescu 2018). Courtesy of the author.

FIG. 12 Digital tools to assess the reliability of a hypothetical digital 3D reconstruction, retrieved from <http://3dvisa.cch.kcl.ac.uk/project6.html> (screen capture 20.10.2024).

FIG. 13 Documentation related to five different parts of the Kloster Altenberg, the last edited model in ScieDoc: <http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=24> (screen capture 16.10.2024). The "evaluation" field has been enlarged here for a better legibility.

FIG. 14 The approach that consists in visualising information through glyphs and icons especially derives from cartography (above), where it is particularly used to express quantity or flux (Bertin 1967). Below, we can see examples of glyphs specifically used to represent uncertainty (Pang, Wittenbrink, and Lodha 1996) regarding (from left to right): vector fields of winds and currents, line glyphs showing the gaps between two differently interpolated surfaces, line glyphs connecting particle positions along two streamlines calculated using different methods. Elaboration by Irene Cazzaro based on the above-mentioned publications.

FIG. 15 A simple monochromatic rendering can be an alternative to photorealism when textures are not available. This model represents the Traianeum in Pergamon, 200 AD (elaboration by Irene Cazzaro based on Lengyel and Toulouse 2016).

FIG. 16 "Diplomatic" visualisation method (Apollonio, Fallavollita, and Foschi 2021) according to which, rather than a photorealistic rendering or a neutral mono-material, the texture of the original drawing is used. Here on the top is a model of a square tomb developed starting from some drawings by Mauro Guidi (on the bottom) taken from Cesena Nuova, Atlante 41, Carta 48. Elaboration by Irene Cazzaro based on the above-mentioned paper, retrievable at <https://cris.unibo.it/handle/11585/847767> (open access from 11/01/2023).

FIG. 17 Variations in the line type to visualise uncertainty (Strothotte, Masuch, and Isenberg 1999). Courtesy of the authors.

FIG. 18 Use of wireframe to visualise the most uncertain parts (Kensek, Dodd, and Cipolla 2004). Courtesy of the authors.

FIG. 19 Use of scanlines to obtain textures with different levels of detail (Potter et al. 2007). Courtesy of the authors.

FIG. 20 Transparency variations: the more transparent, the more uncertain (Stefani 2010). Pilot project of the French national digitisation programme "3D monuments"led by the UMR 694 MAP laboratory: <http://www.gamsau.map.cnrs.fr/3D-monuments/projets/projet_sgdesert_presen-presen.php>. Courtesy of the author.

FIG. 21 Superimposition of a schematic render to the photorealistic one, with variations on transparency (Strothotte et al. 1999). Courtesy of the authors.

FIG. 22 Use of a cartoon effect to visualise uncertainty (Freudenberg et al. 2001). Courtesy of the authors.

FIG. 23 Variations in the level of detail (Heeb and Christen 2019). CC BY 4.0.

FIG. 24 Creation of sketches (Heeb and Christen 2019). CC BY 4.0.

FIG. 25 Colour-coded uncertainty levels (Kozan 2004). Courtesy of the author.

FIG. 26 RGB Colour mapping (Georgiou and Hermon 2011). Courtesy of the authors.

FIG. 27 The ten uncertainty levels in the project “Byzantium 1200”, 2011. Courtesy of the authors.

FIG. 28 Source-based colour scale applied to a drawing by Palladio (Apollonio, Gaiani, and Sun 2013). Courtesy of the authors.

FIG. 29 The five-level uncertainty scale for The Swedish Pompeii project (elaboration by Irene Cazzaro based on Dell’Unto et al. 2013).

FIG. 30 Probability map (Perlinska 2014). Courtesy of the author.

FIG. 31 Ten-level uncertainty scale (Resco and Figueiredo 2014). Courtesy of the authors.

FIG. 32 Comparison between a spectral and a non-spectral scale (Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018). Courtesy of the authors.

FIG. 33 Green-to-red qualitative uncertainty scale (Landes et al. 2019). Courtesy of the authors.

FIG. 34 Two different scales to visualise uncertainty (Grellert et al. 2019). Courtesy of the authors.

FIG. 35 Uncertainty scale allowing different granularity, here in the 7+1 variant, applied to the Villa Pisani in Bagnolo by Andrea Palladio (Apollonio, Fallavollita, and Foschi 2021). <https://cris.unibo.it/handle/11585/847767> (open access from 11/01/2023).

FIG. 36 Reconstruction of an archaeological site and superimposition of an uncertainty scale by Pablo Aparicio Resco. It is possible to switch between the two images by means of a slider. The uncertainty scale has been updated with respect to the 2014 one: instead of purple (a misleading colour), grey has been chosen. <https://parpatrimonioytecnologia.wordpress.com/2022/06/06/hacia-una-nueva-version-de-la-escala-de-evidencia-historico-arqueologica/> (screen capture 31.10.2024).

FIG. 37 Use of different points of view to highlight different features of the model (Heeb and Christen 2019). CC BY 4.0.

FIG. 38 Selection of variants of Egyptian columns through an interface that allows the combination of a base, eight shafts and four capitals (Kensek 2007). Courtesy of the author.

FIG. 39 Variants of the same tower according to different documentation (Heeb and Christen 2019). CC BY 4.0.

FIG. 40 Three examples among the many spectrograms used in scientific disciplines. On the left: the RF (radio frequency) spectrum of a battery charger over time; top right: spectrogram of an arterial blood pressure; bottom right: melodic range visualiser. <https://commons.wikimedia.org/wiki/File:3D_battery_charger_RF_spectrum_over_time.jpg> (PD); <https://www.researchgate.net/publication/301644768_Detecting_heart_rate_while_jogging_blind_source_separation_of_gait_and_heart-

beat>; (CC BY 4.0) <https://commons.wikimedia.org/wiki/File:Sonic_visualiser_melodic_range_spectrogram_example.jpg> (PD).

FIG. 41 Two heat maps visualising temperature variations. The larger one, using a scale from blue (cold) to red (hot), represents the different temperatures around the world; the smaller one, on bottom left, uses a lightness gradient to visualise on a matrix the different temperatures over a year in the same place. The months are given on the x-axis, the days on the y-axis. <https://commons.wikimedia.org/wiki/File:Average_Temperature_In_The_Southern_Rockies.png> (PD); <https://commons.wikimedia.org/wiki/File:World_heat_map. png> (PD).

FIG. 42 Historical heat maps in greyscale drawn by hand (Wilkinson and Friendly 2009) and the first results on Google Images (screen capture 10.01.2023) when typing “heat map”. We can see that now they usually follow the colours of the spectrogram or a reduced green-red scale. Elaboration by Irene Cazzaro.

FIG. 43 Explanation of hue, lightness and saturation as variation in wavelength. Elaboration by Irene Cazzaro based on <https://www.di.univr.it/documenti/OccorrenzaIns/matdid/matdid311142.pdf>.

FIG. 44 On the left: the visible spectrum of light according to Newton; on the right: the formation of intermediate colours. <https://commons.wikimedia.org/wiki/File:Newton%27s_color_circle.png> (PD); elaboration by Irene Cazzaro based on <http://hyperphysics.phy-astr.gsu.edu/hbase/vision/newtcol.html>.

FIG. 45 The Farbenkugel by Otto Runge (left) and the colour triangle by James Clerk Maxwell (right). <https://upload.wikimedia.org/wikipedia/commons/9/94/Runge_Farbenkugel.jpg> (PD); <https://upload.wikimedia.org/wikipedia/commons/4/42/Maxwell_color_Triangle_Luckiesh_1921.png> (PD).

FIG. 46 Goethe’s colour wheel with associated symbolic qualities, 1809. Source: <https://en.wikipedia.org/wiki/Theory_of_Colours#/media/File:Goethe,_Farbenkreis_zur_Symbolisierung_des_menschlichen_Geistes-_und_Seelenlebens,_1809.jpg> (PD).

FIG. 47 Light entering the eye and arriving to the retina, where it is processed by rods and cones. <https://askabiologist.asu.edu/rods-and-cones> (CC BY-NC-SA 3.0).

FIG. 48 Comparison between the colour spaces by Newton and Helmholtz. <https://opg.optica.org/josaa/fulltext.cfm?uri=josaa-34-7-1099&id=367369> OAPA - Copyright Transfer and Open Access Publishing Agreement.

FIG. 49 Psychological theory by Ewald Hering: here the oppositional colours discovered by Hering are positioned in a circle around the one adopted by Newton, so as to complement it. <https://commons.wikimedia.org/wiki/File:Ewald_hering_colors. jpg> (PD).

FIG. 50 The generation of colour oppositions according to Hering's theory. <https://doi.org/10.3390/su15054341> (CC BY 4.0).

FIG. 51 The stage theory: both the trichromatic theory and the opponent theory are incorporated at different levels (respectively receptor and neural stage). Elaboration by Irene Cazzaro based on <https://www.ncbi.nlm.nih.gov/books/NBK11538/figure/ch28kallcolor.F16/?report=objectonly>.

FIG. 52 The Munsell (left) and NCS (right) colour systems. <https://commons.wikimedia.org/wiki/File:Munsell_1943_color_solid_cylindrical_coordinates.png> (CC BY-SA 3.0); <https://commons.wikimedia.org/wiki/File:Animation_of_the_NCS_Colour_System.gif> (CC BY-SA 4.0).

FIG. 53 Comparison of some RGB and CMYK chromaticity gamuts on a CIE 1931 XY chromaticity diagram <https://en.wikipedia.org/wiki/Color_space#/media/File:CIE1931xy_gamut_comparison.svg> (PD).

FIG. 54 The stages of colour appearance in a culture according to Berlin and Kay (1969). Visualisation by Irene Cazzaro.

FIG. 55 Felix Thürlemann, identification of the four psychological primaries according to Hering's theory. Here they are arranged in a series that can be infinitely repeated (or closed in a circle). Coloration of the diagram that in the original paper was presented in black and white, with the names of the respective colours in each area (1982). Visualisation by Irene Cazzaro.

FIG. 56 Different graphical tools to add information to a map (elaboration by Irene Cazzaro based on Bertin 1967).

FIG. 57 Studies on visualisation styles and tools (Tufte 1990; 1997): above, two different colour scales have been applied to the same map to show how, in that case, the one with minor colour variation with respect to reality (on the left) works better and has become a standard in cartography; however, this is different from the use of false colours in 3D digital models. As we can see below, there are some fields in which a colour scale proves to be more effective, such as in the animation of this thunderstorm. This means that choosing a correct visualisation depends on the aim of our work. Courtesy of the author.

FIG. 58 Comparison between uncertainty scales used in different domains (mainly architecture and archaeology) with descriptions in different languages. Visualisation by Irene Cazzaro.

FIG. 59 Source-based uncertainty scale (Apollonio 2015). Courtesy of the author.

FIG. 60 Relationships between a source-based uncertainty scale and the operations done to reconstruct an element: interpretation, deduction, conjecture, etc. (Apollonio 2016). Courtesy of the author.

FIG. 61 left: Byzantium 1200 source-based scale of knowledge; right: Modification of the scale on the left by changing the colours and reducing the levels from 10 to 8. The scale is still source-based, with some adjustments in the description and order of the levels (Ortiz-Cordero, León Pastor, and Hidalgo Fernández 2018). Courtesy of the authors.

FIG. 62 Iconicity scale according to Moles (1971). From the representation with higher degree of similarity to the referent, we have: 3D representation, photography, illustration, scheme, pictogram, diagram, ideogram, word-image, onomatopoeia, arbitrary word, abstract symbol, unspoken symbol. Visualisation by Irene Cazzaro based on <https://visualdsgn.fr/degre-iconicite-representation-visuelle/>.

FIG. 63 Qualitative uncertainty scales: on the left, evaluation of reconstruction variants in Sciedoc; on the right, evaluation of overall, archaeological, comparative and documentary reliability (high, medium, low) in the 3DVisa platform. <http://www. sciedoc.org/>; <http://3dvisa.cch.kcl.ac.uk/project6.html>.

FIG. 64 The level of knowledge is expressed by a qualitative judgement (high, moderate, weak), but correlated to archaeological uncertainty through a description (Landes et al. 2019). Courtesy of the authors.

FIG. 65 Another example of correlation: the two scales used for defining the plausibility of the variants and the categorisation of the used sources (Grellert et al. 2019). Courtesy of the authors.

FIG. 66 This scale concerns the relationship between a source (no matter which kind) and a reconstruction element involving more or less objectivity, consistency, deduction, hypothesis (elaboration by Irene Cazzaro based on Dell'Unto et al. 2013).

FIG. 67 Here we can see as well the connection to the sources, but the stress is on the type of conjectures we do in analysing them (Apollonio, Fallavollita, and Foschi 2021). <https://cris.unibo.it/handle/11585/847767> (open access from 11/01/2023).

FIG. 68 Different granularity in the uncertainty scales proposed by Apollonio et al. (2021), see the link in the previous caption. In the scale with 5 levels, the 3-4 and 5-6 are collapsed (differentiating the authors of indirect sources is no longer relevant in this case). In the scale with 3 levels, 1-2 are collapsed, as well as the levels from 3 to 6: in this case, the only differentiation that remains is between direct sources, indirect sources and pure hypotheses. This might be used when the maximum accuracy is not required or the range of available sources is not so wide.

FIG. 69 The matrix proposed by Paradis and Beard (1994) with the two sets of parameters indicating the basic requirements for casual observation to become useful data (location, theme, time) and the evaluation of data quality (accuracy, resolution, consistency, lineage). Visualisation by Irene Cazzaro.

FIG. 70 Shape, material and appearance concur to the definition of uncertainty (Apollonio 2016). Courtesy of the author.

FIG. 71 Uncertainty classification according to more than one parameter. The table on the left (elaboration by Irene Cazzaro based on Thomson et al. 2005) has been then taken up by Aurélie Favre-Brun, who groups the nine categories into three macro-categories (Favre-Brun 2013): quality (accuracy, precision, completeness), coherence (consistency, lineage, currency), objectivity (credibility, subjectivity, interrelatedness). Courtesy of the author. The diagram on the right is an elaboration by Fabrizio Apollonio identifying the connections between terms composing these three macro-categories (Grellert et al. 2019). Courtesy of the authors.

FIG. 72 A similar matrix (Favre-Brun 2013) to evaluate the information corresponding to each element in which the construction is segmented. The evaluation is done by attributing different values to spatial, dimensional, temporal, visual and morphological uncertainty. Courtesy of the author.

FIG. 73 Some of the colour scales found in the ColourBrewer. The selected one is colourblind safe. <https://colorbrewer2.org/#type=diverging&scheme=RdYlBu&n=3> (screen capture 19.10.2024).

FIG. 74 Example of documentation for the model of the new synagogue in Wroclaw (Poland), in which a simple "certainty" matrix related to the entire structure was included. Information and sources of the project are accessible here: <https://www.new-synagogue-breslau-3d.hs-mainz.de/>. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 75 Classification of some of the most used 3d viewers according to their features: above we can see the most developed ones (Smithsonian, Sketchfab, CyArk); in the middle those offering basic possibilities (MyMiniFactory, p3d.in, 3D Warehouse), below we have interfaces that generate previews of the downloadable models, without allowing further interaction. Visualisation by Irene Cazzaro.

FIG. 76 The ScieDoc interface traces the process that led to the reconstruction by means of sources and argumentation. A numerical evaluation of uncertainty is also allowed. <http://www.sciedoc.org/> (screen capture 31.10.2024).

FIG. 77 Uncertainty data visualised on the model once imported in ArcGIS (Perlinska 2014). Courtesy of the author.

FIG. 78 Visualisation of the "missing parts" of a sculpture reconstructed and uploaded to 3D Hop. Here the user can choose which elements to display: the original ones (which are reality-based, therefore certain) and/or the integrations, which are always, to some extent, hypothetical. <http://vcg.isti.cnr.it/3dhop/> (screen capture 31.10.2024).

FIG. 79 The use of colour scales (in the form of gradients) in Plas.io. Gradients are not exactly what we are looking for; still, a colour is attributed to a parameter – height, in this case. Attributing colours according to a value is what we also seek for uncertainty visualisation. <https://plas.io/> (screen capture 31.10.2024).

FIG. 80 The application of colour to different elements based on their nature in Potree. A similar visualisation can also indicate uncertainty levels. Here the colours can be changed according to the user's needs. <http://potree.org/potree/examples/classifications.html> (screen capture 31.10.2024).

FIG. 81 The interface of the DFG viewer and some of the uploaded models. <https://3d-repository.hs-mainz.de/> (screen capture 14.11.2023).

FIG. 82 Virtual reconstruction of the Speyer synagogue in its second Romanesque phase (about 1250), in the context of the project SpSya1250. The different kinds of software that have been used are, from top left clockwise: SketchUp, Blender, Rhinoceros, Archicad.

FIG. 83 Screenshot of the Wikipedia page that is under development (screen capture 25.01.2023).

FIG. 84 The already existing Wikidata page about the former synagogue in Speyer (screen capture 25.01.2023).

FIG. 85 Applying different structural categories to the building and identification of the types of structural elements. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 86 Simple uncertainty scale elaborated for the models to be uploaded to the DFG viewer. Visualisation by Irene Cazzaro.

FIG. 87 The model of the Speyer synagogue uploaded to the DFG Repository, with its metadata (screen capture 25.01.2023).

FIG. 88 External and internal view of the synagogue. Renderings uploaded to Wikimedia Commons. Visualisation by Irene Cazzaro.

FIG. 89 Application of the uncertainty scale to the exterior and interior of the synagogue. Visualisation by Irene Cazzaro.

FIG. 90 Tables documenting the reconstruction steps and the choices made to reconstruct every single object as defined in the semantic segmentation. Visualisation by Irene Cazzaro.

FIG. 91 Evaluation of uncertainty based on morphology, position, dimensions, texture, historical period. Visualisation by Irene Cazzaro.

FIG. 92 Uncertainty evaluation based on the assessment of objectivity, quality and coherence parameters, according to Thomson et al. (2005). This evaluation has been performed on four elements belonging to different categories: "still existing", "reconstructed by inference based on direct sources", "reconstructed by analogy", "reconstructed by hypothesis". Visualisation by Irene Cazzaro.

FIG. 93 Variant of the Speyer synagogue with circular windows. Visualisation by Irene Cazzaro.

FIG. 94 Variant with circular windows: levels of uncertainty applied using Rhinoceros. The levels of uncertainty are still the same; just the shape of the windows has been changed. Visualisation by Irene Cazzaro.

FIG. 95 Variant of the synagogue in its Gothic phase (around 1350). Visualisation by Irene Cazzaro.

FIG. 96 The uncertainty scale applied to the 1350 Gothic variant using SketchUp. Visualisation by Irene Cazzaro.

FIG. 97 Calculation of the average uncertainty for the model of the Speyer synagogue. Visualisation by Irene Cazzaro.

FIG. 98 At LOD 1 or 2, we would consider the (average) uncertainty level of the entire building, without differentiating it according to its elements. In this case, the average uncertainty level would be 3. Visualisation by Irene Cazzaro.

FIG. 99 If we imagine working at the detail of the single element, in this case the portal, a further subdivision into parts is probably necessary: in this case, we would indicate the level of uncertainty of each single sub-element. This visualisation is a pure example: the sources that we have to reconstruct the portal don't allow reasoning at this level. Visualisation by Irene Cazzaro.

FIG. 100 On the left: the model with the "pure" RGB colours identified in the handout. Variations, however, may be possible. In the model on the right, the colours are still perceived as blue-green-yellow-red. These have been taken from the colour scale by Apollonio et al. (2021). Visualisation by Irene Cazzaro.

FIG. 101 A colourblind-safe uncertainty scale according to the ColorBrewer by Cynthia Brewer. Here the four colours used in the previous visualisations have been replaced by the series "blue", "light blue", "yellow", "orange". Visualisation by Irene Cazzaro.

FIG. 102 Adoption of a scale based on the variation in lightness from black to white. Visualisation by Irene Cazzaro.

FIG. 103 The application of textures (stripes and dots) besides plain colours may define all the levels of the scale. Visualisation by Irene Cazzaro.

FIG. 104 Adoption of a scale based on the variation in lightness from red to white. Visualisation by Irene Cazzaro.

FIG. 105 Adoption of a scale based on the variation in lightness from green to white. Visualisation by Irene Cazzaro.

FIG. 106 Adoption of a scale based on the variation in lightness from blue to white. Visualisation by Irene Cazzaro.

FIG. 107 Uncertainty expressed through different degrees of transparency – as far as they can be distinguished. Visualisation by Irene Cazzaro.

FIG. 108 Combination of opacity, transparency and wireframe to visualise more uncertainty levels. Visualisation by Irene Cazzaro.

FIG. 109 Mesh produced by Sander Münster and elaborated by Irene Cazzaro. The pictures taken by Irene Cazzaro have been initially used.

FIG. 110 In this case, the mesh has been used to visualise the still existing parts of the building, whereas a non-photorealistic model with colours indicating the different degrees of uncertainty (according to the scale seen before) represent all the source-based reconstructed elements. Visualisation by Irene Cazzaro based on the previous figure.

FIG. 111 Attribution of "wall surface" as boundary surface type. Visualisation by Irene Cazzaro.

FIG. 112 The attributes related to the still existing part of the wall are added; as a generic attribute, the uncertainty level is also included. Visualisation by Irene Cazzaro.

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FIG. 114 Attributes were added to the roof in the same way. Here the uncertainty level is "1-hypothesis". Visualisation by Irene Cazzaro.

FIG. 115 Attributes are added to closure surfaces. Visualisation by Irene Cazzaro.

FIG. 116 Attributes are added to the variant with circular windows. Visualisation by Irene Cazzaro.

FIG. 117 The attributes are applied to the entire building, at another level of the hierarchy. Visualisation by Irene Cazzaro.

FIG. 118 The attributes are applied to the entire building, at another level of the hierarchy. Visualisation by Irene Cazzaro.

FIG. 119 The attributes are applied to the entire building, at another level of the hierarchy. Visualisation by Irene Cazzaro.

FIG. 120 The CityGML export. Visualisation by Irene Cazzaro.

FIG. 121 Visualisation of the model and of some elements that compose it, together with the assigned attributes, in FZK Viewer. Visualisation by Irene Cazzaro.

FIG. 122 Visualisation of the variant with circular windows and its related attributes in FZK Viewer: the deducted wall. Visualisation by Irene Cazzaro.

FIG. 123 Visualisation of the variant with circular windows and its related attributes in FZK Viewer: the circular windows. Visualisation by Irene Cazzaro.

FIG. 124 Gothic variant: the attributes are added to the entire building. Visualisation by Irene Cazzaro.

FIG. 125 Gothic variant: the attributes are added to every single element. This is only an example concerning the windows that have been transformed in the passage from the Romanesque to the Gothic synagogue. Visualisation by Irene Cazzaro.

FIG. 126 The structure of the model in CityEditor. Visualisation by Irene Cazzaro.

FIG. 127 The visualisation of the Gothic variant and its attributes in FZK Viewer: here the entire building can be seen. Visualisation by Irene Cazzaro.

FIG. 128 The visualisation of the Gothic variant and its attributes in FZK Viewer: Gothic windows. Visualisation by Irene Cazzaro.

FIG. 129 The visualisation of the Gothic variant and its attributes in FZK Viewer: deducted part of the wall. Visualisation by Irene Cazzaro.

FIG. 130 Adding the uncertainty property in Archicad. Step 1. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 131 Adding the uncertainty property in Archicad. Step 2. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 132 Adding the uncertainty property in Archicad. Step 3. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 133 Adding the uncertainty property in Archicad. Step 4. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 134 Adding the uncertainty property in Archicad. Step 5. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 135 Adding the uncertainty property in Archicad. Step 6. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 136 Adding the uncertainty property in Archicad. Step 7. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 137 Adding the uncertainty property in Archicad. Step 8. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 138 Adding the uncertainty property in Archicad. Step 9. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 139 Adding the uncertainty property in Archicad. Step 10. Visualisation by Igor Bajena. Courtesy of the author.

FIG. 140 Application of the average uncertainty level "3-deduction" to the entire building. Visualisation by Irene Cazzaro based on the model by Katarzyna Prokopiuk.

FIG. 141 Application of the uncertainty level "3-deduction" to walls, doors and windows. Visualisation by Irene Cazzaro based on the model by Katarzyna Prokopiuk.

FIG. 142 Application of the uncertainty level "1-hypothesis" to the ceiling and the floor. Visualisation by Irene Cazzaro based on the model by Katarzyna Prokopiuk.

FIG. 143 The uncertainty parameter is still accessible once the CityGML file has been exported and opened with FZK Viewer. Visualisation by Irene Cazzaro based on the model by Katarzyna Prokopiuk.

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Many unresolved challenges surround source-based 3D reconstruction, visualisation, and documentation in archaeology, art, and architectural history. In this context, here we focus on evaluating source-based 3D reconstructions, emphasising uncertainty assessment of destroyed or never built artefacts. Key questions address expressing and sharing uncertainty in data models, examining the efforts to define standards for 3D models ensuring authenticity, transparency, and accessibility. Various strategies for visualising uncertainty are discussed, aiming to establish uniformity. Stressing the importance of sustainability, the study advocates for sharing models via virtual research environments, promoting open access and complying with Linked Open Data principles. The proposed workflow categorises and visualises uncertainty in 3D reconstructions, with the aim of sharing them through online repositories. International collaboration has refined and will continue to refine the workflow and assumptions, enhancing uncertainty assessment.

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