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Uncertainty in Hypothetical 3D Reconstructions: Technical, Visual and Cultural ‘Transitions’

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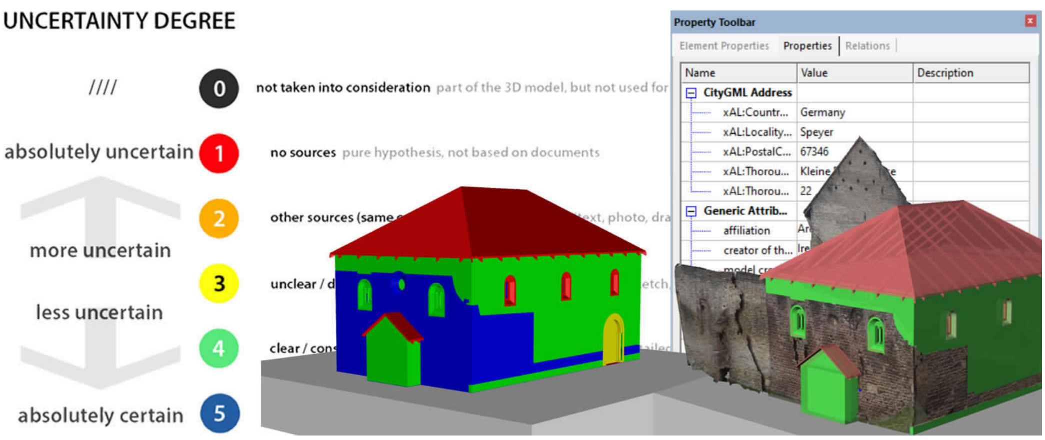
Abstract

Uncertainty assessment is fundamental when dealing with digital 3D reconstructions of hypothetical artefacts. In this framework, a range of uncertainty scales based on different classifications and visualisation techniques have been proposed through time without reaching a standard. Besides this, we argue that, even starting from a very simple uncertainty scale (which can also become more complex if needed) and assuming that it becomes widespread, a variety of challenges arise at different levels: at least a technical, a visual and a cultural one, which are here analysed describing the different kinds of ‘transitions’ that they can convey.
At a technical level, the uncertainty scale can be applied to different levels of detail (allowing transitions between them), can be communicated through platforms (generating transitions of knowledge) and hopefully by means of (a transition to) standard exchange formats.
At a visual level, a transition should be guaranteed between different uncertainty visualisation techniques, but also to infographics representing uncertainty data in more complex ways.
At a cultural level, we should take into account that this transition of knowledge may occur in different domains and have different targets, in a balance between complexity and adaptation depending on the audience we refer to.
We conclude with two goals for the future: the integration of the uncertainty documentation as a property in the CIDOC CRM ontology for cultural heritage and the visualisation of uncertainty directly on suitable online viewers.

Keywords
Uncertainty, hypothetical 3D reconstructions, documentation, visualisation, sharing



The uncertainty scale and some examples of documentation and visualisation of uncertainty. (Author’s visualisation).

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Introduction

When dealing with digital 3D reconstructions of destroyed or never built artefacts, therefore reconstructions that remain, to some extent, hypothetical, we should declare their uncertainty level. For this reason, a number of uncertainty scales [Strothotte 1999; Kensek 2007; Apollonio 2016; Landes 2019] have been elaborated, without reaching a standard so far. As an example, here we employ a slight variation of an uncertainty scale that may also allow different granularity [Apollonio 2021], which seems to have a huge potential in the application in various fields, since it contains as few ambiguities as possible and every level is accurately defined and differentiated. It may also be adapted to the users' needs and allow different degrees of complexity, always keeping a scientific dimension. This scale (fig.1) has been applied to a range of different projects uploaded to the DFG Repository [1], such as the digital reconstruction of the medieval Synagogue in Speyer (1250), and further applications are planned over the next few months.
However, in the framework of a simple uncertainty scale to be used in the DFG Repository, apart from the definition of the levels of uncertainty, which is already a tricky operation for which no standard has been set, when dealing with uncertainty representation and communication, we face different kinds of challenges that emerge when we want to share our results in an effective way and with a heterogeneous audience. As we will see in the next paragraphs, these challenges are mainly based on the concept of 'transition' and they occur at least at three different levels: a technical, a visual and a cultural one.

Technical transitions

In order to communicate uncertainty data in a clear and effective way, first of all, we should decide at which level(s) of detail we want to operate and, consequently, which interfaces and formats we may use to spread the obtained results. In this context, we can recognise three different types of technical 'transitions':

- The 'transition' of the uncertainty scale to other levels of detail of the model;
- The 'transition' of information among users by means of online platforms to share the models;
- The adoption of standard exchange formats (therefore, a format 'transition') to enhance the process of knowledge sharing.

Transition to other levels of detail (LOD)
In the example seen before, the model of the synagogue has been divided into the main elements that compose it, in a semantic segmentation done according to the sources that were found. Anyway, we can imagine working at lower detail, therefore having just the possibility of giving a general uncertainty value referring to the whole building. For this reason, the calculation of the average uncertainty of the model has been performed (fig. 2): this means that at another level of detail (fig. 3 left) – 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 and a single colour (green, according to the scale in fig. 1) would be used to describe it. This is why we should also consider the level of uncertainty in relation to the level of detail and

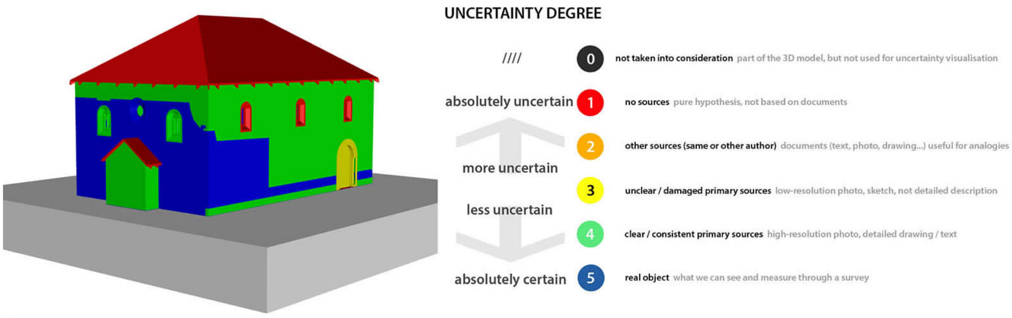


Fig. 1. The uncertainty scale and some examples of documentation and visualisation of uncertainty. (Author's visualisation).

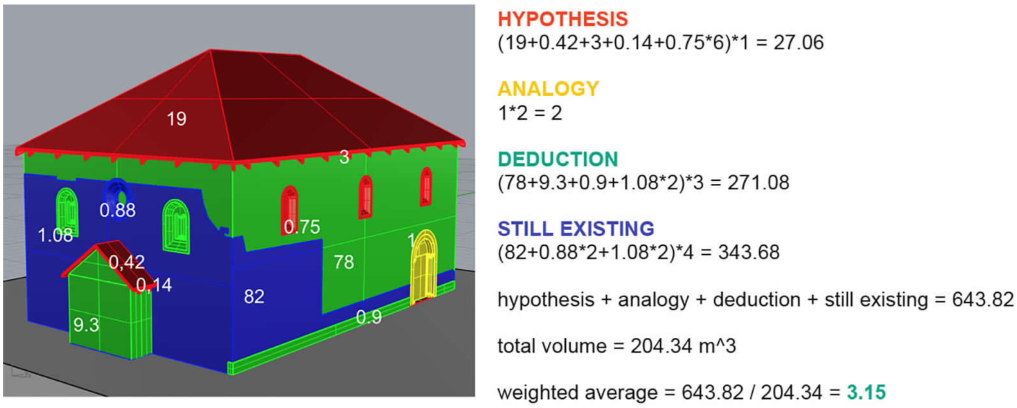


Fig. 2. Calculation of the average uncertainty for the model of the Speyer synagogue. (Author's visualisation).

imagine transitions between them. 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 represented below (fig. 3 right) is just an example and would be a nonsense from a scientific point of view, since we don't have accurate sources that allow us to work at that level. In the paragraph *Transition to standard exchange formats* we will see how to integrate and share uncertainty data at two different levels of detail.

Transition of data among users of online platforms

The visualisation of uncertainty data directly on an online viewer is a challenge for the future. At this moment, there is no 3D viewer that directly visualises uncertainty. Anyway, some of them use colours to visualise other parameters or distinguish between 'original' parts and 'integrations' (fig. 4).

We can thus imagine that our simple colour scale will be applied to a viewer in the near future. In this context, 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 DFG Repository project, according to the examples found online.

By now, we can keep trace and communicate the uncertainty assessment through the DFG repository in the following ways:

- 'Sharing the 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 platform, although the native software is usually needed to visualise it, which can represent a limit;

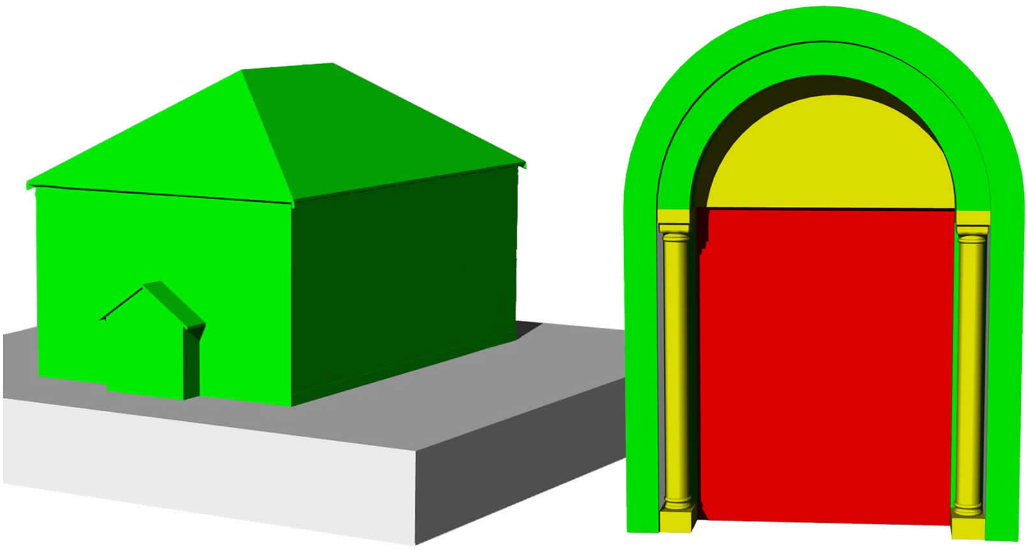


Fig. 3. (left) At LOD 1 or 2, we would consider the (average) uncertainty level of the entire building, without differentiating it according to its elements; (right) if we imagine working at the detail of the single element, a further subdivision is probably necessary. (Author's visualisation).

Fig. 4. (left) Visualisation and choice of the elements to display in 3DHop http://vcg.isti.cnr.it/3dhop/ (accessed 18.01.2023); (right) The application of colour to different elements in Potree http://potree.org/potree/examples/classifications.html (accessed 18 January 2023). (Author's visualisation).

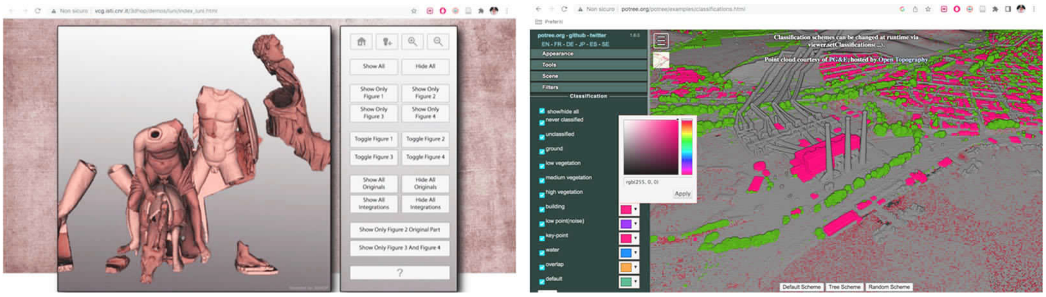


Fig. 5. Example of workflow that can be applied to SketchUp using the extension City Editor, allowing to add attributes and to export the file in .gml format. The 'uncertainty level' has been added as a generic attribute. (Author's visualisation).

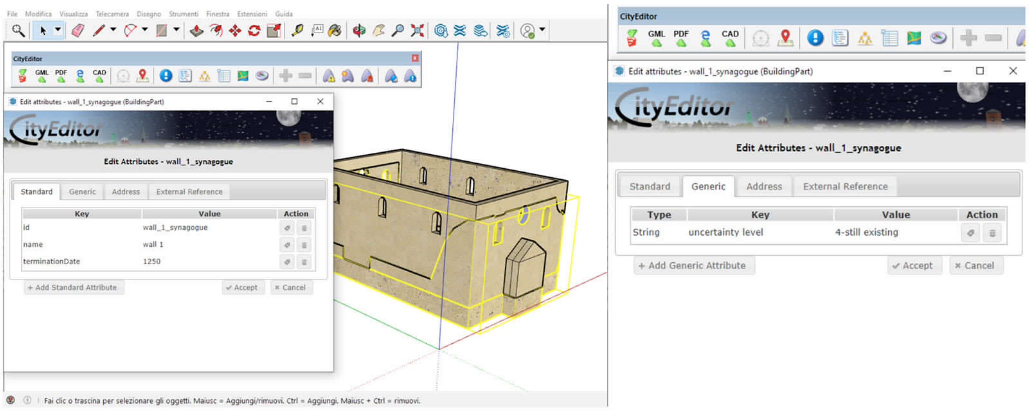
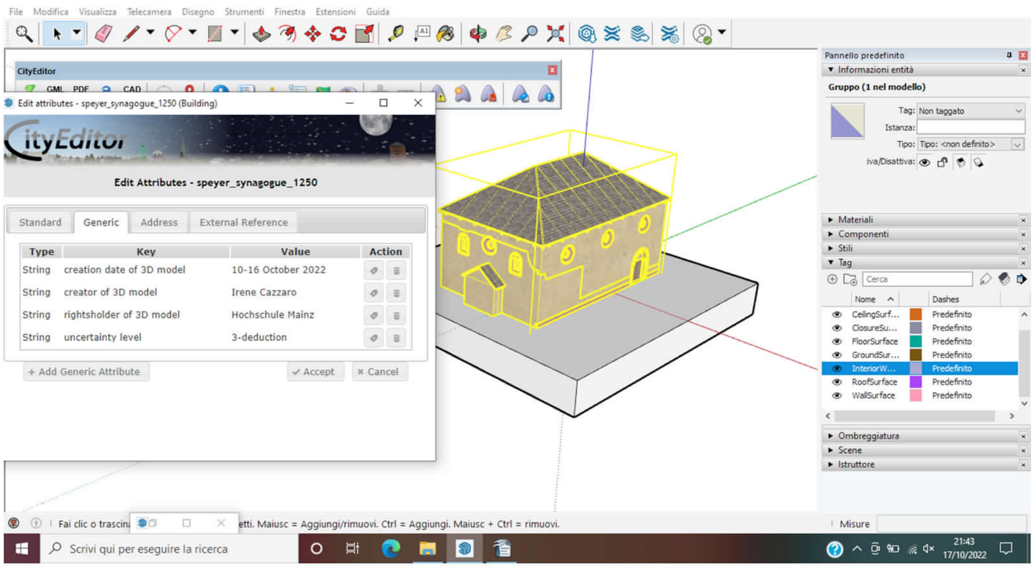


Fig. 6. The standard and generic attributes, including the uncertainty level, are also applied to the entire building, for which the average uncertainty has been calculated. Information is thus stored at two levels: the entire building and the single parts. (Author's visualisation).



- 'Using documentation tables'. These are structured in such a way that, to each element obtained by semantic segmentation, a description of the reconstruction process, a list of the used sources and an assessment of the level of uncertainty with related argumentation are attributed. The tables are then uploaded to the repository, becoming accessible in .doc or .pdf format to all the interested users;
- 'Uploading files saved in standard exchange formats'. To avoid the problem of having models and associated data in a particular format depending on the used software, we should rely – and have relied – on standards to spread them, such as IFC and City GML, which can be opened with free viewers such as FZK Viewer and Open IFC Viewer. This will be analysed in the next paragraph.

These three methods can be used alone or together as they deal with different technical ways of considering and sharing uncertainty.

Transition to standard exchange formats

As we said before, one of the simplest ways to allow interoperability is 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. To obtain a CityGML file, the model is imported in SketchUp, so that it is possible to work with the City Editor extension. The uncertainty values are applied at two levels: the entire model (fig. 6) and its single parts (fig. 5). At the end, the GML file is 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 (fig. 7).

A similar result can be obtained starting from Archicad. Even in this case, the uncertainty values according to the given scale are applied to the model, which is then saved in IFC format. Similarly to the previous case, when the file is opened with Open IFC Viewer, we can see that uncertainty data remain accessible (fig. 8).

The level of uncertainty should, first of all, be included in the metadata of the reconstruction and there have been some proposals in this regard [Statham 2019]; the following step would be the integration of uncertainty data into the CIDOC CRM ontology, both human and machine-readable, which is one of the standard reference models (probably the best-known one) used in the Cultural Heritage field, even though it especially concerns extant

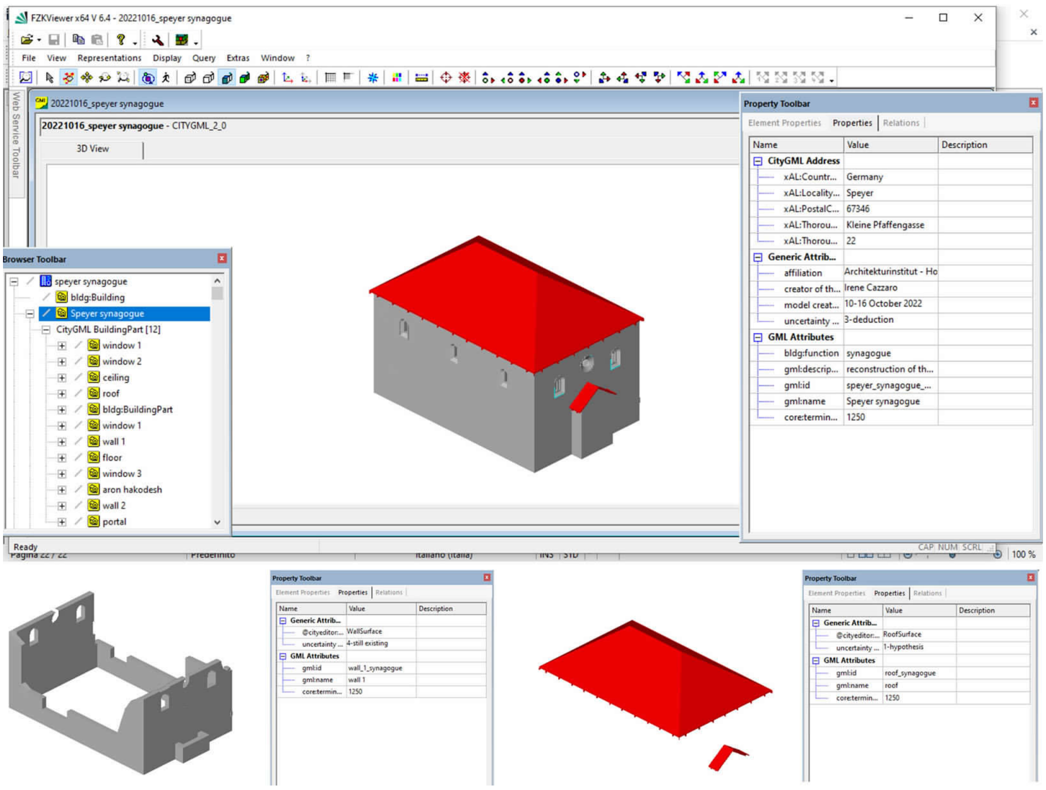


Fig. 7. Visualisation of the model and of some elements that compose it, together with the assigned attributes, in FZK Viewer. The uncertainty data – as well as the other attributes – remain at both levels of the hierarchy. (Author's visualisation).

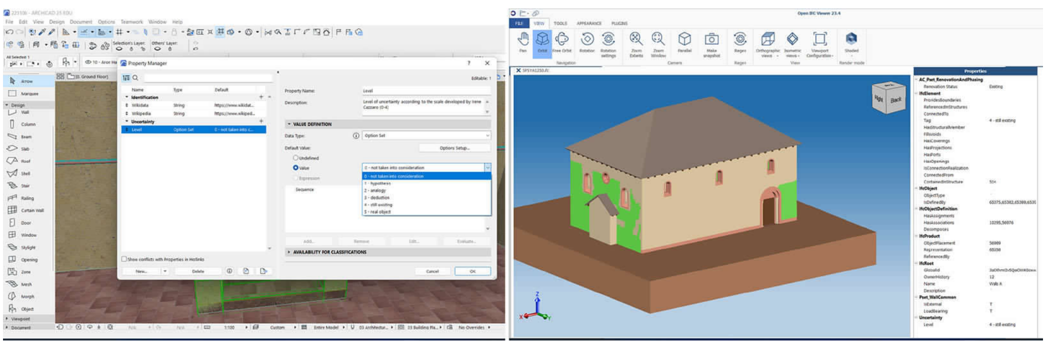


Fig. 8. Workflow in Archicad: the property related to uncertainty is created through Property Manager and applied to all the single elements. The model is then saved in IFC format and opened with Open IFC Viewer: we can see that all the added properties are preserved. (Courtesy of Igor Bajena).

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, similar to the examples seen before for IFC and CityGML standards. Some attempts to incorporate data about uncertainty and critical reasoning in CIDOC CRM have been made during the last years, but a standard property has not been established by now: the process is quite long and many debates are taking place inside the related community.
Franco Niccolucci and Sorin Hermon have tried to incorporate data related to fuzzy logic (thus probabilistic assessments of uncertain elements based on values between 0 and 1) into CIDOC CRM [Niccolucci 2017], proposing some new and more specific properties, for instance 'Z1 Reliability Assessment', which is then bound to existing properties and elements such as 'P90 has value and E60 number', the last one ranging from 0 and 1. They also mention other already existing attributes that can be used to document hypothetical reconstructions, among which:

- 'P15 was influenced by' (to declare the motivation of an argumentation);
- 'P33 used specific technique' – connected to 'E29 Design or procedure' (to document the technique and process supporting interpretation, thus explain the choices that have been made);
- 'P70 is documented in' – connected to 'E31 Document' (for the background documentation related to the used sources);
- 'P14 carried out by' – connected to 'E39 Actor' (to declare the author of a particular hypothesis).

The extension 'CRMinf' [2] also goes in this direction, allowing the integration in CIDOC CRM of metadata about argumentation and inference making.

Visual transitions

Transitions to other ways of visualising uncertainty on the model
In the previous part of the study, we have focused on a scale in which basic RGB colours were chosen, so that they could be easily communicated and shared; nevertheless, the scale should also allow flexibility to some extent. Here we take into account a number of visual variants that may be useful on particular occasions.

A colourblind–safe variant
A colour scheme found on the 'ColorBrewer' [3], especially employed in cartography, has been used here to generate a visualisation variant for colourblind people (fig. 9). Among the colourblind–safe schemes, this was the closest one to the scale we have proposed.

Different degrees of lightness and use of textures
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 of the building (fig. 10 left): according to the orientation, two different shades of grey are perceived. An alternative may be the use of textures (in this case stripes and dots) that, together with simple plain colours such as black and white, can already define a four-level scale that may be also used by people who don't properly perceive colours (fig. 10 right).

Combination of more visual styles
As we saw in the last case, if we want to visualise more variations without using colours, a combination of different techniques may also be considered. Wireframe and transparency can be a possibility (fig. 11 left). Another solution, if we just want to distinguish what is still on site and what has been reconstructed starting from archival sources (source-based), would be replacing the still existing elements with their actual (reality-based) mesh obtained by survey (fig. 11 centre). The levels of uncertainty, for the source-based part of the model, can still be indicated by using colours (fig. 11 right) or a combination of the techniques described before.

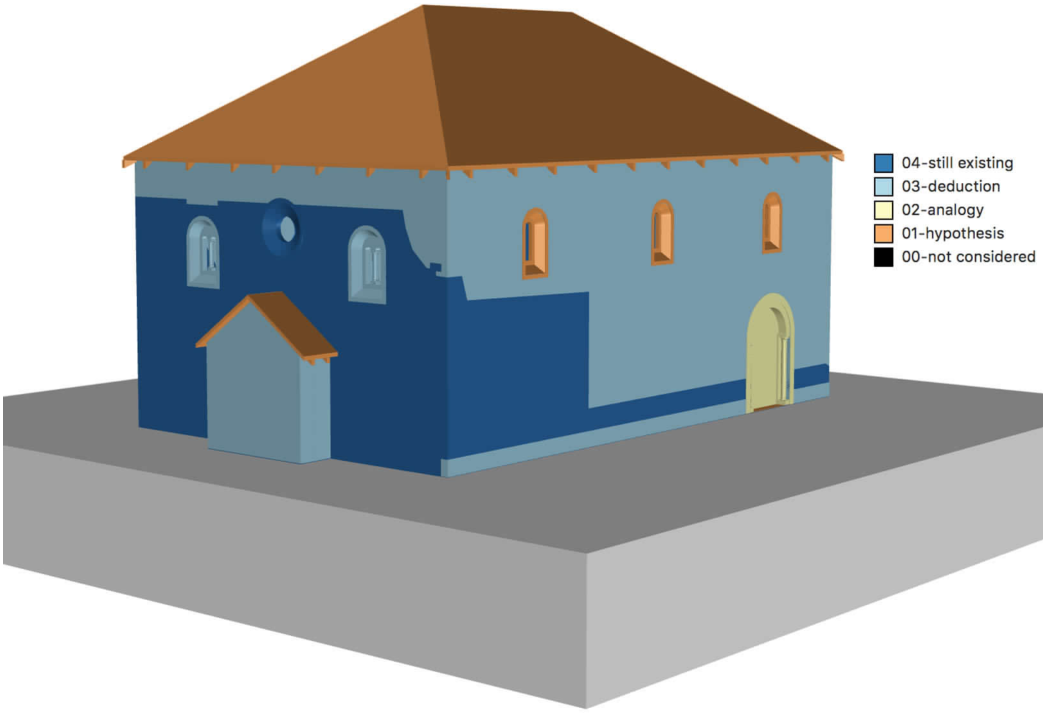


Fig. 9. A colourblind–safe uncertainty scale according to the ColorBrewer by Cynthia Brewer. Here the four colours used in the previous visualisations have been replaced by the series 'blue', 'light blue', 'yellow', 'orange'. (Author's visualisation).

Transitions to complex matrixes to document uncertainty

Until now, we have used a very simplified scale in which, apart from the different visual techniques that can be employed, uncertainty is assessed through 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 linear variation, be it a qualitative judgement (very good, good, sufficient, etc.), an assessment of the type of source (drawing, photograph, written text, etc.) or also of the operation done to reconstruct an element (survey, deduction, analogy based on different sources, etc.).

This is the most intuitive way of communicating uncertainty: the scale, based on a few recognisable colours or on the other visual combinations seen before, allows the understanding of information with minimum effort.

Nonetheless, we should observe that uncertainty evaluation isn't a binary process for which a result can generically be 'right' or 'wrong' and sometimes not even the definition of a number of degrees between 'right' and ''wrong' is sufficient: this assessment is indeed a more complex process in which we can recognise a range of 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 already know from many examples of infographics, it is possible to work with more than two parameters, combining the two Cartesian coordinates with a range of colours and symbols.

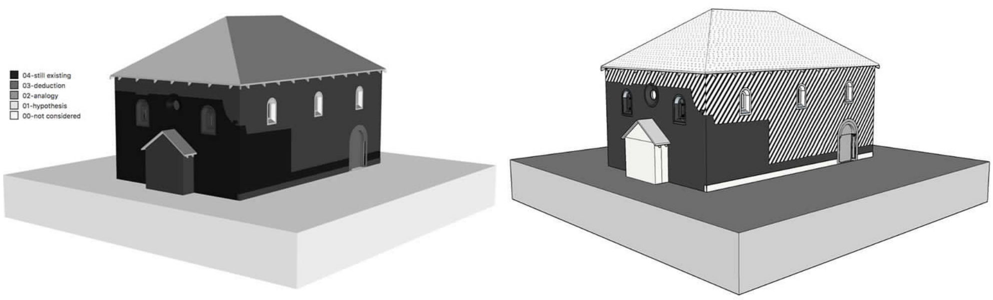


Fig. 10. (left) Adoption of a scale based on the variation in lightness from black to white; (right) the application of textures (stripes and dots) besides plain colours may define all the levels of the scale. (Author's visualisation).

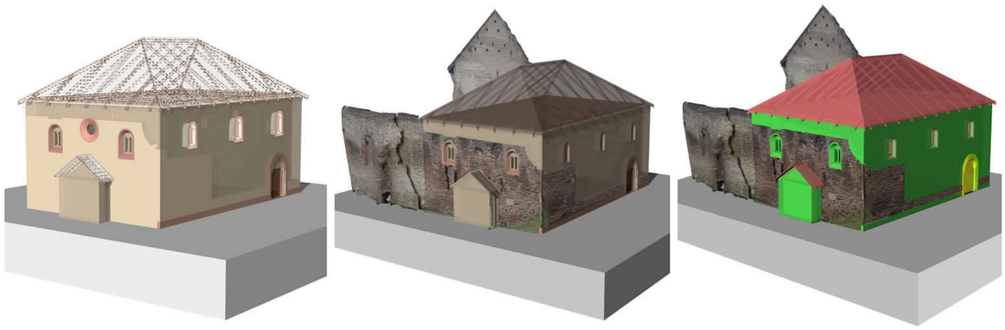


Fig. 11. (left) Combination of opacity, transparency and wireframe to visualise more uncertainty levels; (centre) mesh produced by prof. Sander Münster and elaborated by the author; (right) combination of the mesh and the colour scale to indicate uncertainty. (Author's visualisation).

The matrix presented here below (fig. 12) is elaborated starting especially from [Favre-Brun 2013; Grellert 2019; Apollonio 2021], where a variety of parameters that are in some cases interrelated concur to a global (or, at least, as general as possible) definition of uncertainty.
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.
These are the most complete uncertainty evaluation methods, but they may be not so immediate to understand, therefore they are probably more suitable for expert users rather than for a wider public. This depends on – and raises issues connected to – the audience involved in the process, which will be the focus of the next paragraph.

Cultural transitions

The creation of a workflow for digital reconstructions, first of all, depends on the domain and target. Different disciplines may be involved, from architecture to art history, archaeology, computer science. For this reason, it is important to set up a common terminology,

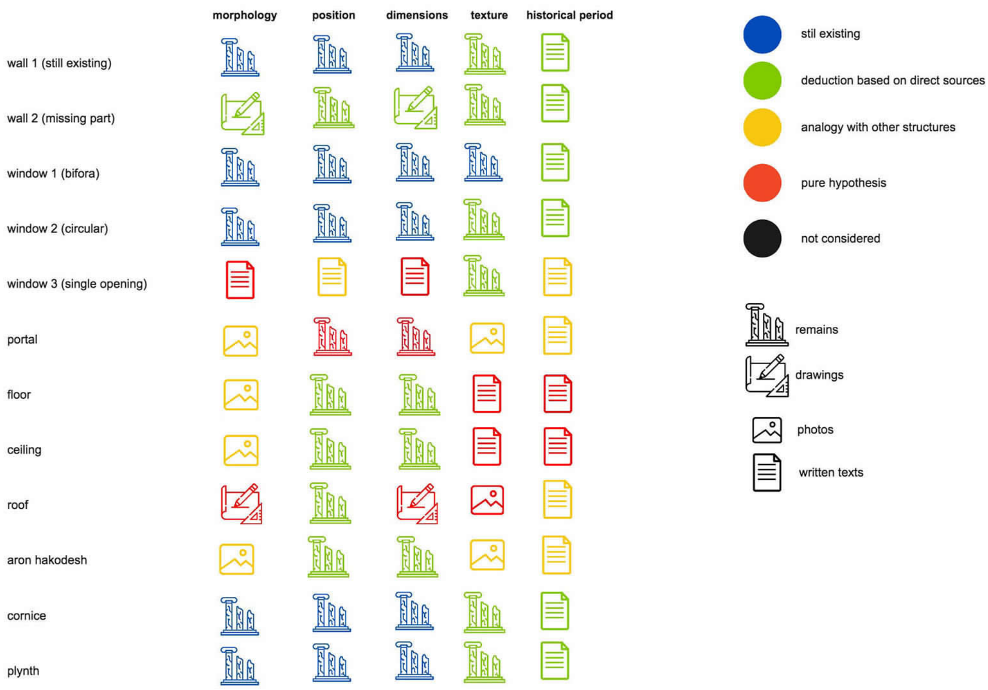


Fig. 12. Evaluation of uncertainty for each element of the reconstruction based on five parameters: morphology, position, dimensions, texture, historical period. Icons indicate the kind of document used to obtain that information and colours indicate the level of uncertainty. (Author's visualisation).

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 every scholar tends to use his/her own uncertainty scale without reaching a standard.
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 [4], 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 simple colour scale proposed at the beginning (fig. 1) has been and will be tested on students [5]. By now, the results, collected by means of a survey [6], 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, but also clear information should be given to students and, at the same time, the support of an instructor is also needed.
Similar issues have been studied in the engagement field at least since 1956, when a taxonomy was developed to differentiate the learners' depth of understanding according to six increasingly complex levels [Bloom 1956], from the 'knowledge' and 'comprehension' levels (the mere recall of what has been learnt and the understanding of its meaning) until the 'evaluation' level, in which ideas can be compared with the ability of discriminating among them.
This taxonomy has then evolved into a set of best practices concerning visualisations in computer science [Naps 2002], among which we mention the provision of resources that help learners interpret the graphical representation; the adaptation to the knowledge level of the user [7]; the support through dynamic actions and feedback; the integration of explanations in visualisations.
Learner–built visualisations proposed during courses and workshops, in this context, can be relevant in order to advance through the levels of the taxonomy by Bloom [Bloom 1956] and complying with the best practices by Naps [Naps 2002]; these concepts are also in line with other studies [Stasko 1993; Byrne 1996]. The levels of student engagement, in a field in which technology has "advanced faster than our understanding of how such technology impacts student learning" [Grissom 2003, p. 87] have been compared, proving that (obviously) 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.

Conclusions

With these different levels of 'transitions', we have tried to propose some methods and workflows to consider uncertainty documentation a vital part of 3D digital reconstructions concerning hypothetical artefacts, but also to deal with the challenges that emerge when we have to share these data.
Interoperability is already allowed by the tools we have; at this point, two goals for the future would be the integration of uncertainty data into CIDOC CRM as a standard property and the visualisation of uncertainty directly on some specific 3D viewers devoted to cultural heritage, such as the already mentioned DFG Viewer.
As far as different targets are concerned, all these studies seem to confirm that no single visualisation system is suitable for every user or learner and visualisations alone may not increase the communication of knowledge beyond a certain threshold. Engagement is fundamental, as well as the communication with a potential instructor and the presence

of further explanation in the light of scientific accuracy. This seems to be witnessed by many university courses, in which an increasing amount of time is employed in preparing instructions for students following these principles.

Notes

[1] The DFG Repository, used to upload these models with metadata and paradata (data about the reconstruction process) is being developed by the Institute of Architecture of the Hochschule Mainz: https://3d-repository.hs-mainz.de/ (accessed 5 February 2023).

[2] General information can be found in https://www.cidoc-crm.org/crminf/ (accessed 5 February 2023). The last version to date was published in October 2019 in https://www.cidoc-crm.org/crminf/sites/default/files/CRMinf%20ver%2010.1.pdf (accessed 27 December 2022).

[3] https://colorbrewer2.org/#type=diverging&scheme=RdYlBu&n=3 (accessed 5 February 2023).

[4] This is being discussed in international research groups such as the DFG Network 'Digitale Rekonstruktion' and the 'CoVHer project' for the computer-based visualisation of architectural cultural heritage. https://digitale-rekonstruktion.info; https://covher.eu/project/ (accessed 5 February 2023).

[5] The same issues are the focus of the 'CoVHer project' for the computer-based visualisation of architectural cultural heritage .https://covher.eu/project/ (accessed 5 February 2023).This will result in the publication of a book with guidelines for digital 3D reconstructions, which will be soon tested in workshops for university students.

[6] The survey has been conducted 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.

[7] 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.

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