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The Critical Digital Model for the Study of Unbuilt Architecture

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Abstract. The virtual (re-)construction of architectural artefacts that never existed or were destroyed is a research topic that currently presents several problems. This study, starting from a state of the art briefly described, tries to answer various questions: describe what a Critical Digital Model (CDM) is and what qualities it must fulfil to be scientifically constructed, visualized and evaluated. The qualities described are the followings: constructive aspects, the geometric accuracy and qualification of the 3D models; Traceability, use of sources and documentation, and the quality of historical (re-)construction; Accessibility and interoperability, compatibility with the publication on platforms/repositories and Data model Exchange formats; Visualization, graphic output to communicate scientific content throughout the 3D models. In particular, the latter quality is thorough, and some case studies are presented. Among these case studies, particular attention is given to the diplomatic representation and to the representation of the degree of uncertainty of the historical reconstruction of the model.

Keywords: Digital Reconstruction, Hypothetical Reconstruction, Architectural Drawing.

1 Introduction

Thanks to the advent of the digital revolution a new way of studying and representing the past has become increasingly important in the academic world and in the field of the digital entertainment (such as films and video games). This new way makes use of the so-called virtual 3D reconstructions, that is, figurative and textual sources-based 3D modelling of artefacts that no longer extant or have never been built.

Today architects, art historians, restorers and archaeologists [1, 2,3] use this medium to study and represent the past. The large production of these studies and models has created an international debate [4, 5, 6] that concerns above all the scientific reliability [7] of these (re-)constructions. Two important guidelines have been drawn up in this regard; the London Charter [8] and the Seville Principles [9]. These documents have defined general guidelines on the scientific nature of Computer-based Visualisation of Architectural Cultural Heritage (CVCH) models, and for its use concerning intellectual integrity, reliability, documentation, sustainability and access of heritage artefacts. Despite some proposals [10, 11,12] and several projects dedicated to the subject (e.g. CARARE [13]; 3D-ICONS [14]), the scientific community has not yet succeeded in establishing operational standards that would allow the visualization of the degree of the hypothesis of the data model adopted, or what the data model behind the 3D visualization looks like, or how the process adopted could be mapped or referenced in the 3D model.

The goal of this paper is to give, within the field of a CVCH 3D model, a scientific description, of the Critical Digital Model (CDM), and labels the main quality it should have. Among its qualities, we will study in depth the Visualization.

For the time being, the outputs/results of virtual 3D reconstructions are not yet fully considered scientific products due to the lack of any international strict guidelines to validate the models.

As we will see in more detail, the sources for virtual reconstruction can be both descriptive or figurative documents and archaeological remains. Here we will focus on the first case, even though the principles and qualities described are universal and are not related to a specific case.

If the reference documents are hand-made drawings (by the author or posthumous survey drawings), typical interpretation problems are known. For example, the original drawings of the plans and elevations may be inconsistent. In this case, the scholar will have to understand which path to take, whether to give greater importance to the plan or the prospect or look for an intermediate road that takes into account the information of the plan and that of the elevation together. More generally, the original documents are never exhaustive in their description and always leave gaps or parts to be interpreted. Besides, these gaps may affect the geometric architectural aspect, but it can also affect other characteristics such as construction and material. In conclusion, there is always an interpretative work in these (re-)constructions and the fundamental question is how to construct, represent and evaluate a 3D model of this type by limiting as much as possible subjectivity.

2 Research topic and case studies

In the field of architectural representation, the advances of digital technologies walk side by side with the development of new tools and methods for 3D data acquisition, documentation and dissemination of information related to architectural-archaeological heritage. Virtual reconstruction in archaeology and architecture [15] opened the debate to a wide range of theoretical problems related to documentation [16], analysis and interpretation of hypothetical reconstruction [17], transparency in the reconstruction process [18], and to the definition of new protocols for processing spatial data (acquisition, manipulation and management) [19, 20]. Within this wide context, in order to validate the entire 3D modelling hypothetical reconstruction process and to facilitate the exchange and reuse of information, as well as collaboration between experts in various disciplines, a common and shared heritage of methods and practices is necessary in order to make the knowledge behind any 3D digital hypothetical reconstruction accessible and reusable [21]. The source-based reconstructive process is the result of a highly complex decision-making process [22], through which, the data used and the decision adopted, accumulates an unknown, thus unpredictable and unquantifiable, degree of uncertainty and/or reliability [23].

Without a properly degree of confidence, expressed by the uncertainty/reliability of the incorporated data, the 3D model final output cannot be adequately evaluated from a scholarly point of view. For that reason, a structured hypothetical reconstruction modelling process is based on different levels of interpretation, characterized by a progressively increasing level of uncertainty. It is a complex and interconnected analysis and interpretation of documentary sources affected and/or characterized by different degrees of (a) coherence/consistency, (b) accuracy/metric quality and (c) subjectivity/perceptiveness [24]

3 The Critical Digital Model (CDM)

3.1 What is a Critical Digital Model?

The name Critical Digital Model deliberately refers to two studies in the field of digital elaboration of original drawings. The idea of the CDM derives from the ecdotics of the written text. In philology, it is the theory and practice of the critical edition of the text. In textual criticism, the critical edition of a text is the reviewed and enriched re-publication of the same text aimed at restoring its original form, and responding to the author's will, on the basis of the comparative study (collation) of each passage of the different witnesses existing direct and indirect, whether they are manuscripts or printed texts. The edition, therefore, is presented with a critical apparatus that reports varying lessons. It may also present a *codicum* coat showing the familiarity between the various texts put together to trace its archetype.

Ecdotica of the written text has a well-established history and is a discipline that has shared rules and standards. The same cannot be said about the ecdotics of drawings that has seen the light only in recent years with the publication of the Critical National Edition of Piero della Francesca's De Prospectiva Pingendi [25]. In this work, a critical edition of Piero's drawings was proposed for the first time.

Another study in which the critical term is proposed is Hubertus Günther's Critical Computer Visualization in Art History Teaching [26]. In this study, some typical problems of the virtual (re-)construction of unbuilt architectures based on graphic sources, are presented. However, several complications remain open such as that of visualizing the procedures adopted and the differences made in the proposed solutions. Questions to which our study tries to give some possible answers.

However, these two apparently distant studies, i.e. the Ecdotics of Piero's Drawings and the Critical Computer Visualization, have one main idea in common: the reconstruction of the original document, by filling the gaps and inconsistencies of the sources. To do this work it is necessary to accurately describe the methodology used and to display the proposed results in a transparent and transmissible way.

In this sense, the CDM wants to be a step forward in the path traced by these studies in different areas. The CDM, therefore, is an attempt to accurately define a transmissible methodology for constructing, viewing and evaluating 3D models of architectures that never existed or were destroyed.

The first question is to give a shared and concise definition of CDM: it is a 3D Computer-based Visualization of Architectural Cultural Heritage model based on reference documents of architectures never extant or destroyed.

The reference documents can be textual, they can be more or less accurate descriptions of the original artefacts, or they can be figurative: original drawings, photos, study models, or architectural remains in situ or preserved in museums.

The CDM can be used for scientific dissemination or as a three-dimensional reference document for scholars of architectural heritage. For this latter objective, the digital CDM should limit as much as possible the personal contribution to the interpretation of the sources and should document the criteria followed for the construction and representation of the 3D model in the clearest and transmissible way.

However, this concise definition is not sufficient to define a virtual (re-)construction. Therefore, we will try to describe the qualities that a CDM model should have.

1. Constructive aspects: the geometric accuracy and qualification of the 3D models;
2. Traceability: use of sources and documentation, and the quality of historical (re-) construction;
3. Accessibility and interoperability: compatibility with the publication on platforms/repositories and Data model Exchange formats;
4. Visualization: graphic output to communicate scientific content throughout the 3D models;

For each of these qualities a scale of values expressed in the Latin alphabet is assigned: A, B, C, D, E, where A is the maximum score and E the minimum score. These four main qualities do not have a hierarchy between them and express autonomous qualities from each other. Therefore, each CDM can be associated with about five values; for example (DEABA) or (CCBDA). In this way, the qualitative value of a CDM will not be associated with a single judgment but will be the overall evaluation of various qualities. For example, the "Visualization" quality could have a high evaluation while having a mediocre "traceability" or vice versa. The next sections report a brief explanation of these four qualities and an in-depth analysis of the "visualization".

3.2 Constructive aspects

The constructive aspects of the CDM are evaluated through five points of analysis:

- The digital representation method used;
- The level of detail (LoD);
- The geometric quality;
- The scale of representation;
- The semantic segmentation.

Regarding the first category, the author must declare the digital method adopted for the construction of CDM. There are two methods of digital representation: the mathematical (i.e. NURBS models) one and the numerical one (i.e. MESH models).

Then the CDM can be mathematical, numeric or hybrid (numeric and mathematical). Parametric representation methods are not considered true representation methods because they do not influence the intrinsic nature of the model. A parametric model can be mathematical or numerical.

About the second category. The level of detail refers to the scale of representation adopted for the construction of the CDM. The LoD could be evaluated with five grades: Poor, Low, Medium, Good and High and refer to it at reference scales according to building typologies: for example, a model of a villa that can be printed in 1:50 scale without losing detail is medium/tall; while a model of a building that can be printed in 1:200 is low.

About the third category. The geometric quality regards two different aspects. The first is the use or not of mathematical geometric profiles for the construction of three-dimensional entities. For example, if the geometric generator curves used to model the mouldings or the sections used to model the vaults can be extracted and identified as mathematical curves. A CDM where it is not possible to extract precise geometric generator curves (e.g. mesh models with discretized surfaces) should be placed at the lowest-quality step on the scale of 5. The second geometric aspect concerns the topological nature of the model. The use of closed and non-self-intersecting volumes. This is a particularly important factor for the calculation of the average uncertainty level of the model, weighted on the volumes of the elements, explained in section 4.8. Thus a model consisting of closed and not self-intersecting volumes is a high-quality CDM according to this category.

About the fourth category, the scale of representation is linked to the tolerance of the digital representation adopted and to the type of building in question. The author must report the unit of measurement adopted for the representation and construction of the model (e.g. centimetres, with a tolerance of 0.01).

The last category regards semantic segmentation by layers or groups. This quality does not enter into the merits of the quality of the segmentation but only assesses whether the segmentation exists or not and if it is usable (semantic quality is part of the "quality of historical reconstruction"). For example, if a CDM presents a study of the architectural order, topologically divided from the geometric structure of the rest of the model, but not organized into layers and sublayers, in this case, the CDM would have an average semantic segmentation quality.

Accurate descriptions of all these qualities complement the CDM and are required for its scientific validation.

3.3 Traceability

The quality of the sources concerns the quantity and quality of the reference documents used for the construction of the CDM.

The sources can be textual or figurative. The formers are exclusively textual descriptions. The figurative documents are original drawings, photos, sculptures, or even still existing rests of the original object.

The evaluation of the quality of the sources can be assessed according to four criteria:

- Consistency of sources (e.g. if the plan is consistent with the section and the façade);
- Quality of the documents used (e.g. if the graphic source is a scan or a photo and what is its resolution. If it is colour-corrected or not, if it is grayscale. If the original drawing is damaged);
- Completeness of the sources with respect to the object described (are the sources sufficient to describe the object entirely?);
- Types of sources (e.g. Textual or figurative sources).

The quality of historical (re-)construction is based on five categories:

- Comparative quality with sources (e.g. if the section of the CDM is equal to the section of the source);
- Structural quality (e.g. structural reliability with the technologies of the time. Alternatively, similarity with the construction systems adopted by the author of the project).
- Surface quality (the fidelity and the reliability of the materials or textures adopted for the representation of the CDM according to material available in that age);
- Typological quality. Any conjecture must be aligned with the architectural configuration of analogous case studies, otherwise, the author of the CDM must justify with robust references any atypical choice (e.g. if the theme is a church, the altar is expected to be in front of the aisle and at a higher floor quote, differently, proves must be provided).
- Semantic quality. Whether the digital CDM presents a semantic study of architecture or not and if it is accurate with regards to the field of study.

3.4 Accessibility and interoperability

The characteristics described above guarantee a certain level of quality of the CDM model. By consulting this documentation any scholar can immediately see if that particular CDM is reusable for specific scientific purposes. Nevertheless, a CDM well documented can serve both academics for scientific purposes and the public for educational or entertainment purposes (video game, films).

Thus, traceability is the key factor for re-usability. In this sense, the creation of a comprehensive reference platform for the storage and exchange of these three-dimensional models and data would be desirable. This platform should allow the users to classify, catalogue and filter these models effectively, and to present them to the public. In this sense, some studies and projects are already carrying out this idea (Patrimonium.net [27]).

Currently there are several internet platforms or projects (e.g. Inception-project Horizon 2020 [28]) on the digital collection of the European architectural heritage. Most of these platforms are note exclusively dedicated to architecture never extant or destroyed. Therefore, it would be useful to have a digital 3D repository able to store and transmit together with the finished product, that is the 3D model, also all the information essential for a critical evaluation of the work: the document sources; how these sources have been used (paradata); the technical nature of the three-dimensional model (numerical, mathematical or mixed); semantic study, if any, etc. This kind of platform would be able, therefore, to offer two different and complementary interpretations: the first dedicated to scholars, that is, architects, engineers, art historians, archaeologists and all experts in the sector; the second devoted to the general public, non-experts in the sector.

3.5 Visualization

Visualization is the quality of the CDM that describes the methodologies adopted for the representation of 3D models produced. In other words, the graphic methods adopted to describe the models.

The visualization can, therefore, vary from photorealistic to abstract, such as that to describe the degree of uncertainty adopted in the reconstruction of the 3D model. To date, there are several studies on this topic, but a shared standard has not yet been reached. The following paragraph is an attempt to describe a possible methodology for viewing the models without compromising the original information contained in the source drawings

4 The Visualization of the CDM

4.1 Premise

The hypothetical reconstruction process of unbuilt architecture requires to find solutions to missing parts, inconsistencies, design deficiencies, substrate faults, geometry discrepancies, undefined materials. To add the third dimension and generate a complete model coherently, it is necessary to fulfil lacks and correct issues of different nature trying to limit as much as possible personal interpretations. Nevertheless, the deduction/induction process is necessary to make conjectures, this highlights that the subjective interpretation is an unavoidable aspect of the reconstruction process [19, 29]. These issues are not only present at the geometric level but also at the shading level.

To visualize the digital models resultant from the reconstruction of never built or no more existent architecture, today the operators in this field usually choose between photorealistic (PR) or non-photorealistic (NPR) solutions.

From a certain point of view, the PR solution is the one with a greater chance of adding subjective conjectures [30]. However also the NPR solution of using a single white or grey material has its risks. For example, applying a single precise material to the whole scene, even if it is as neutral as possible such as white or grey, may induce the observer to think that the entire building is covered with a continuous layer of plaster, or even more grayscale-like reconstructions under unfavourable circumstances can contribute to the erroneous idea that antiquity was a colourless age [31]. Either way, people may subconsciously still perceive a different atmosphere from the one drawn by the original author. Thus, depending on the material and colour that are chosen, if they are different from the ones of the original reference, the perception of the spaces might change significantly. Thus in the next sections, we will present alternatives, to PR or NPR mono-material shadings, that might contribute preserving the graphical quality of the sources while being at the same time a valid visualization solution that add as little subjective conjectures as possible.

4.2 Photorealistic (PR) shading

With the traditional drawing techniques representing realistic materials was difficult or too time-consuming, in fact, in the ancient technical drawings of architectures, the definition of materials and surface texturing was often, schematized through simple hatches or monochromatic solid fillings, described with brief texts, or postponed to later not documented design phases. Furthermore, even when the surface chromatic aspects are represented accurately the natural colour of the paper or the ageing of the document may affect the shade of the drawing, adding chromatic aberration, that increases the uncertainty. Given that, even if clear documental sources about materials and colours are available, which is already rare, producing a photorealistic view of the model, free of subjective interpretations, is still challenging. However, for some applications (e.g. entertainment, games assets, movie sets) the photorealistic aspect is indispensable. In most of these cases, the scientific accuracy of the model has secondary importance [32] and the creation of a model transmissible and reusable is not crucial, however, it is still possible if the level of uncertainty and the sources used are precisely declared.

4.3 Non-photorealistic (NPR) shading

If there are not enough documents on construction materials, surfaces appearance and colours, and if the PR representation is not necessary, to limit as much as possible ambiguities and misinterpretations, is preferable to apply an alternative NP representation method. The most widespread NP solutions in digital reconstructions are the following:

- Abstract multi-coloured textures (solid colours or patterns): usually used to indicate the level of uncertainty or other aspects of the models that are not directly visible from the shade-less model.
- Neutral mono-material: deliberate avoidance of the definition of the materials (usually single white or grey material applied to the whole scene).
- Wire (with hidden edges or not): only the edges of the model are visible, without shadows and textures.
- X-ray/translucent/alpha: usually adopted to show inside or behind the model, or to indicate uncertainty.
- Flat shading: a model coloured only without any shadow or highlight usually used to focus the attention on the texture colour or to represent models that are captured with photogrammetry techniques.
- Ambient Occlusion: proximity shadowed model, mostly used to enhance the perception of 3D details without needing to define any specific material or light emitter.
- Black and white: patterns textures and materials are recognizable from the renderings but there is no colour information which limits the conjectures.
- Texture derived from original drawings.
- Stylized hand-painted texture.

Most of these graphical styles, even if they do not add further subjective interpretations, if used as the only representation method, might be hard to read or might generate ambiguities. For example, the use of abstract coloured textures, especially if they present patterns, might disturb the perception of the object shape and proportions, or if the colours are similar to plausible construction materials they might be confused by laypersons for the actual colours of the object. Furthermore, when proper lights and shadows are not applied (wire, x-ray, flat shading) the third dimension might be hardly readable. A more readable solution which is borderline between photorealistic and abstract is the black and white graphical style, which are basically photorealistic renderings converted to greyscale, this might be a good solution for those cases where the surface textures and materials are known but not the colours.

4.4 The surface appearance of the CDM

Even if there are a lot of examples of architectural reconstructions that make use of the photorealistic style [33, 34, 35, 36], a lot of times, the application of photorealistic shaders is deliberately avoided propending for a more abstract graphical style to limit the addition of further subjective conjectures at shading level [37, 38]. However, both the solutions, if not carefully documented and presented, might lead to ambiguities and misinterpretations. The CDM aims to address also the aspects related to the shading and texturing, that is why the photorealistic solution must be adopted only if reliable documental sources support it. For all the other cases abstract graphical styles are preferable. If reliable sources on the surface appearance are not available, the CDM might become an occasion not only to restore the third dimension of the authorial drawings but also to incorporate, at texture level, additional information which is most of the times lost in the process or hidden into the attached documental sources. In the next sections, possible graphical alternative to photorealism compatible with the vocation of the CDM will be proposed.

4.5 Tridimensional transposition of bidimensional graphical style (*Diplomatic* representation)

The application of a neutral mono-material is often the preferred solution when there are no reliable sources on surface appearance. However, in this way, the graphical style of the original drawings used as sources would not be visible on the model anymore. One of the key characteristics of the critical version of texts is that no part of the original text is usually removed, only additional notes and parts of other texts are added to clarifying concepts, correcting errors, or interrelating sources. The CDM has the same ambition but transposed to 3D models.

Within the theoretical assumptions adopted to define and outline the Critical Digital Model (see 3.1), a method of representation, called *Diplomatic*, is established, which is focused on the conventions, protocols and formulae that have been used by original hand-made document creators, in order to increase understanding of the processes of document creation, of information transmission, and of the relationships between the artifacts which the documents purport to represent and reality, with the aim of reproducing the values, the knowledge and qualities of the original drawings. Thus instead of applying a neutral mono-material, that would not add any information to the reconstruction, a texture extracted from the original drawing might be preferable. In this way, the model would not be only a possible “what if” represented with an aseptic look, but it would be a medium to disseminate and transmit the graphical quality of the documental sources, the aesthetic of the strokes, the cultural value of the use of colours and hatches, the quality of the architectural spaces, the intrinsic cultural and historical value of all these and other aspects directly retrievable from the original drawings. This type of shading might also be considered as a secondary shading variant for the models where a photorealistic solution is possible, in this way both the information about the graphic quality of the sources and about materials and surface finishing can be stored into the model at once.

Fig. 1. Mauro Guidi, Sepolcro antico di figura quadrata con portico di due gradini, Cesena Nuova, Atlante 41, Carta 48 [39]: 3D CDM (top); Original drawing (bottom).

Images from 1 to 5 exemplifies this concept on five different case studies belonging to different authors, geographic areas, architectonic styles and periods. The techniques used to achieve these results were:

- texture projection and manual mesh painting (Fig. 1)
- texture projection and procedural mapping (Fig. 2)
- texture projection and texture cloning (Fig. 3)
- postproduction of render passes (Fig. 4)
- procedural mapping and postproduction (Fig. 5)

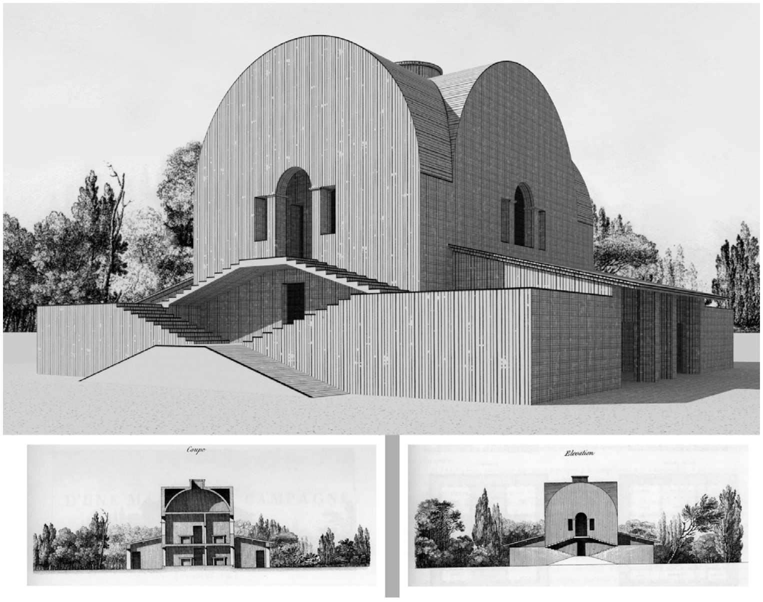

Fig. 2. Claude Nicolas Ledoux, Maison d’un employè, Cité idéale de Chaux, Tome 1, Pl. 17 [40]: 3D CMD (top); Original drawing (bottom).

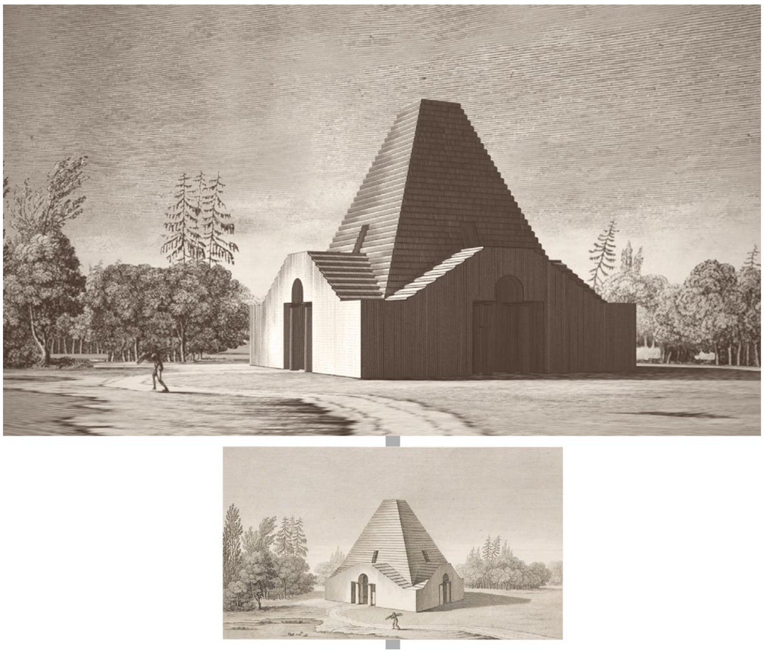

Fig. 3. Claude Nicolas Ledoux, Atelier des gardes de la forêt, Cité idéale de Chaux, Tome 1, Pl. 102 [40]: 3D CMD (top); Original drawing (bottom).

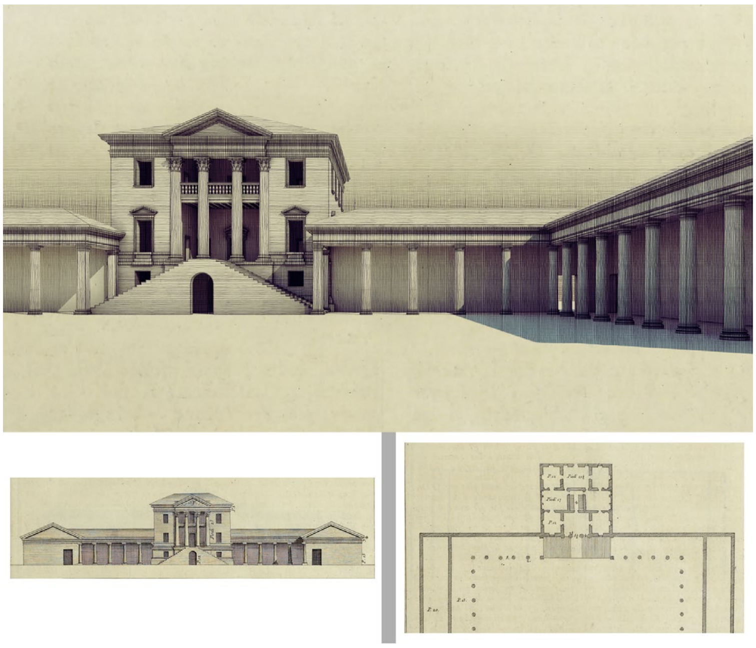

Fig. 4. Original drawing (left) and 3D CMD (right) of “Villa Ragona Cecchetto, Ghizzole, Montegaldella (PD)” by Andrea Palladio [41], tav. XLI

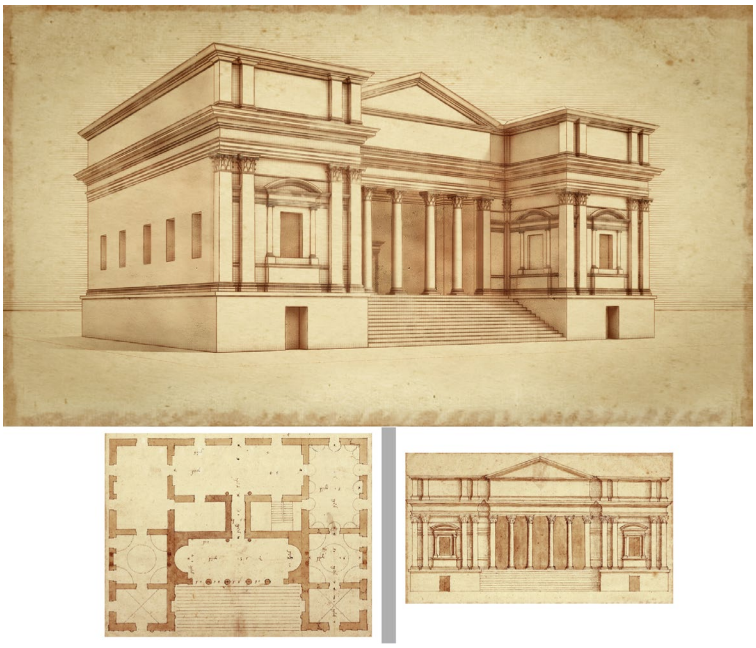

Fig. 5. Andrea Palladio, Villa Pisani, Bagnolo, RIBA collection, XVII/16 [42]: 3D CMD (top); Original drawing (bottom).

4.6 False colours to express the uncertainty

When the sources are too many and too different and when they have not an adequate level of quality to be able to apply the technique proposed in 4.6, there are other ways to incorporate information about sources directly into the model. For example, shading the model with false colours. Adding information at texture level in the form of colours allows the viewers to retrieve information about the model without needing to access external sources. This method was widely used for example to add information about the type of sources used and/or information about the reliability of the reconstruction [43, 44, 45]. This idea was at the centre of international debate for many years because it is a process suitable to be standardised (Arbeitsgruppe Digitale 3D-Rekonstruktion [46]). The main reasons why in many years no method was adopted as a standard is probably because the proposed methodologies were specifically designed for single case studies or at most for specific application fields, but they were not flexible enough to be applied to other cases or fields, another reason might have been that the more all-inclusive methodologies were too complex and time-consuming to apply to simpler cases and/or some classifications of sources and models were ambiguous or overlapping if applied to other fields.
Given these premises, the scale of uncertainty proposed in this section tries to be as flexible as possible by focusing the attention not on the type of sources but on the reliability of the sources, and every class is precisely defined to try avoiding overlapping and ambiguities.

4.7 Optimized scale of uncertainty

Starting from a vast series of proposals, developed over the past few years [47,48, 21, 49], we tried to improve the several variations of the scales of uncertainties that were used in the various reconstruction projects in the field of architecture, design and archaeology to make it suitable to address the following primary issues:

- synthetic descriptions of each level of uncertainty with as less ambiguities as possible
- descriptions valid for either architecture, design or archaeology fields
- predisposition to granularity, to allow its application to harder and simpler cases while returning comparable results (the scale of 7 levels is compactable into 5 or 3 levels to the need)
- avoid ambiguous colours that might be perceived with opposite meanings (i.e. not used red for maximum reliability or green for minimum reliability, because the average observer would unconsciously apply the traffic light symbology to the colours, perceiving opposite meaning)
- HSV colour intervals as wide as possible (colours with too close HSV values might be hard to distinguish on the shaded model)
- Assign a colour also to neutral, irrelevant or not considered elements (they will not contribute to the average level of uncertainty of the model)

Concerning the number of colors for classification tasks (search and distinguishing), several publications showed that only a small number of different hues can be processed, by human vision, and use effectively with a low error rate. Healey [50] stated that only five to seven different hues can be found accurately and rapidly on a map. Furthermore, MacEachren [51] affirmed that, if the task is to precisely identify a certain color in a plot, the detection rate can plummet when the number of colors increases (detection rate for 10 colors: 98%; for 17 colors: 72%). Other issues that were considered were about people with colour perception problems and the cases where the model can only be visualized in greyscale. However in the former case, because the types of colour vision deficiencies are several and very different we were not able to find an acceptable solution that worked sufficiently well for every one of them, so we prioritized the perception of people with normal colour vision, or with minimal colour vision deficiencies. About the greyscale issue, we concluded that converting a scale of colours with a scale of shades of grey is not a good solution, because lights and shadows can always deceive the viewers. So, for that, we think that it would be better to convert the colours to black and white graphical patterns instead of using different shadings of solid grey. However, also the patterns might be deceiving because they might be hard to distinguish in minute elements and they might mix up with the edges of the model making the shapes less distinguishable. Thus, these are issues that need further study.

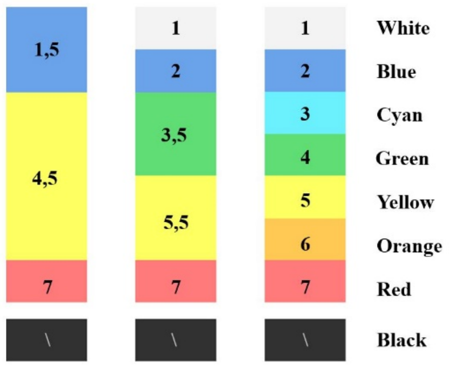

Fig. 6. Granularity of the scale of uncertainty.

To allow flexibility but at the same time to guarantee consistency we propose to use a scale of 7+1 steps (compactable to 5+1 and 3+1) assigned to colours that are easily nominable (black, red, orange, yellow, green, cyan, blue, white) (Fig. 6). We decided to not provide precise RGB values or RAL codes, but to assign wider intervals for each step of the scale, to improve flexibility. This choice was made to encourage the use of the same scale for projects were too bright or too dull colours would have not matched to the overall graphical style presentation and would have caused the adoption of a different colour scheme. The steps of the scale are no more than 7+1 to guarantee maximum recognizability. The red is assigned to the most uncertain level and blue to the less uncertain level. The colours are sorted following the order of the colours in the visible spectrum of light so once identified the lower and upper bounds the intermediate colours are easily derivable, the same colour schemes are used in many different scientific fields such as in the analysis of stress, deformation, temperature, pressure. We assigned the white colour (or light grey) to the level with maximum reliability. In some applications, this level of uncertainty might also be effectively substituted by the colour of the object in case of photographic textures extracted from real rests of the object. All those elements that will not be considered for the analysis but that are still useful to define spatial relationships with the object of study will be coloured with black (or dark grey).

A number from 1 to 7 is assigned to every level of the scale (the neutral level is identified with a backslash "\"), in this way it will be possible to extract an average numerical value for each model that would return the average uncertainty of the whole model. To achieve more reliable results not affected by the segmentation of the model, this number must be weighted with the volumes of each element that is why it is very important to model every single element with closed volume.

A theme of discussion regards the fact that some elements contribute more than others to the final aspects of the object especially in architectural cases, thus some elements are less important and should be considered less than others. For example, the walls against the soil of the cellars are a lot less relevant compared to the columns mouldings and architraves of the main façade, however, the volume of the walls might affect the global average value of uncertainty much more than the volume of the architectonic order. A solution for this might be providing two different average uncertainty values, one that is a simple average weighted with the volumes of each element which is more objective, and another one that applies multipliers to the volumes of the elements according to the perceived relative importance. This second value is a lot more subjective, but if the assigned weights are clearly provided it will be easily retro-traceable and might give more plausible results (Fig. 7).

Every level of uncertainty is carefully defined in Table 1 and clarified in Table 2. Every level is differentiated by the other according to the consistency, the state of conservation and the author of the sources used, in this way any overlapping is avoided. In the scale with five levels of uncertainty, the levels 3 and 4 are collapsed as well as 5 and 6, in this way the authors of the sources that are not direct/primary sources are not relevant anymore. In the scale with three levels of uncertainty, the levels 1 and 2 are collapsed and levels from 3 to 6 are collapsed as well, in this case, the elements derived from surveys of real remaining and elements derived from clear and consistent direct sources have the same level of uncertainty, and all the other sources except the elements modelled without sources will have the same uncertainty. To every level of the scale is assigned a number that will be used to calculate the average uncertainty level of the model, the collapsed levels in the scales with 3 and 5 steps will be numbered with the average of the collapsed levels. Even if the three scales are comparable, they have very different accuracy, especially the scale at three levels must not be used for cases where maximum accuracy is required.

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)

Table 2. Level of uncertainty scale, with 7+1 levels, graphical explanation.

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

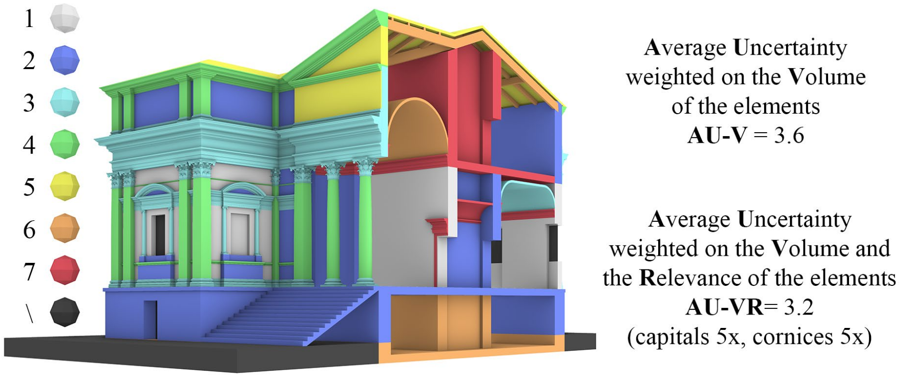

Fig. 7. Andrea Palladio, Villa Pisani, Bagnolo: Color map of level of uncartainty (7+1 levels) of 3D hypothetical reconstruction, after RIBA XVII/16 (left); Two average of uncertainties (right)

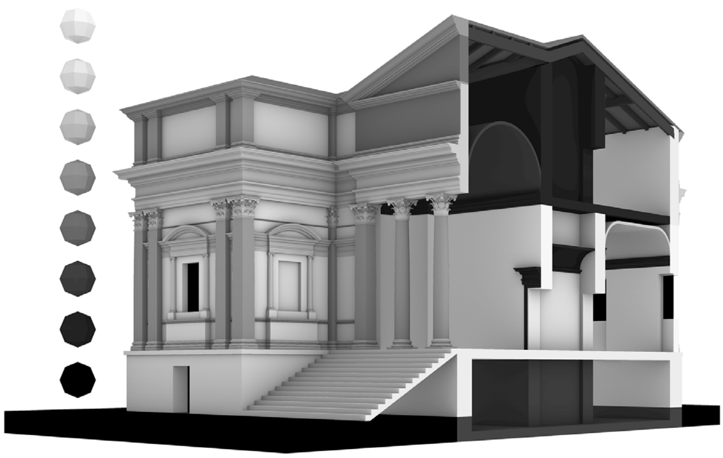

Fig. 8. Andrea Palladio, Villa Pisani, Bagnolo: Grey scale map of level of uncartainty (7+1 levels) of 3D hypothetical reconstruction after RIBA XVII/16.

5 Conclusion

In this study, we described the Digital Critical Model and what qualities it must possess to be scientifically assessed. The qualities described are the following. Constructive aspects: the geometric accuracy and qualification of the 3D models. Traceability: the use of sources and documentation, and the quality of historical (re-)construction. Accessibility and interoperability: compatibility with the publication on platforms/repositories and Data model Exchange formats. Visualization: graphic output to communicate scientific content throughout the 3D models. In particular, the latter quality is thorough, and some case studies are presented. Among these case studies, particular attention is paid to the diplomatic representation and to the representation of the degree of uncertainty of the historical (re-)construction of the model. Some problems have not been explored here and will be addressed in future research and publications. The most important question remains the search for shared standards for the construction, visualization and evaluation of virtual (re-)constructions of drawn or no more extant architecture. Furthermore, the question of a shared and transmissible methodology that can visualize and communicate both the procedures adopted and the different qualities of the historical (re-)construction of the model is still central. In this sense, this study is a proposal to share reflections and possible solutions to well-known problems, with the scientific community and does not represent a definitive solution yet. The hope is that these studies (together with all the literature on the topic) can stimulate a debate and lead the research in the direction of shared standards between scholars and enthusiasts. In an increasingly globalized world, where virtual reality seems to be within everyone's reach, being able to share methodologies and standards on virtual reconstructions of architectural artefacts could be an important step forward for the valorisation, conservation and transmission of architectural heritage (existing and virtual).The definition of shared Standards, Methodology and Glossary can give a critical reference to the international scientific community working on historical virtual reconstructions and might set a scientifically recognized method to validate the models. These standards can be a reference also for the world of digital entertainment (films and video games) which have an increasingly important and powerful role in the collective perception of our past.

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