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Essay

The Three-Dimensional Model as a 'Scientific Fact': The Scientific Methodology in Hypothetical Reconstruction

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Abstract: For more than thirty years, 3D digital modelling has been used more and more widely as a research tool in various disciplinary fields. Despite this, the 3D models produced by different research, investigation, and speculation activities are still only used as a basis and as sources for the production of images and scientific contributions (papers in journals, contributions in conference proceedings, etc.) in dissemination and cultural activities, but without having yet assumed full autonomy as a 'scientific fact', as a product of research, or as a means of scientific debate and progress. This paper outlines the context in the field of architecture and archeology in which the use of 3D models has become increasingly widespread, reaching a level of full maturity, and how the field of hypothetical reconstruction can be characterized as an autonomous/scientific discipline through the definition and adoption of a scientific, transparent, verifiable, reusable, and refutable method. In this context, the definition of the 3D model as a product of scientific speculation and research is proposed.

Keywords: hypothetical 3D reconstruction; scientific methodology; 3D modelling; uncertainty; virtual research environment

1. Introduction

Over the last 30 years, hypothetical 3D (digital interpretive) reconstructions have been widely used in the context of cultural heritage [1–5], especially as a useful tool for reconstructing physically non-existing historical artefacts (no longer existing, altered, or never having existed) [6–10]. While 3D reconstructions were initially used and seen as digital replacements for analogue research and presentation methods such as physical drawings and models, they have recently been transformed, establishing themselves through a specific epistemology of this research practise (digital 3D reconstruction) [11–13]. This process is strongly driven by the opportunity of digital modelling to support research [14–16], not only the through visualization of results, but through an evaluation of historical sources and their correspondences [17], the identification of geometric principles in a historical creation process [18,19], or the classification and systematization of historical objects concerning dependencies, similarities, or singularities [20]. Furthermore, these 3D digital reconstructions are produced within research fields involving interdisciplinary working groups which, in turn, employ multiple sources of knowledge [21]. In this context, as a concrete example of how such collaboration can be promoted and of the distinct roles that various disciplines can play in advancing digital 3D modelling, we mention the DFG Netzwerk 3D-Rekonstruktion [22], which offers researchers the opportunity to exchange across locations, topics, and activities. The network grew out of the Arbeitsgruppe Digitale 3D-Rekonstruktion [23], which emerged from the 1st Annual Digital Humanities Conference in German-speaking countries (25–28 February 2014, University of Passau) [24]. The AG Digitale 3D-Rekonstruktion brings together colleagues who have worked on the topic from the perspectives of architecture, archeology, building history, and art history, as well as computer graphics and computer science. The members of the working group used the opportunity to create a platform for the closer exchange and solid establishment of digital 3D reconstructions of cultural heritage within digital humanities. The primary

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goal of the working group was to bring together stakeholders from the German-speaking area to address questions of clarifying terms and working methodologies, as well as the documentation and long-term archiving of digital reconstruction projects and 3D datasets. The results of the work are incorporated into jointly developed guidelines and a *Handbook of Digital 3D Reconstruction of Historical Architecture* [8], which is based on them.

All of this raises questions about procedures and strategies for accessing, exchanging, and archiving digital assets along with the underlying knowledge base [17,25–29]. Such knowledge must be broadly defined and involves the interrogation, compilation, harmonization, and contextualization of information sources and the processing of any new knowledge derived from them.

The purpose of this position paper is to propose an up-to-date perspective to perceive, handle, and recognize three-dimensional models, considering the long trajectory already acquired in this field through different projects and research initiatives. The paper aims to systematize the most crucial aspects in order to establish three-dimensional models as scientific facts that assume full autonomy. It is evidently a multifaceted issue and, therefore, will be addressed through different perspectives: from an experimental methodology proposed for the reconstructive procedure to the necessary requirements for and the possible uses of three-dimensional models. Finally, a definition of the three-dimensional model as a scientific product is proposed, hoping that it will contribute to the systematization of good practises and to the recognition of the three-dimensional reconstruction and its outcomes as an autonomous scientific field.

The following section reconstructs, albeit not extensively, the state of the art and requirements that have emerged in recent years concerning the subject matter. Section 3 deals with the subject of the 3D model as a research product, addressing its demarcation as the product of an experimental methodology. The next section provides the elements that should be able to define the 3D model as a 'scientific product' and what uses this would lead to. Section 5 reports the latest projects and proposals carried out that define and use 3D models as scientific products. The Conclusion section proposes, in summary, a possible definition of the 3D model as a scientific product.

2. State of the Art and the Emerging Needs

The growing interest in these topics is also demonstrated by the financing of numerous projects at the European level regarding the topic of the digitalization of cultural heritage (see, i.e., Inception [30], Time Machine [31], V4Design [32], Crosscult [33]), but also by the extensive scientific literature dedicated to the topic extensively examined by Münster [34], providing a comprehensive overview of the use of digital 3D technologies in humanities with regards to, among others, scenarios, user communities, and epistemic challenges.

All these projects continue to deepen and refine the work started by the London Charter [35] and the Seville Principles [36] in specific contexts, as neither of the two offer a scientific methodological system. They deal, in fact, with the topic of the applications of ICT technologies to the field of cultural heritage, but without going into the details of more limited and specific areas, such as the case of the study of hypothetical reconstructions in the field of archeology [37] or architecture that no longer exists or was never built.

The work carried out in some recent research projects [22,38], which sought to lay the foundations for the definition of shared good practises and possible methodological and operational standards for the academic/scientific community of reference, fits into this context.

The results that are emerging, not only from these activities, and the attention paid to the epistemic and methodological issues related to 3D reconstructions, as evidenced by the extensive scientific literature in this regard, demonstrate the full maturity and scientific autonomy of this practise.

The 3D model—in its various and multifaceted characteristics—can become and can be considered an autonomous "scientific product", and this awareness leads to the need to create open digital archives of scientifically authenticated 3D models, based on standard mechanisms for the conservation, peer review, publication, updating, and dissemination of 3D models.

Consequently, reconstructions must abide by specific scientific requirements and standards to be formally considered as scientific processes and to ensure that their outcome—i.e., the reconstructed object—will also be widely considered as a valid research product. Such standards must include reliability, validity, and usefulness so that the reconstructions can be examined and evaluated by other researchers and then be used as a point of reference for further studies.

However, establishing scientific standards for the reconstruction process only partially addresses the problem. Emphasis should be equally put on the long-term preservation and publication of the reconstructions using a standard and widely applied format, while also being accompanied by the related metadata. Such aspects are fundamental to ensuring transparency and to creating accessible and comparable reconstructions. The creation of Virtual Research Environments [39–41] can be considered as a means through which data and reconstructions can be securely archived while also being easily accessible to different scholars. Such means could offer a significant step forward in sharing meaningful data in humanities. These challenges include what Koller et al. [42] already stated in 2009 and what was subsequently developed in some research streams, namely (i) digital rights management for 3D models (authorship) [43], (ii) clear representation of different degrees of uncertainty in 3D reconstructions [27] (discussed in more detail in Section 4), (iii) version control for 3D models [44,45], (iv) metadata structures effective [46], (v) long-term preservation [47], (vi) interoperability [48], and (vii) 3D research. Other concerns include the ability to apply computational analysis tools and the organizational structure of a peer-reviewed 3D model repository (see Section 5).

3. The 3D Model as a Research Product: An Experimental Methodology

Three-dimensional reconstructions are one of the most widespread means of research and visualization in academic and entertainment fields. The large production of these models has encouraged, in recent decades, an international debate on their scientific reliability [49–51].

Within this scope, two macro-categories—now also recognized in the scientific literature [52,53]—in which 3D models produced in the fields of architecture and archeology can be collected and then distinguished using Raw Models and Informative Models are as follows:

1. 3D digitization—here meant as reality-based modelling (i.e., point cloud model) [54,55]—is the process of converting something into its digital form, i.e., the technological transfer/casting of a real object into a digital resource;
2. 3D reconstruction—here meant as sources-based modelling [11,56]—requires the researcher's interpretation of documentary data to create a hypothesis of a physically non-existing object (no longer existing, altered, or never having existed).

In both cases (reality- or sources-based), it is a process [57] that begins with the collection of documentary sources or the collection of data based on reality, defines a semantic structure of the case study, interprets its forms (consistency dimensional, geometric and morphological), and produces a 3D digital model that is semantically enriched (see Figure 1).

Research does not start from observation, but from practical problems or from a theory that has run into difficulties.

The scientist attempts to solve the problem that the theory has encountered by making a conjecture; that is, they propose a hypothesis from which to deduce a series of consequences. This is where the researcher's creativity comes into play—the ability to connect elements that already exist with other elements; that is, they must be able to imagine a conjecture that can be falsified.

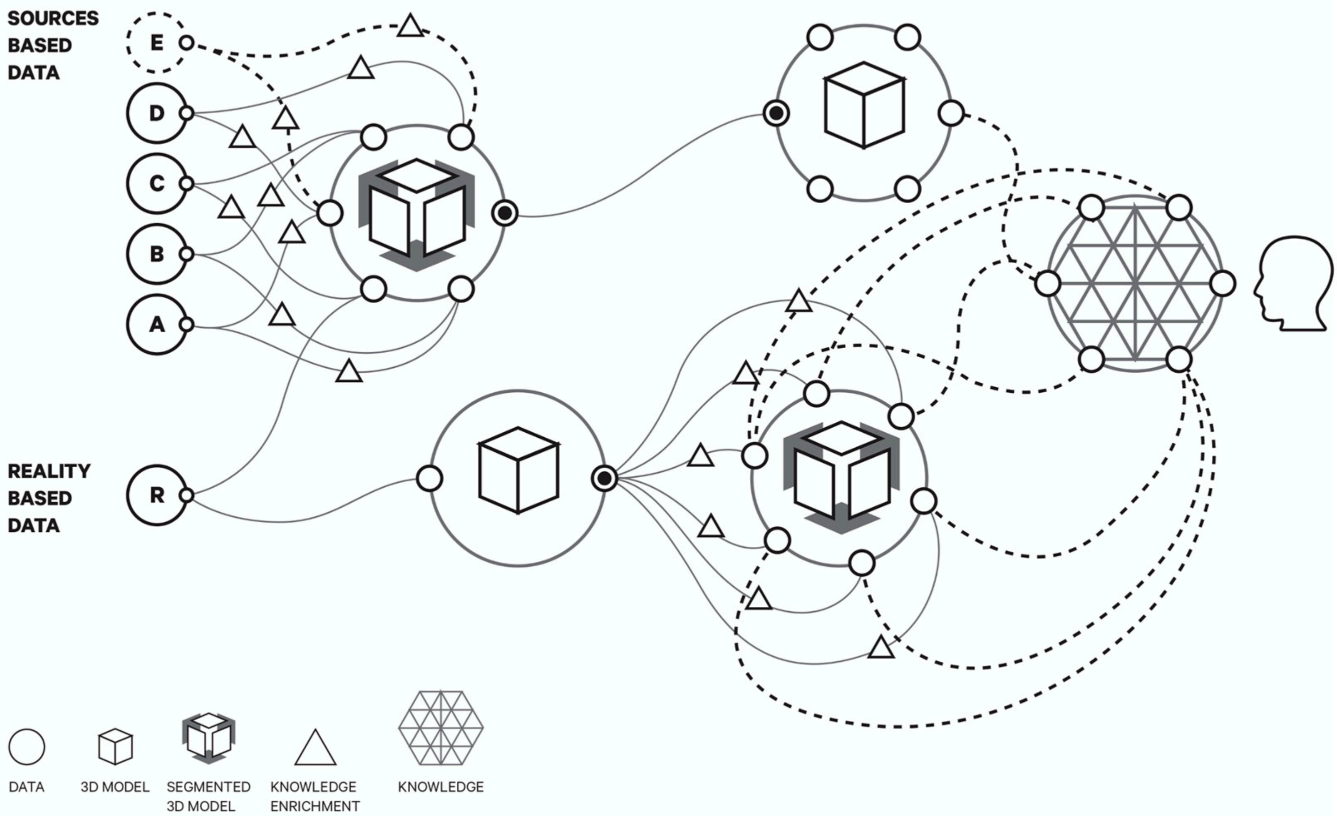

Figure 1. The reconstructive reality-based/sources-based procedure: conceptual map.

The conjecture is subjected to experimental checks to verify whether the predictions are realized, attempting to refute it (falsification); that is, to find errors, weak points, and inconsistencies to correct and improve it. Experiences and observations are important but, as can be seen, they are preceded by theory, unlike what happens with the inductive method.

In the search for errors, new problems may unintentionally emerge, which will form starting points for other searches.

If an error appears during the experimental verification, the hypothesis is falsified and a new conjecture must be formulated; if, however, it resists the evidence that attempted to refute it, the hypothesis is not confirmed, but is simply not denied and can be provisionally accepted as being more valid than others.

The scientific method adopted in the context of hypothetical 3D reconstructions can be traced back to Popper's deductive method, which involves three steps [58,59] as follows:

- Problem;
- Conjecture;
- Refutation.

It is a deductive method that proceeds through trial and error, conjectures, and refutations until it gets ever closer to understanding a given reality.

As Latour states [60], scientific fact must not be considered the starting point of the analysis with which influencing social variables are associated, but must be considered the result of a complex network of elements at play. A scientific result can proceed to scientific fact status only through the support and cooperation of a variety of allies that are internal or external to the laboratory or department.

According to Latour, and as reported by Margiotta [61], a scientific result and a technological object have in common the fact that they are 'black boxes', where it is extremely complex to understand the mechanisms that led to the creation of the result. We must limit ourselves to knowing only the incoming (input) and outgoing (output) elements. The results of the activities, once consolidated, are cited or used without being questioned anymore. Knorr-Cetina [62,63] distinguishes the "informal" reasoning that characterizes the laboratory from the "literary" reasoning that is the basis of the scientific article, whereas the need for transparent and reproducible scientific evidence should be for the thorough systematization and documentation of the 'informal reasoning' behind it. The scientific article, far from being a faithful "report" of the research carried out, is instead a subtle rhetorical exercise that "forgets much of what happened in the laboratory" and reconstructs it selectively. In the article, the process will be rationalized, and every move of the researcher will be organically derived from specific objectives set at the start.

The 3D model, as the result of a scientific research process, can allow us to overcome these limitations, but it must be able to guarantee the following values that are specific to science and scientific knowledge:

- Transparency (refers to the practise of openly sharing all aspects of the research process, including methodologies, data, analysis, and results, allowing other researchers to understand, evaluate, and replicate the study);
- Authenticity (refers to the genuineness, credibility, and trustworthiness of the study and its findings);
- Traceability and reproducibility (refer—on the one hand—to correctly documenting and tracking the origins of data and results throughout the research process and—on the other—to the ability of other researchers to duplicate the study and achieve the same results, ensuring that the findings are robust and reliable);
- Comparability (refers to the possibility of comparing with other outcomes in terms of analysis, error detection, data verification, and validity, etc.);
- Interoperability (refers to the practise of allowing the efficient exchange, integration, and utilization of information across diverse platforms to enhance collaboration, facilitate data sharing, and ensure that the research findings can be readily accessed and used by different researchers and institutions);
- Reusability (refers to the possibility of using the 3D model output for various applications, such as 3D printing, animation, analysis, etc.).

Three-dimensional modelling—oriented towards both the reconstruction [64] and the digitization of heritage objects [65]—takes up consolidated methods that were used in historical studies long before the advent of computer-assisted techniques [66]. Examples of this include the use of the model as a tool to study the appearance of architecture of the past or to construct one's buildings, which scholars have been using since the Renaissance [67–69], and when reconstruction acquired new importance in the field of the history of architecture [70] and of archeology [71,72], establishing itself as an autonomous discipline, especially regarding lost architecture.

Virtual 3D modelling techniques have added further layers of complexity of information and their transformations/interpretations (for example, through interpretation or selection of documentary sources [73,74]), as in the specific case of the 3D reconstruction of objects that no longer exist [10]. Three-dimensional digital modelling approaches require modelling (therefore, thinking and imagining) a building in a holistic way, restricting one's ability to be vague [75] and instead requiring one to be precise and accurate, both in measurements and in defining the shape of all architectural parts. As a result, 3D reconstructions force their creators to include any missing information that the available archeological data and documentary sources—due to gaps, incompleteness, and low graphic or descriptive quality—are not able to provide; for example, on parts of buildings not shown in the images or that are impossible to be readable/interpretable.

This increases the complexity of both the research process and the definition of a reconstruction method that satisfies the principles and their scientific values.

The methodology aims to rationalize and systematize the process of the hypothetical reconstruction of lost or never-built architecture, sharing the results through 3D models and encouraging the standardization of 3D scientific reconstructions at an international level, contributing to defining the 3D reconstruction of architectural models of the past as an autonomous discipline.

4. The 3D Model as a "Scientific Product": Definition and Use

Evidence that 3D models in the fields of architecture, archeology, cultural heritage, and digital humanities, in general, are taking on scholarly value is given, for example, by some scientific journals (i.e., *DAACH—Digital Applications in Archaeology and Cultural Heritage*, *Studies in Digital Heritage*, and journals from the publisher Taylor & Francis [76–78]) that have already opened their publications to 3D digital models of cultural heritage sites, monuments, and paleo-anthropological remains, accompanied by associated academic articles. The goal is to offer the possibility of a full peer review for all 3D models, encouraging their use like any other apparatus, by placing the models within the body of the article, similar to a figure, diagram, etc.

These are initiatives from policies aiming to democratize access to research, improve the inclusion of all stakeholders, strengthen accountability for research integrity, facilitate the self-correcting process of science, expand the transparency and sharing of all research content, and improve the rigour and reproducibility of research (TOP) [79]. To support open scientific exchange and enable best practises in sharing and archiving research data, it must also comply with the FAIR Principles [80,81]—Findable, Accessible, Interoperable, and Reusable—so that other researchers can find and use it.

In Barzaghi et al. [82], within a comprehensive literature review touching on other FAIR principles applied to cultural heritage data, the authors also discuss 3D models as cultural heritage research data, alongside their creation, selection, publication, archival, and preservation. Although 3D models offer unique insights and analytical opportunities in cultural heritage research and digital humanities, their adoption as a research product is still limited, due to a long list of reasons. The literature on FAIR principles and research data management in the humanities often overlooks 3D models as research data because of their limited adoption in the cultural heritage sector. The lack of shared standards for the publication and exchange of 3D digital assets limits access and usability, while inadequate metadata often hinders the assessment of the relevance of 3D models for future use, and many digital assets remain in private archives [83]. Blundell et al. [84] emphasize the importance of metadata throughout the life cycle of digital assets to address the specific needs of 3D models, urging the development of an interdisciplinary metadata standard. Quantin et al. [85] propose a FAIR-aligned solution for the long-term archiving and online publication of 3D research data, introducing a new metadata schema mapped to the Europeana data model [86].

For this reason, research data, including, but not limited to, protocols, analytical methods, raw data, processed data, code, software, algorithms, and study materials, must be deposited in a repository that enables preservation and open access for maximum reuse.

But for a 3D model to be considered and used as a scientific product, many steps must be taken, starting with its definition, such as in the context of research evaluation procedures. In some of these procedures, such as ANVUR-VQR [87], besides the traditional and established research products—such as monographs, journal articles, and contributions to conference proceedings—other products, such as thematic maps, drawings, prototypes of instrumentation, devices of technological interest, databases, software, etc., are also considered.

Furthermore, the maturity achieved and the wide dissemination and production of 3D models in the fields of architecture, archeology, cultural heritage, and digital humanities should be considered among the products of research, as highlighted in the seminar on 'Information and Training Seminar on Evaluation' [88] (p. 14).

But, to substantiate this definition, something else is also needed. Picking up on what was stated by Koller et al. [42], some progress has been made in some recent research areas, i.e., CoVHer [38] and DFG-Netzwerk's "Digitale 3D-Rekonstruktionen als Werkzeuge der architekturgeschichtlichen Forschung" [22], trying to define

- shared good practises;
- reference standards for the academic/scientific community;
- a common and shared nomenclature;
- an appropriate taxonomy.

But most relevant is the possibility to create platforms that are able to assure the long-term preservation of models resulting from scientific research [42]. These platforms should allow for the verification, transparency, repeatability, and refutation of scientific findings. Additionally, they should enable the evaluation of results through formal geometric accuracy, descriptions of the methodology adopted, clear and transparent documentation, visualizations of 3D models, and their related uncertainty in the hypothetical reconstruction process.

From its starting point, the analysis and interpretation of data on which any hypothetical reconstruction models are built accumulate an unknown degree of uncertainty and are therefore unpredictable and unquantifiable [27,89]. Subjectivity, in fact, in the interpretation of data is perfectly normal and should not undermine our overall confidence in science. Without a certain degree of confidence, expressed by the uncertainty of the incorporated data, the final model cannot be criticized or adequately evaluated from an academic point of view. Very often, uncertainty and reliability are understood and used as alternative and complementary terms, but from an epistemological point of view, they are not [90]. In principle, scientific research should be reliable and valid when it comes to measurements and data collection. Reliability, in fact, consists of obtaining the same result every time the same instrument and the same method are used under the same circumstance to make the same measurement. Validity refers to how accurately a method measures what it is intended to measure. Uncertainty, on the other hand, due to the innate subjectivity that characterizes all data collection, analysis, and interpretation, is inherent in science [91] (p. 221), [92] (p. 116), [93] (pp. 62–84). The information necessary to complete the hypothetical virtual model cannot always be obtained uniquely and unambiguously from the data sources or drawings we have at our disposal. Faced with the complexity that characterizes any hypothetical reconstruction procedure, we have no choice but to rely on models; this means idealization and approximation [94] (pp. 34–35). Given our limitations and the complexity we have to deal with, this means that the explanations produced in any area of science are uncertain [95] (p. 23). Another source of uncertainty in scientific explanations is that we are always working with limited information; we have increasingly limited and indirect epistemic access to the past the further back our field of study goes. All the information collected, analyzed, and interpreted can be conveyed using different visualization technologies, defining a structured modelling process based on different levels of interpretation, which is characterized by a progressively increasing ordinal scale of uncertainty.

The hypothetical reconstruction procedure (see Figure 2) is influenced by various factors, each of which plays its role and has its weight in reaching the outcome. Therefore, a structured modelling process is based on different levels of interpretation, characterized by a progressively increasing level of uncertainty. Different types of information (deduced or induced) can be conveyed through different solutions, adopting (i) new 3D symbology (e.g., a set of 3D glyphs), (ii) visualization animation techniques, (iii) rendering techniques, and (iv) a combination of text metadata and 3D visualization.

In [96], a method that uses density slicing colour to represent uncertainty was first proposed, and was then further developed [97,98] based on the definition of a structured modelling process and different levels of interpretation. The degree of uncertainty of reconstruction is displayed by a sliding pseudo-colour scale that divides the rendered objects into a few colour bands to express the separate levels of interpretation/uncertainty.

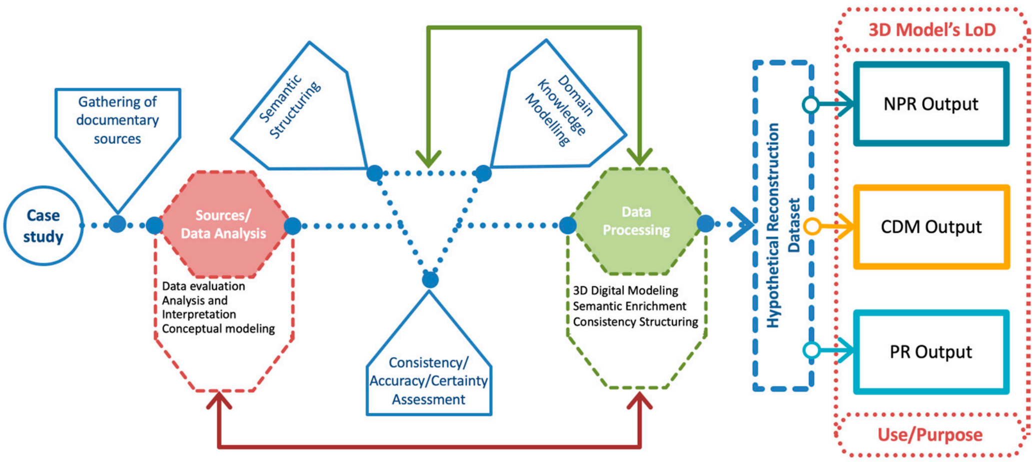

Figure 2. Hypothetical reconstruction workflow (NPR is for Not Photo-Realistic; CDM is for Critical Digital Model; PR is for Photo-Realistic).

This first proposal was only able to represent the different levels of uncertainty linked to the coherence/relevance of the data sources used. Any hypothetical reconstruction, in fact, is not a binary process, but a more complex and interconnected analysis and interpretation of documentary sources involved and/or characterized by different degrees of

- Coherence/relevance;
- Accuracy/quality of data;
- Subjectivity/objectivity.

A schematic representation of the interference and interconnection between these three aspects is in Figure 3, where each node of the mesh (which is not hierarchically presented, meaning that each of the three sides of the conceptual map do not represent a kind of scale, increasing from one edge towards the other) represents the different levels of the interrelationship between coherence, accuracy, and subjectivity (and their own elements which they are composed of) in the definition of each constituent element of the reconstructed artefact.

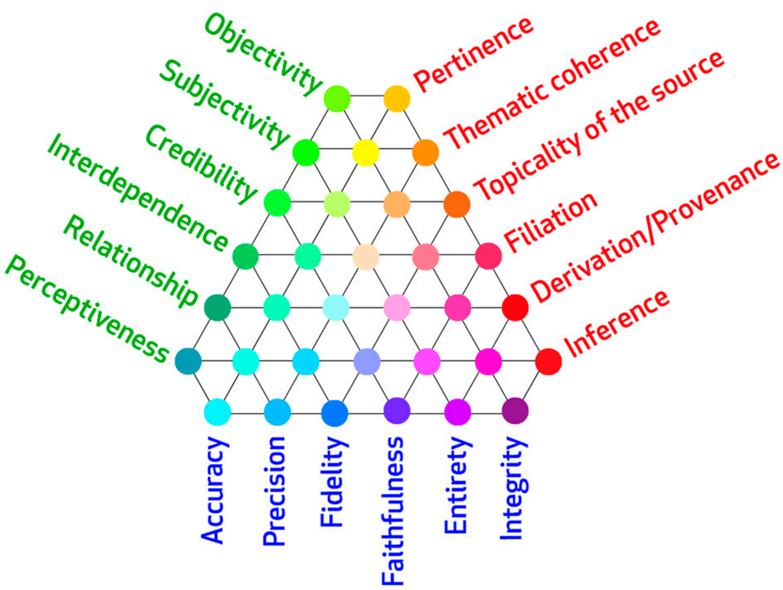

Figure 3. The interrelation between coherence, accuracy, and subjectivity: conceptual map.

5. The Latest Projects and Proposal Defining and Using 3D Models as a Scientific Product

Regarding, however, the development of platforms for sharing 3D models as products of research [99,100], some of the main examples can be found in Germany, mainly thanks to the long tradition of research and activities dedicated to digital reconstruction, including DFG -Netzwerk and Arbeitsgruppe Digitale 3D-Rekonstruktion [22,23].

The IDOVIR research project [101] aims to make results in the field of digital architectural reconstruction available in a comprehensible, permanent, and open access form and to facilitate the scientific discussion of research results. Central to this project is textual argumentation; that is, a qualitative analysis that connects a digital reconstruction with the sources and which only allows us to trace the connection between the sources used and the reconstruction. At the same time, the project infrastructure should significantly support and structure the communications of those involved in the genesis of a reconstruction [102].

DFG-3D Viewer [103] constitutes a 3D digital visualization infrastructure for 3D historical reconstructions that are capable of offering a permanent infrastructure, providing, on the one hand, the sustainable accessibility and archiving of raw datasets and meta-information, and, on the other, enabling collaboration by generating 3D web models from common data types, as well as professional discourse on virtual models [104–106].

Other international projects, again over the last few years, have begun to define some methodological issues, such as through the Scientific Reference Model (SRM), a low-threshold method which is used as a documented and published basic model. The structured SRM represents an important state of work and knowledge, which clarifies essential information about the object, its components, its credibility or scope of hypotheses, and copyright. This SRM is made available for further research, modification, and refinement, as well as for further derivatives (special applications). Therefore, the SRM represents a traceable referential outcome of an academic investigation into a material object that physically no longer exists [107].

Similar is the case of the Critical Digital Model (CDM), which aims to be able to characterize the descriptive qualities of the 3D model produced by a hypothetical reconstruction, including the following: the construction aspects, geometric accuracy, and qualification of the 3D models; traceability, use of sources and documentation, and quality of historical reconstruction; accessibility and interoperability, as well as compatibility with publication on platforms/repositories and data model exchange formats; and visualization and graphic outputs to communicate scientific content through 3D models [108].

Another example is a proposed methodology that aims to rationalize the reconstruction process of architecture that no longer exists or was designed but never built. As thoroughly stated in [108], such methodology should centre on the sources; the method of representation; and the visualization. The methodology presented is based on an iterative process of calibrating inputs and outputs based on the reiteration of experiments. It is a two-fold methodology, concerning, from one point of view, comparable models of identifiable sources that can be used and reused according to different purposes (e.g., visualization, creation of a virtual environment, historical record, analysis, geometric study, 3D printing, etc.) (see Figure 4). Yet, from another point of view, the methodology also focuses on fostering learning and on facilitating and promoting knowledge related to architectural cultural heritage.

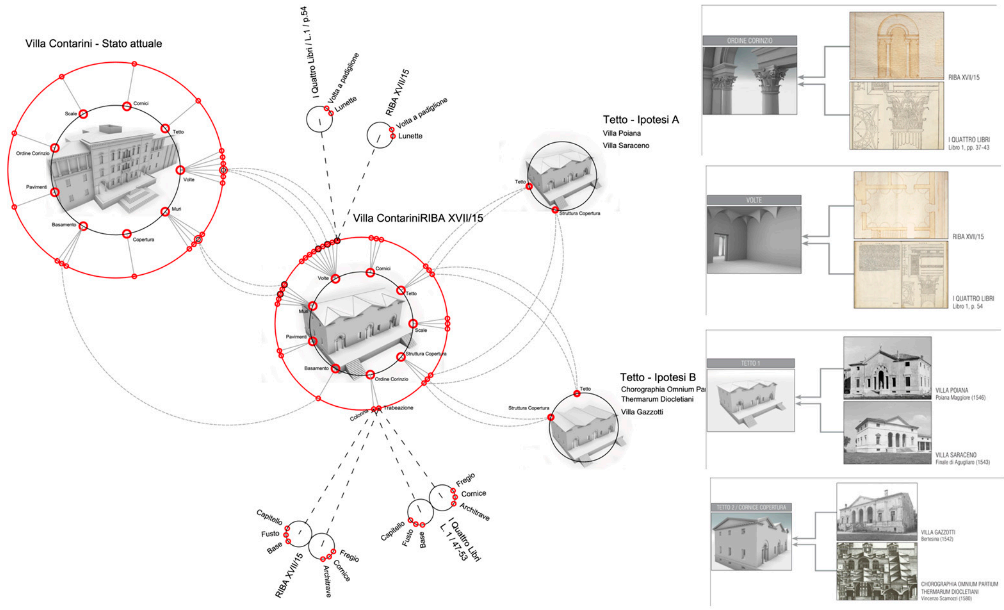

Figure 4. Formalization of semantic knowledge: cognitive graph.

6. Conclusions

So far, despite the long tradition of definition of charters and principles, neither an academic culture nor mechanisms that are capable of making 3D digital models scientifically evaluable, reusable, and refutable have yet been established. Some ongoing research, in addition to a series of technical requirements, includes developing methodological and procedural approaches, trying to define the levels of standardization at the level of nomenclature and taxonomy that are capable of providing tools and means to document procedures and their results, as well as making the logic underlying each 3D model transparent.

The level of maturity reached in this area, thanks to the effort made in the analysis and systematization of the theoretical and practical aspects of the discipline, can help share hypothetical 3D reconstructions as scientific products and contribute to the increasing awareness that not all methodologies produce results that suitable for any type of scientific use.

A proposed definition of the 3D model as a scientific product could be as follows:

A 3D model (or three-dimensional model) resulting from a 3D digitization or a 3D reconstruction is meant as a mathematical representation of a three-dimensional object, in which the information contained is structured and linked together according to a particular logical model (semantic structure). To be submitted for evaluation, it must present recognizable elements of specificity concerning pre-existing (reality-based) 3D models or the results of a logical-deductive procedure that, through the interpretation of data, creates a hypothesis of a past object, can be linked to publications, or can be accompanied by documentation that is suitable for adequate evaluation. It must also be uniquely identifiable and unambiguously referable to the author(s)/creator(s) who created the 3D model to be evaluated.

The hope is that the debate and research conducted will favour and encourage an even greater standardization of 3D scientific reconstructions at an international level and contribute to defining the 3D reconstruction of architectural models of the past as an autonomous discipline.

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