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3D Research Challenges in Cultural Heritage V

Paradata, Metadata and Data in Digitisation

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Editors

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Contents

Documentation and Publication of Hypothetical Virtual 3D Reconstructions in the CoVHer Project

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Abstract. The CoVHer Erasmus+ project addresses the long-standing lack of standardisation in hypothetical virtual 3D reconstruction and modelling in architectural heritage research. It aims to develop best practices for the 3D reconstruction of lost or never-built architectural heritage, enhancing research quality, transparency, and reusability. The collaborative effort includes contributions from five European universities and two private companies, focusing on architecture, archaeology, digital humanities, and art history. The presented workflow of documentation is the result of the joint effort in extensions of the approaches of the Scientific Reference Model (SRM) and Critical Digital Model (CDM), which strive for faithful reconstruction, documenting all decisions and inferences and advocate open licensing and use of non-proprietary formats to promote accessibility and reusability. The developed methodology aims to provide tools for the scientific evaluation of hypothetical reconstructions and support data exchange between researchers.

Keywords: hypothetical virtual 3D reconstruction · lost and never-built architectural heritage · computer-based visualisation

1 Introduction

Virtual 3D reconstruction and 3D modelling in architectural heritage research have lacked standardisation for many years. Significant theoretical issues and unresolved challenges persist, particularly regarding the documentation of procedures, decision-making processes, methods employed, and results sharing. Despite well-known theoretical guidelines [1, 2], the academic community involved in virtual 3D reconstructions has yet to reach a consensus on a unified standard for scholarly approved 3D models.

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The CoVHer Erasmus+ project[1] aims to address these issues by developing and promoting best practices for the hypothetical virtual 3D reconstruction of lost or never-built architectural heritage. This research presents a methodology to improve the quality, transparency, and reusability of 3D models. This collaborative effort includes contributions from various disciplines, including architecture, archaeology, digital humanities, and art history.

The method developed is based on the principles of the Critical Digital Model (CDM) and Scientific Reference Model (SRM). The CDM aims to reconstruct objects of study as faithfully as possible to the original author's intent at a specific moment, documenting all subjective choices, additions, and inferences [3]. The SRM can be considered as the predecessor of CDM. It is a clearly described methodology, explaining step by step how to prepare and structure the project of the reconstruction, tearing attention to the aspect of using data exchange formats and open access repositories for sharing and re-using the results [4]. By using these methodologies as foundations, the CoVHer project emphasises the need for an appropriate rigour of work in terms of structured data acquisition, semantic enrichment of the 3D model, assessment of the scientific value and sustainable data sharing.

2 Data Acquisition: Capturing the Process

The data acquisition process is critical to accurately and reliably reconstruct lost or hypothetical architectural heritage. This process involves collaboration with other scientific disciplines, each with its own standards and methods, which has made a single standard for data acquisition impractical until now. The European CoVHer project outlines methodologies and best practices to ensure scientific integrity and transparency in data collection and acquisition.

Proper documentation, including metadata and paradata, is essential for transparency and future research. Metadata details the sources, dates, accuracy, and significance of data points, while paradata records decision-making processes, assumptions, uncertainties, and limitations during reconstruction. Scientific research and archaeological discoveries, as well as original architectural drawings, constitute the documentary sources incorporated to enhance the accuracy and authenticity of the reconstruction.

Advanced digital techniques, [5] such as 3D scanning, photogrammetry and laser imaging, capture detailed data, which undergo critical analysis and verification to ensure accuracy and reliability. All that data needs thorough critical analysis and verification to assess its accuracy and reliability [1].

This involves identifying and addressing uncertainties and inconsistencies in the data to enhance the overall reliability of the reconstruction. [3] Evaluating the precision and correctness of the data collected from various sources and clearly documenting the assumptions, uncertainties, and limitations encountered during the data acquisition process provide context and transparency.

The CoVHer project aims to set clear objectives, adopt rigorous methodologies, and ensure comprehensive documentation through metadata and paradata. This structured

[1] Project Number: 2021–1-IT02-KA220-HED-000031190. More information about project is available on the website https://covher.eu/, last accessed 2024/07/27.

approach facilitates comparison between virtual reconstructions and progress in the field. An example from the AFRIPAL[2] project, focusing on the city of Mustis in Proconsular Africa, illustrates the reality-based data acquisition framework. The project's data collection follows the principles of CDM and SRM and the Integrated Digitally Enabled Environment (IDEE), [6] enabling digital data processing, analysis, storage and sharing. The following case shows how, at the data-capturing stage, the information that forms the basis for the Informative Model (IM) was entered into the Raw Model (RM). The organisation of data acquisition was based on the following framework presented in Table 1.

Table 1. Framework for the organisation of data acquisition

Scope and data sources	Objectives	Recipients
• Photogrammetric models of individual details and objects • LiDAR 3D scans • Geodetic surveys • Archaeological surveys • Archive images	• Archaeological and architectural documentation • Virtual 3D reconstruction in BIM with attributed information, data, and sources • Virtual anastylosis of scanned elements • Publication of results – informative virtual tour • Archaeological and architectural documentation	• Professionals • Laypersons

On-site data collection utilized a Network-Attached Storage (NAS) system, with files uploaded and archived daily. The data organization involved coordinating existing and new systems. An excavation plan was created using an orthophoto map from a Unmanned Aerial Vehicle (UAV) and geodetic survey points, subdivided into a 10x10 meter grid with marked structures (Fig. 1a), facilitating collaboration among researchers and simplifying analogue data collection. Due to limited excavation time and weather, correct naming (Fig. 1b) of digital files and paper documentation was crucial.

Photographs for documentation and photogrammetry included an in-camera prefix (e.g., C2_B5_L2_number) for systematic naming. Post-organization used this prefix as a

[2] The archaeological work was conducted under the project "(Reading) African Palimpsest: The dynamics of urban and rural communities of Numidian and Roman Mustis (AFRIPAL)," a grant from the National Science Centre (NCN), no. 2020/37/B/HS3/00348. The directors of the project are Jamel Hajji (Institut National du Patrimoine) and Tomasz Waliszewski (University of Warsaw).

keyword in IPTC metadata[3] managed by a script in ExifTool[4], saving time by automating the process for approximately 33,000 photographs.

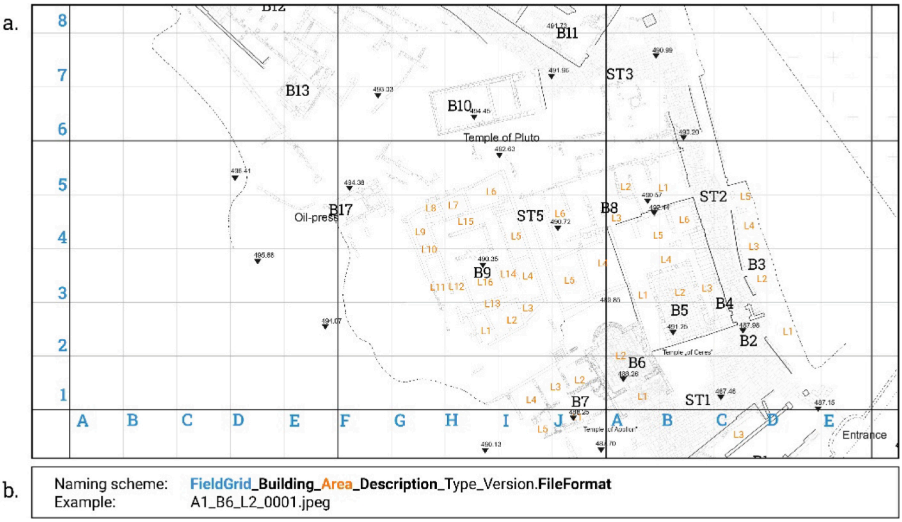

Fig. 1. a: Excavation plan with 10 m 10 m grid, building and area labels. Drawing by Magdalena Antos. b: Naming scheme for files (bold ones required)

Systematic naming enabled filtering of images in cataloguing software (e.g., Adobe Lightroom Classic) by specific areas or structures. Additional keywords, such as indexes of architectural elements, were added to classified images, which were then used to create photogrammetric models. The same process tagged archive images, previous photographs, and LiDAR scans, following manual data verification and interpretation. It was preceded by manual verification and interpretation of the data in BulkRenameUtility[5].

3 Semantic Enrichment of 3D Models

The beginning of the development of a hypothetical virtual 3D reconstruction is the preparation of the semantic segmentation of the model into elements that can be given a specific meaning. Semantic segmentation is the essence of working with heritage assets because it is the culturally encoded meaning that gives a physical object its historical value. It is then the clue of the digitalization process to maintain object's significance

[3] International Press Telecommunications Council. (2024). *IPTC Photo Metadata Standard* (Version 1.4). Retrieved from https://iptc.org/standards/photo-metadata/, last accessed 2024/07/24.

[4] Harvey, P. (2024). *ExifTool* (Version 12.58) [Software]. Available from https://exiftool.org/, last accessed 2024/07/24.

[5] TGRMN Software. (2024). *Bulk Rename Utility* (Version 3.4.3) [Software]. Available from https://www.bulkrenameutility.co.uk/, last accessed 2024/07/24.

through such semantic enrichment. Without semantic segmentation and enrichment, we only have raw models that are of limited use in the scientific field. This leads to a data classification that should be determined to integrate the relevant Levels of Geometry (LoG) and Information (LoI). The use of Building Information Modelling (BIM) allows for the definition of such information within the Level of Information Need standard. [7] This encompasses not only the aforementioned LoG and LoI coefficients but also the analysis of the purpose of the data (Why?), the timing of its delivery (When?), the responsible party (Who?), and the specifics of its delivery (How and What?) (Fig. 2).

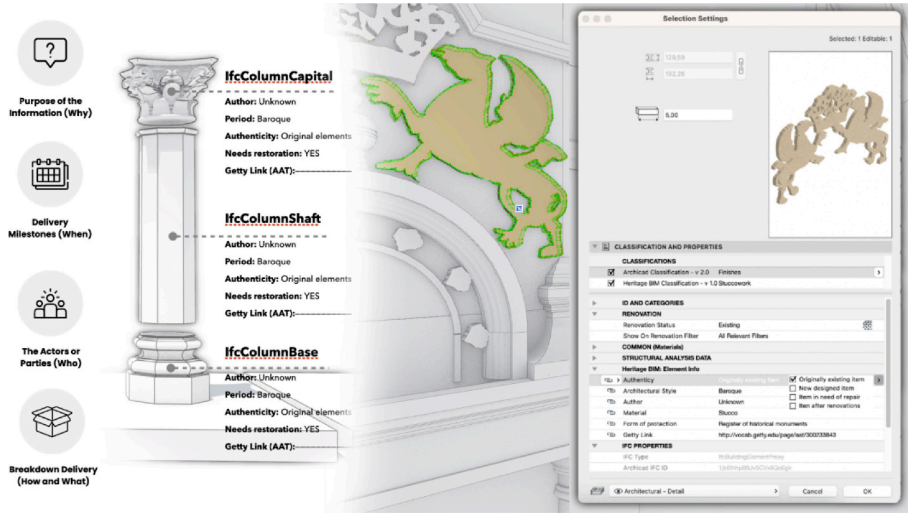

Fig. 2. Level of Information Need and classification assessment in BIM software of choice – Graphisoft Archicad.

To ensure correct data interpretation and its accessibility to researchers, it is essential to use interoperable data formats. OpenBIM standards, part of BIM, facilitate direct communication and data exchange through taxonomies and ontologies in building SMART data dictionaries (bSDD). The recommended format for exchanging model data is the Industry Foundation Classes (IFC) format, which ensures interoperability and consistency among different platforms and stakeholders.

Effective models require meticulous geometric and semantic segmentation. Geometric segmentation represents spatial relationships of heritage assets, while semantic segmentation adds meaning to elements, contextualising and naming them. Semantic enrichment involves integrating comprehensive metadata and paradata into 3D models, including attributes like material properties, historical context, and state of conservation and the level of uncertainty. This detailed information aids heritage interpretation, management, and risk reduction.

Integrating model data with metadata and paradata enhances the precision and efficiency of creating virtual reconstruction models. These 3D models can incorporate complex geometries of individual building elements and detailed semantic data provided by experts, resulting in more accurate and informative virtual reconstructions [8].

4 Scientific Value Evaluation: Knowledge Representation in Terms of Levels of Uncertainty

Semantically segmented and enriched 3D models are knowledge representations by themselves and are more than an interface to embedded knowledge. Proper documentation and dissemination are necessary to make this embedded knowledge accessible. A key aspect is assessing and communicating the reconstruction's uncertainty. One effective method is using uncertainty scales, which investigate and visually communicate the uncertainty of each element in the 3D model through false-colour views.

Colour Code			Uncertainty	Description
1.5	1	1	lowest uncertainty (~0 to 14% uncertain[1])	The analysed feature[2] of the 3D model is derived mainly from good quality **reality-based data**, which reaches the target LoD[3].
	2	2	low uncertainty (~14 to 28% uncertain)	Reliable conjecture based mainly on clear and accurate **direct[4] / primary[5] sources**, which reach the target LoD. When reality-based data is unavailable, available but unusable, or not reaching the target LoD.
4.5	3.5	3	average-low uncertainty (~28 to 43% uncertain)	Conjecture based mainly on **indirect/secondary sources**, by the **SAME AUTHOR/S**, which reach the target LoD. Or logic deduction/selection of variants. When **direct/primary sources are available**, but minimally unclear, damaged, inconsistent, inaccurate, or not reaching the target LoD.
		4	average uncertainty (~43 to 57% uncertain)	Conjecture based mainly on **indirect/secondary** sources by **DIFFERENT AUTHOR/S** (or unknown authors), which reach the target LoD. When **direct/primary sources are available**, but minimally unclear, damaged, inconsistent, inaccurate, or not reaching the target LoD.
	5.5	5	average-high uncertainty (~57 to 71% uncertain)	Conjecture based mainly on **indirect/secondary sources** by the **SAME AUTHOR/S**, which reach the target LoD. When **direct/primary sources are not available** or unusable.
		6	high uncertainty (~71 to 86% uncertain)	Conjecture based mainly on **indirect/secondary** sources by **DIFFERENT AUTHOR/S** (or unknown authors), which reach the target LoD. When **direct/primary sources are not available** or unusable.
7	7	7	highest uncertainty (~86 to 100% uncertain)	Conjecture based mainly on personal knowledge due to missing or **unreferenced sources**.
\	\	\	abstention	not relevant, not considered, left unsolved, missing data and missing conjecture (it does not count for the calculation of the average uncertainty)

Fig. 3. Source-based CDM scale of uncertainty

Various scales for assessing and visualizing uncertainty in 3D reconstructions exist [9–11], each with different descriptions, granularity, and colours. These scales sometimes extend into multidimensional matrices (e.g., extended matrix[6] [12]). Despite the recognition of the importance of uncertainty assessment and visualisation, a shared standard approach is lacking due to the need for tailored scales for specific projects, which compromises comparability across projects.

The CoVHer Erasmus+ project developed good practices to create new scales of uncertainty that are reusable, exhaustive, unambiguous, and objective. These principles ensure the scales' reusability in similar contexts, completeness, lack of overlap, and user-independence. The scale developed for the CDM [3] was improved and extensively tested in the CoVHer project, proving effective for assessing hypothetical reconstructions of lost or never-built architecture (see Fig. 3). [13] Additionally, a new methodology for mathematically quantifying average global uncertainty was introduced.

The methodology introduces two mathematical formulations to quantify uncertainty in a clear, synthetic, transparent and user-independent manner. These formulas yield a single percentage value by averaging the uncertainties of each element, weighted by their volume and possibly a user-assigned relevance factor. This provides a concise summary of uncertainty assessment, useful for quick comparisons of hypothetical reconstructive models in 3D web-based repositories. However, these synthetic measures should complement, not replace, false-colour visualisation.

The formulas are Average Uncertainty weighted on the Volume (AU_V) and Average Uncertainty weighted on the Volume and Relevance (AU_VR). It is important to note that higher uncertainty in hypothetical reconstructions does not imply lower scientific value; well-documented high-uncertainty models can enhance understanding by critically integrating diverse sources and advancing scientific discourse.

5 Publication of the Results: Open Infrastructure for Virtual 3D Reconstruction

The scientific community still perceives 3D models as a tool for visualisation in the form of renderings, but not as a result worth of a 3D publication in the sense of sharing the 3D model. 3D data is often unavailable, and when data is published, it is not prepared for reuse or verification. Therefore, the CoVHer project adopts the SRM approach by designating proper data publication as a determinant for research transparency. The data publication package should consist of three parts: documentation of the modelling, analysis and decision-making (paradata), a 3D model prepared for reuse in an open data exchange format (3D data), and an appropriate package of contextual information about the published 3D resource (metadata) [4].

5.1 Paradata

Virtual 3D reconstructions are a multi-stage process. In addition to the mentioned earlier documentation of data acquisition and evaluation of uncertainty, considerable relevance

[6] ExtendedMatrix-Glossary, https://www.extendedmatrix.org/discover/glossary, last accessed 2024/07/24.

is also attributed to the analysis of historical source materials. Documenting the decisions made at work can be time-consuming and requires appropriate structuring. Therefore, the Reconstruction-Argumentation Method (RAM) [14] is used within the platform IDOVIR[7]. This method is based on a pre-determined semantic division of the object and assigns sources and argumentations to identified elements. The IDOVIR guarantees consistency with predefined templates and the rapid generation of paradata packages. These packages include the visualisation of the sources in combination with their interpretation alongside the argumentation. The metadata provides the necessary copyrights and serves as scientific citations but can also be marked hidden if the copyright is not clarified. This step is still necessary, even though the EU copyright law is changing. [15] The latest updates of the IDOVIR also include bibliographic input, enhancing the traceability of decision-making based on various authors.

5.2 3D Data

Publication of 3D data is challenging due to the lack of standardised formats and the variety of modelling techniques and software. Creating a reusable 3D file that integrates easily with other data requires following specific rules. Guidelines in this matter for data on the web were developed as a 5-star deployment scheme for Linked Open Data[8]. Those assumptions can be translated towards 3D data.

The minimum required in terms of data publication to gain one star is to make the file available under an open licence (OL). Two stars can be achieved if our model has structure (MS), which, in the case of models, can be applied by use of structure in the model layers. Three stars requires file conversion to one of the neutral formats (NF). Four stars require the attachment of a set of structural elements properties (SEP) of the model, and five stars require the addition of a link to external data repositories to provide context to the information and creation of a Linked Open Model (LOM) [4].

Achieving four stars on this scale requires open, structured formats that preserve the semantics of the objects. Formats that meet these requirements include IFC and City Geography Markup Language (CityGML). Both formats successfully stored information on virtual 3D reconstruction during courses with architecture students who tested the formats as part of an elective class on the virtual reconstruction of wooden synagogues [16].

5.3 Metadata

Despite many metadata schemas for cultural heritage objects, no solution has been found for the hypothetical 3D reconstruction of cultural heritage. Current 3D repositories either omit issues related to research uncertainties or do not address them comprehensively. [17] The problem is related to the heterogeneous nature of 3D reconstructions. They are digital products requiring technical specifications and copyright declarations, typically provided in commercial repositories oriented for data reuse. Additionally, 3D models are used to visualise history, which many cultural heritage repositories prioritise over technological

[7] https://idovir.com/, last accessed 2024/07/24.

[8] https://5stardata.info/en/, last accessed 2024/07/24.

aspects. Furthermore, 3D models are part of research, with metadata usually found only in specialised virtual research environments (VRE) [18].

The CoVHer project addresses these challenges by presenting a documentation scheme combining all these aspects in a new web-based open-access repository according to the SRM approach. Developed within the framework of the VRE WissKI[9], it provides triplestore storage using the CIDOC CRM-referenced application ontology of OntPreHer3D[10], oriented towards creating data deposits in the repository. It is a further development of OntSciDoc3D ontology, which was tailored for documentation in VRE. [19] The system uses five main documentation units: people, organisations, projects, heritage objects and virtual reconstructions. Users create semantic relationships between those units during data input. Entities are referenced through identifiers pointing to controlled vocabularies and authority files to reduce data ambiguity. In the end, ontologically encoded metadata, supported by controlled vocabularies and a package of 3D files and paradata, allows the creation of comprehensive scientific documentation of 3D models (Fig. 4). This publication supports future model reuse for applications like 3D printing or virtual reality. The interoperability of 3D file formats provides a solid foundation for creating derivatives aimed at disseminating lost architectural heritage, with reference to relevant documentation.

6 Conclusion

This study presents the current methodology for working with hypothetical virtual 3D reconstructions of lost or never-built architectural heritage developed as a combined interdisciplinary effort by the CoVHer project. The method follows the guidelines of the London Charter and the Seville Principles, shaping a practical (or applicable) way of publishing hypothetical 3D models while preserving the transparency of the reconstruction process and guaranteeing easy access to the research data through precise documentation, self-assessment of the model's level of uncertainty and the accessibility of the research data within a semantic data repository, ontologically tailored to the needs of hypothetical virtual 3D reconstructions. The methodology encourages the creation of paradata through documentation, enriches the research object with metadata, and provides access to the research data through standardised exchange file formats. Thus enabling the assessment of its scientific value. The authors are convinced that the proposed methodology - if followed conscientiously - will lead to a significant rethinking that could establish 3D model-based hypothetical research as a key discipline in the field of cultural heritage. Based on the experiences throughout the workshops, the CoVHer project is testing and establishing a general curriculum on hypothetical 3D reconstructions that is rooted in the concepts of the proposed methodology and aims for the promotion of scientific practices in various disciplines that deal with cultural heritage.

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9 WissKI is a free and open virtual research environment for managing scholarly data and provides benefits of semantic web technology. It works in Drupal content management framework, Available from: https://wiss-ki.eu/, last accessed 2024/07/27.

10 Development of OntPreHer3D ontology can be followed on: https://github.com/igorbajena/OntPreHer3D/, last accessed 2024/07/27.

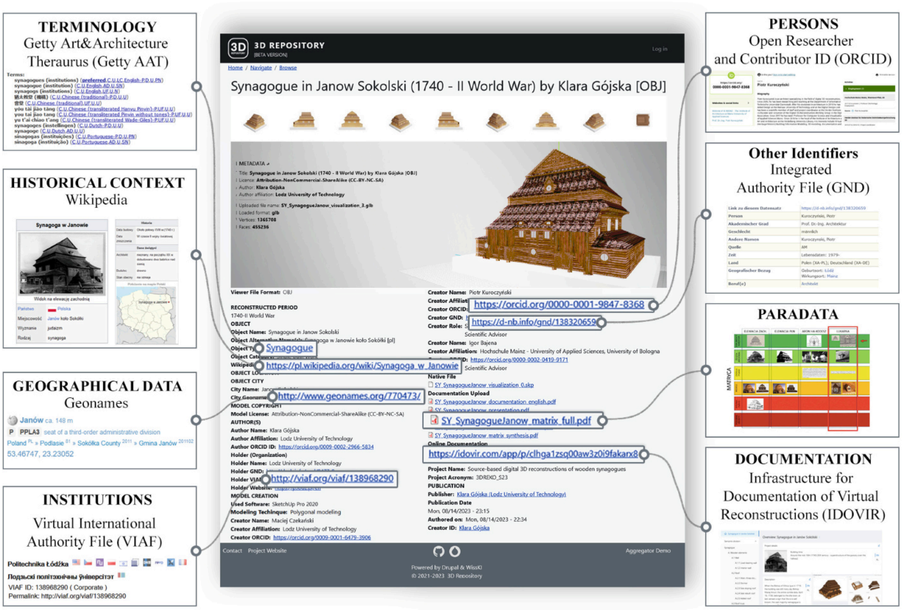

Fig. 4. Cross-referencing of context data on the example of virtual 3D reconstruction of the synagoguein Janów Sokolski by Klara Gójska and Maciej Czeka ski. Entry created during the seminar about virtual 3D reconstruction of wooden synagogues

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