Long Paper

Challenges Faced in Documentation and Publication of 3D Reconstructions of Cultural Heritage

How to Capture the Process and Share the Data?

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Abstract: This paper presents significant challenges in documenting and publishing source-based hypothetical 3D reconstruction of Cultural Heritage (CH). The authors focus on the lack of standardized procedures, difficulties in data sharing due to diverse file formats, and technological limitations in web-based model viewing. They highlight the role of key guiding documents, namely the London Charter (LC) and the Seville Principles (SP), which outline principles for computer-based visualization and virtual archaeology. While these documents emphasize the need for documenting uncertainties, sources, authenticity, and historical rigor in 3D reconstructions, they lack detailed practical implementation guidelines. This gap has led to varied documentation approaches in related fields such as archaeology and architectural history. The authors also discuss principles for the publication of data, including FAIR Principles and the 5-Star Open Data Scheme introduced by Time-Berners Lee. Three main methods of documentation, namely the Knowledge Graph, Reconstruction-Argumentation-Method (R-A-M) and web-based visualization, are examined. Each of these methods offers different advantages and meets varying principles of LC and SP. Three publication methods based on the virtual research environment (VRE), using SciDoc, an institutional repository for documentation of digital reconstruction projects, and Sketchfab, a commercial repository for 3D models, are also discussed. The paper concludes with a presentation of the DFG 3D-Viewer, an infrastructure project for the publication of digital reconstructions and a proposal for a basic metadata schema. The shared metadata schema is a first step towards developing methods for archiving 3D models. The authors also advocate for collaborative efforts among stakeholders and funding institutions to develop standard, comprehensive solutions for preserving digital reconstructions of CH.

Keywords: *3D Models—Documentation—Web-Publication—Metadata Scheme—Source-Based 3D Reconstruction*

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Introduction

The history of humankind has already shown numerous cases of our heritage becoming irreversibly lost. However, emerging technologies provide an opportunity to recreate echoes of the past in the form of digital reconstructions of lost Cultural Heritage (CH). The field of a digital source-based hypothetical 3D reconstruction of material CH (3D reconstruction, in short) allows investigation of the history of the building and presentation of the research results in an easy-to-understand, visual way. Visual communication of the results of research into lost CH also carries the risk of incorrect interpretation. Information related to the level of hypothesis and uncertainty tends to be omitted from 3D models despite the real cognitive value of this type of work lying in the (hi)story behind the creation of the model. The lack of shared standards when it comes to the documentation and publication of 3D modelling of CH means that the history of this process is rarely made public. This, inevitably, results in a loss of valuable information and knowledge. Sharing 3D data is also challenging due to the wide range of existing file formats and their specifications. Without specific standards for data sharing, access to 3D models is difficult (Kuroczyński, 2017). While technical solutions for viewing models on the web are improving, they are technologically limited. Complex models remain difficult to display and often require adaptation to a specific web viewer.

These issues have been taken up as a subject of scholarly discussion by diverse communities. 3D reconstructions were initially regarded as mere visualizations and slow to be recognized as a scholarly method. The summary of these efforts was the publication of the London Charter (LC) in 2006. This document focuses on computer-based visualization and defines principles in terms of implementation (Principle 1), methods and aims (Principle 2), sources (Principle 3), documentation (Principle 4), sustainability (Principle 5) and access (Principle 6). Implementing these principles demands intellectual and technical rigor, which allows the recognition of 3D reconstruction models as scholarly viable. Following the LC, the Seville Principles (SP), published in 2011, describe the application of LC to virtual archaeology of which 3D reconstruction is an integral part. In addition to digitally bringing the excavated object back to life the SP stipulates points specific to digital CH work, which do not appear in the LC. Eight categories of principles are specific to SP: interdisciplinarity (Principle 1), purpose (Principle 2), complementarity (Principle 3), authenticity (Principle 4), historical rigor (Principle 5), efficiency (Principle 6), scientific transparency (Principle 7) and training and evaluation (Principle 8). The principles in the two said documents set out basic criteria for assessing the scholarly value of work related to the use of digital visualizations in the study of lost CH, emphasizing the need to document the 3D model in terms, *inter alia*, of uncertainty, sources, authenticity, and historical rigor. However, no examples of how to prepare the documentation are presented, leaving interpretation of these general principles open. Consequently, in object-oriented disciplines such as archaeology, art, and architectural history, accessibility, and reusability of 3D datasets within 3D reconstruction are not ensured.

How to document hypothetical 3D reconstruction?

Addressing this desideratum, it is necessary to define what documentation means in the context of 3D reconstruction. Here, it is understood as a *set of digital and non-digital materials in the form of texts and multimedia (3D models, 2D images, videos, presentations, etc.) complementing the 3D reconstruction model with additional information concerning the authenticity, hypotheses, source materials and their analysis, as well as archival, historical, archaeological and architectural research that have been conducted, and other materials supporting a good understanding of the reconstruction process*.

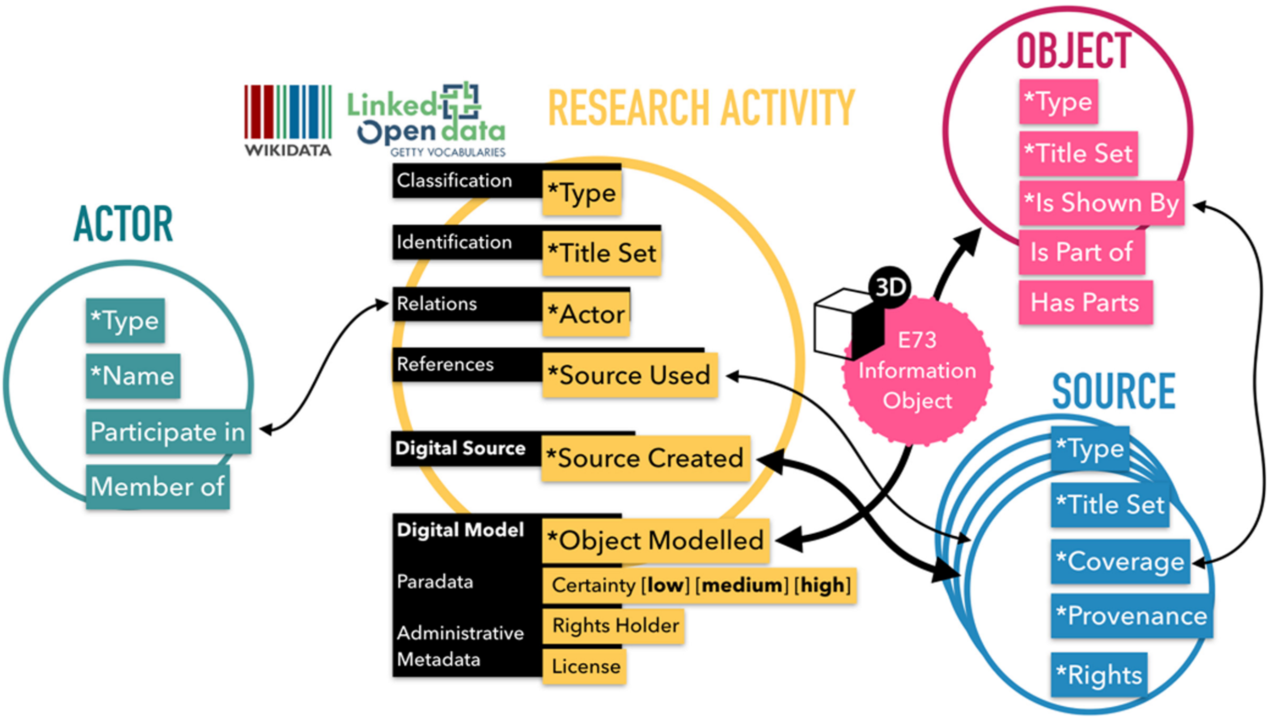

Fig 1. Scheme of documentation constituting the core of the VRE of New Synagogue in Breslau reconstruction project (© Author 2020/CC-BY-SA 4.0).

Preparation of the documentation materials for 3D reconstruction can be challenging. For this reason, a significant part of both the LC and the SP is dedicated to this concern. All those rules have been extracted and compiled in the Appendix, see Table 1. Each sub-point relates to a different aspect of the documentation (the Topic column in Table 1). Three main thematic groups have been identified (the Group column in Table 1):

Documentation Content: Principles containing information on what the documentation should contain in addition to visual materials.

Visual Presentation: Principles defining what kind of issues visual materials should address and how they should be prepared.

Documentation Output: Principles defining how to combine all the collected materials into a homogeneous document that the reader can understand.

According to the said principles, **Documentation Content** should include a list of the source materials used (LC Principle 4.5) along with their paradata, which stands for critical analysis and interpretation of collected sources (LC Principle 4.6, SP Principle 4.5.1). In addition, there should be a description of the research methods (LC Principle 4.7, LC Principle 4.8) and a clear presentation of the assumptions and objectives of the research conducted (LC Principle 4.4, SP Principle 4.2). A good practice in terms of documentation is to adhere to the intellectual property of the materials used (LC Principle 4.3) and to clarify specialist terminology (LC Principle 4.9).

Visual presentation should allow the identification of authentic elements of the object (LC Principle 4.10, SP Principle 4.4.2) and incorporate different levels of interpretation hypotheses through visual identification (SP Principle 4.4, SP Principle 4.4.3). Besides, if alternative reconstruction hypotheses arise, the authors should document them accordingly (SP Principle 4.4.1). The presentation of visual materials should also maintain historical rigor, which means that in the case of objects dated to multiple phases, the earlier phases should be presented. The focus on the ideal form of the reconstructed phase is not necessary (SP Principle 4.5.2). The object should always be presented in the context of its surroundings (SP Principle 4.5.3).

Documentation output should be prepared in a structured manner (LC Principle 3, LC Principle 4.1), ensuring complete research transparency (SP Principle 4.7.1), and making it possible to evaluate it in terms of historical or scholarly rigor (LC Principle 4.2). Documentation should be prepared based on relevant standards, ontologies and terminologies adopted in the target communities (LC Principle 4.12) using the most effective data formats (LC Principle 4.11).

Precise requirements are specified for the content of documentation or presentation of visual materials. Only general guidelines apply to documentation output. It is not clear what is meant by 'relevant standards' and whether such standards exist at all. Some rules can be interpreted subjectively, assuming, for example, that the transparency of the research will be ensured when a list of source materials is given. At the same time, another researcher may understand this as the need to describe the use of particular sources throughout the process. It is also difficult to identify the 'relevant communities' mentioned in LC Principle 4.12. The virtual archaeologists behind the development of the SP constitute one of such communities, but there are undoubtedly many others. The LC principles were intended as a general guide to critical historic visualization practice. Individual subject communities were encouraged to develop specific guides to good practice in their respective fields. The considerations that follow should be treated as an interpretation from the perspective of the architectural community of practice, to which the authors of this paper belong.

Unlike virtual archaeologists, architects have not developed shared rules for conducting 3D reconstructions of architectural heritage. They mainly rely on LC and SP. For this reason, various approaches to documenting such projects have emerged, a selection of which will now be discussed. Methods were chosen based on the authors' practical experience in the 3D reconstruction and exclusively on digital solutions adopted within German academia. The methods presented are being evaluated in the light of LC and SP. Therefore, where applicable, the relevant principle is indicated in square brackets right after the given attribute. A summary of documentation methods in relation to the extracted principles can be found in Table 2 in the Appendix.

The first selected documentation method is the **Knowledge Graph**. It is a structured schema composed of data entities connected to predefined types of interrelationships (Gutierrez and Sequeda, 2021). It requires the creation of a documentation scheme that visualizes the information recorded in the course of the reconstruction. This approach was applied in the project 'The New Synagogue in Breslau: A digital reconstruction', carried out by the Hochschule Mainz – University of Applied Sciences, in cooperation with the University of Wrocław (Kuroczyński et al., 2021). In this project, the documentation is based on the relations between the reconstructed object, the iconographic sources, the research activities concerning the object (including the creation of paradata or 3D models) and the actors involved in the process (Figure 1). The documentation schema was then encoded into a Resource Description Framework (RDF) triple-store database [LC 3, LC 4.1] using Linked Data technology (Berners-Lee, 2006). It will be discussed in more detail in the next section on data publishing. Critical to documentation is the storage of data in the form of triples. A triple can be understood as a descriptive sentence of human language that consists of three parts: a subject, a predicate, and an object (Kiryakov, 2015). A predicate defines the relationship between a subject and an object; it performs the function similar to a verb in a sentence. An example of a triple could be the following sentence: Source Number 1 was used to create the 3D model. In this case, Source Number 1 represents the subject, the 3D model represents the object, and was used to create represents the predicate. Creating triples from raw data forms a relational graph, thus providing a context that allows the stored data to be considered a knowledge resource [SP 4.7.1]. Apart from data, a knowledge graph also requires specifying the language in which it is written, which is called an ontology. An ontology is a descriptive set of concepts, called entities, and possible relationships between them, called properties, in a specific domain. The definitions of entities and properties are coded in a separate formal language such as the Web Ontology Language (OWL). Ontologies ensure a common understanding of terms and provide interoperability of documented data. In the New Synagogue in Breslau: A digital reconstruction project, an existing ontology standard for cultural heritage, the CIDOC Conceptual Reference Model (CIDOC CRM, ISO 21127:2014) was used to develop an Ontology for Scientific Documentation of source-based 3D reconstruction of architecture (OntSciDoc3D) [LC 4.7, LC 4.9]. OntSciDoc3D is an application ontology. It was developed specifically to document the 3D reconstruction process of the New Synagogue in Breslau (Kuroczyński and Große, 2020). Although the OWL file is available under an open license[1], this does not mean that the ontology will work for the documentation of any reconstruction project. Nevertheless, it introduces definitions of terms related to the scholarly documentation of reconstruction models [LC 4.12] which, due to the lack of shared terminology, may be helpful to the architectural community when developing new projects. Documentation using this application ontology is based on the semantic division of the historic building into architectural elements [LC 4.1] to which are assigned 3D reconstructions of their equivalents. Source materials on which the listed elements are identified [LC 4.5] are also assigned. Entries for 3D models include the sources used and paradata in the form of graphic representations and textual analyses of historical plans, photographs, or interior textures extracted from color drawings [LC 4.6, SP 4.5.1]. There is also information, in text form, on the degree, on a three-stage scale (High-Medium-Low) of (un)certainty of the presented reconstruction [LC 4.10]. In addition, the VRE includes contextual information related to historical persons, locations, and events associated with the building. Analogies to other projects used in the process are also included [SP 4.5.3]. All 3D models and source materials are accompanied by copyright information and the publication license [LC 4.3]. The individuals and institutions involved in the project are also recorded. Each entry has been enhanced through the visualization of the 3D model in a web viewer, enabling access without specialized software [LC 4.2, LC 4.11]. The scope of this project did not permit documenting issues of authenticity, visualization of different levels of hypotheses, and construction phases. Given adequate time, resources, and contribution of skilled data and computer scientists, the knowledge graph method, and the use of VRE provide opportunities towards capturing these issues. Another method of documentation is included in a web-based tool for Scientific Documentation for decisions (SciDoc)[2] created by the Technische Universität Darmstadt (TU Darmstadt). It relies on a visual comparison between an image of 3D reconstruction and the used source, enriched with textual argumentation (Grellert et al., 2017).

[1] The ontology owl file is available at: https://www.ontscidoc3d.hs-mainz.de/ontology/. Accessed: 20 January 2021.

[2] SciDoc is an open, free tool available at http://www.sciedoc.org/ (Accessed: 15 December 2023). The activation of a project can be requested at grellert@dg.tu-darmstadt.de.

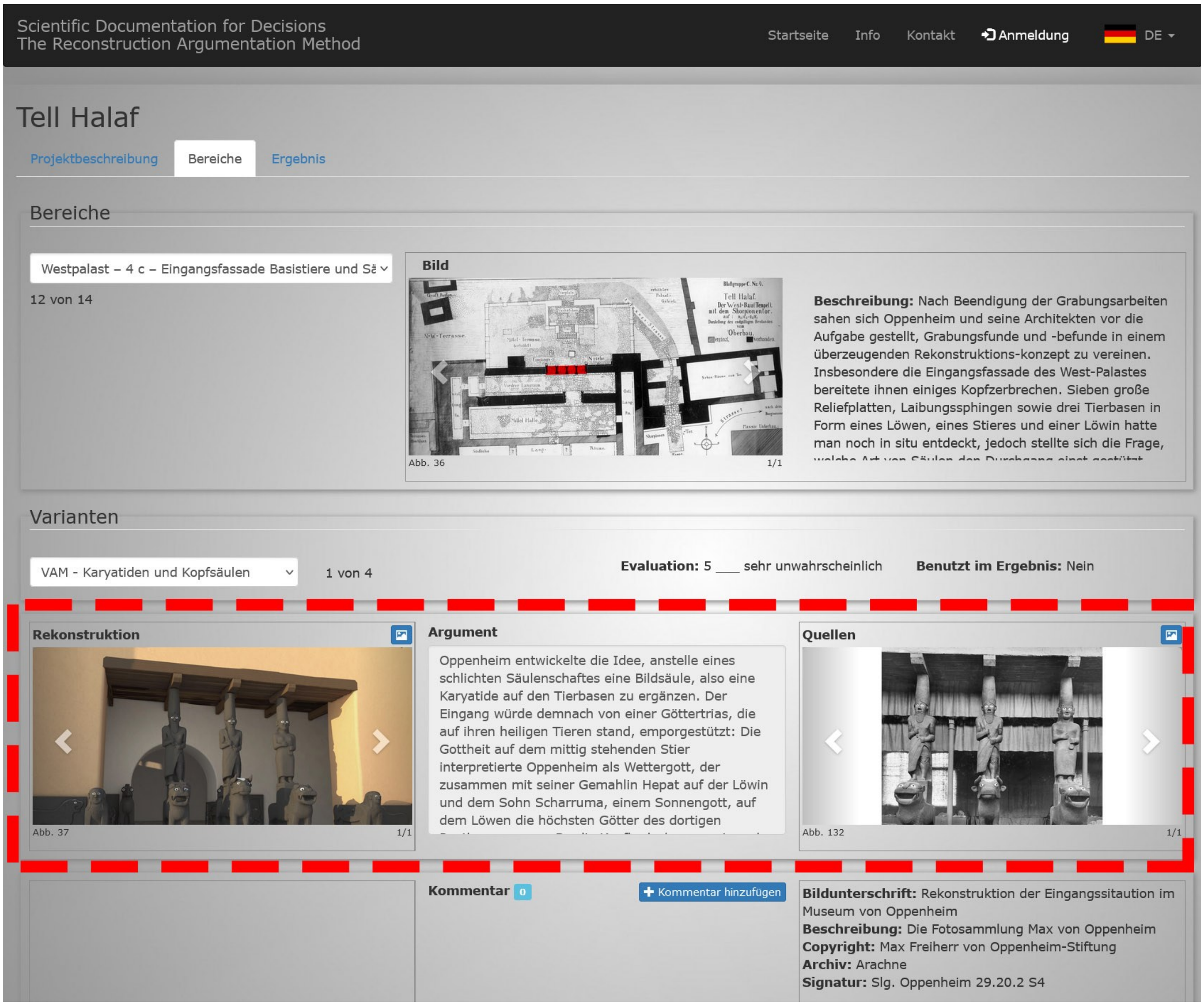

Fig. 2. A screenshot showing the documentation of an area from a sample project from the SciDoc system. The red dashed line is the triple 'reconstruction (Rekonstruktion) – argument (Argument) – source (Quellen)' that forms the core of R-A-M. (© http://www.sciedoc.org/, 03 January 2024).

The introduced **Reconstruction-Argumentation-Method (R-A-M)** represents a triple, but not in the sense of machine-readable data model. In this case, it constitutes a single-row visual combination of reconstruction-argument-source [LC 4.5]. On the left-hand side is the visualization of the reconstructed part, a textual argumentation is in the middle and on the right is a preview of the source used in the reconstruction (Figure 2). This kind of triples allow a quick evaluation of the presented reconstruction's validity compared to historical sources [LC 3, LC 4.2, SP 4.7.1].

As with the previous method, using R-A-M requires dividing the object in advance into smaller parts called areas [LC 4.1]. SciDoc identifies each area through an image created from the source, where the area is marked by colour. Visual materials in the area's triple also provide basic information about their origin [LC 4.3]. Regarding source ambiguity, SciDoc also allows documentation of multiple variants for a single area [SP 4.4.1]. Each variant can optionally be evaluated in terms of the probability of its occurrence through textual information, but without insight into the full probability scale, or definitions of subjective terms adopted by the author [LC 4.10]. However, this method does not provide tools for documentation related to the visual gradation between authentic elements and different levels of reconstruction hypothesis. Despite this, R-A-M provides a predefined documentation layout that is practical and easy to use. Documentation can be prepared on the fly while creating a 3D model by simply taking a screenshot and loading it into the appropriate field in SciDoc. The only requirement is registration in the system and preparation of object division into areas.

The last method of documentation to be discussed here is **web-based visualization**. The main advantage of 3D models is that they can be freely explored in three dimensions. Web models can be viewed without special software and do not require expertise in digital graphics [LC 4.2, LC 4.11]. It is also the simplest and fastest of the methods described. That is why many 3D reconstruction projects often have no other documentation of scholarship supporting the 3D model. However, many web-viewer solutions can saturate the 3D model with additional annotations (Figure 3) [LC 4.1]. Therefore, many reconstruction projects combine documentation with a model published in virtual space. One of the most popular services of this kind is Sketchfab. With over 100,000 models (at the time of writing this paper) in the cultural heritage category, the platform is becoming a leading web-viewer thanks to the exceptionally high-quality 3D model visualization, allowing annotations and virtual tours, as well as the creation of specific applications for cultural and heritage institutions (Flynn, 2019). However, 3D reconstructions are a special kind of digital heritage, where greater value is given to the visualization of authentic elements, different levels of the hypothesis and reasoning than to the visual quality of the 3D model in the web-based 3D viewer.

Evaluation of documentation methods

The **knowledge graph method** makes it possible to obtain a human- and machine-readable overview of the entire process and adapt it to the selected digital reconstruction techniques. Adequate preparation is required beforehand. Following the implementation into the system (which requires specialized knowledge), the user can only see the graph using advanced data acquisition and visualization methods. This, in turn, through the complex web of relationships between data, can make the system difficult to navigate for new users. Despite this drawback, the method is flexible and could meet the documentation principles.

The **R-A-M method** provides visual documentation based on a simple diagram, making it easy to use and read for humans. It also allows immediate comparison of the reconstruction and its sources. Although R-A-M does not meet all the requirements, it is a practical alternative, facilitating adequate documentation with little effort.

The **web-visualization method**, on the other hand, provides virtual access to lost CH. The web-viewer allows free exploration of the three-dimensional space. However, documentation is on the back burner with this method. Annotations can substitute documentation, but they are implemented in very few cases. The need for post-production of the model after uploading to the web-viewer is a barrier. The creation of interactive points, descriptions and preparation of media files all require mastery of an additional tool, and additional resources.

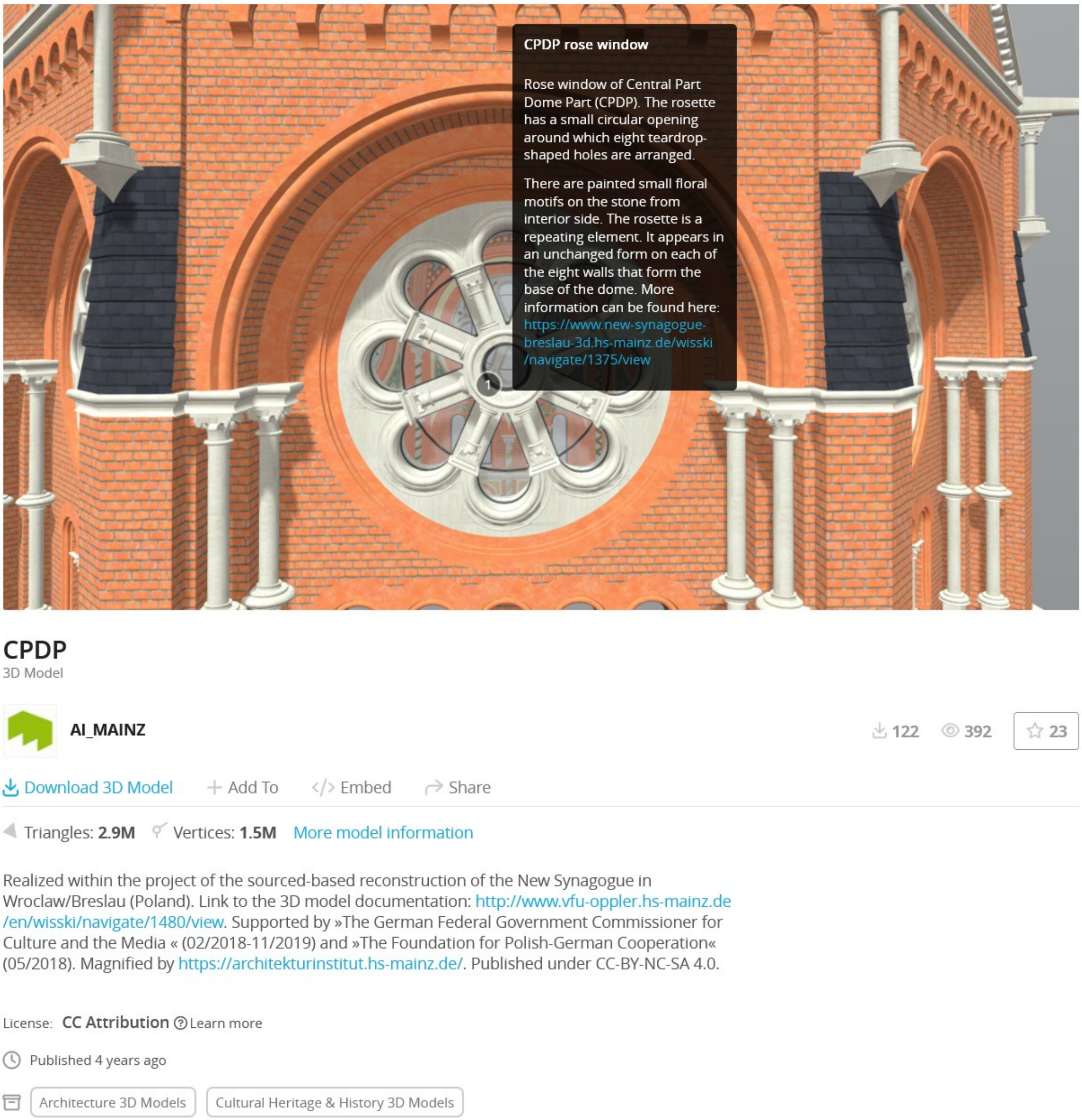

Fig. 3. A screenshot showing an example of 3D model documentation using annotation in the virtual space of Sketchfab web-viewer (© https://sketchfab.com/, 03 January 2024).

The listed documentation methods differ but have one thing in common – they all use tools that require publishing the resources on the web. As a result, project documentation can be accessed using only a web browser. After all, access to the research enabling peer review is key to scholarship. But is documentation sufficient to evaluate the scholarly value of 3D reconstruction work, or does it require more than a 3D file? The following section considers these issues. It presents principles of data publication and how they relate to the documentation methods described above.

How to share hypothetical 3D reconstruction?

Although the concept of documentation is familiar, it is worth considering how it can be understood in the context of 3D models. For this paper, publication is defined as the *public release of a digital* *resource consisting of a 3D reconstruction alongside available documentation that allows exploration, validation, and use of the 3D model by a specific target group*.

The requirements for publication on the web are defined in the LC and the SP in general terms, as these two documents focus on documentation and visual presentation. For this reason, two other documents focused on sharing data on the web are worth considering. The first is the 5-star Open Data Scheme (5OD) (Berners-Lee, 2012). This document presents five levels that can be achieved by publishing data on the web. Level one specifies only making the data available under an open licence, while level five specifies full compliance with the Linked Open Data (LOD) concept. The LOD concept combines both the openness of the data and the referencing between them. Each level is linked to a condition concerning the data format and structure. The second document is the FAIR Guiding Principles for Scientific Data Management and Stewardship (FAIR) (Wilkinson et al., 2016). It emphasizes findability, accessibility, interoperability, and reuse of published scientific data, focusing on ensuring machine readability of data. All recommendations for publishing data on the web, in the context of 3D reconstructions, have been extracted from the said documents and compiled in Table 3 in the Appendix. As before, each principle is assigned a category in the Topic column. On this basis, four main thematic groups are defined as follows:

Findability: principles of the visibility of published data on the web, its indexing, and the importance of metadata;

Accessibility: principles of data access provision, making data easier to read, or using open technology solutions;

Interoperability: principles of formatting data to allow for proper analysis, processing or storage;

Reuse: principles of data preparation for use by independent users and how to describe it to reach potential audiences;

Preservation: principles of ensuring the longevity of published content and preparing data for archiving;

The **findability** emphasizes the need to use unique, global, and permanent identifiers for published data (FAIR Principle F1). This identifier is created automatically by most data repositories in the form of a web link called a Uniform Resource Identifier (URI). It is important to emphasize that every link on the Internet is a URI. Although it is common to refer to any Internet address as a Uniform Resource Locator (URL) the latter is only part of a URI and refers to the location of the resource for which one is searching. This means that placing a resource anywhere on the internet generates its URI. However, not every website guarantees its URI to be long-term and permanent. It is, therefore, essential to publish the data with services that provide a certain level of stability, such as Zenodo[3] , which guarantees the creation of a URI in the form of a Digital Object Identifier (DOI)[4] for each resource published. An alternative method is to publish the data in established digital repositories within libraries and archives (SP 4.7.3) that guarantee permanent identifiers for each deposit. However, depositing 3D reconstructions in libraries or archives can be arduous due to the lack of accepted rules for archiving 3D models and the high costs of managing heavy data.

[3] Zenodo is an open repository for research data from all fields, which is built on the rules of FAIR Principles, available at: https://zenodo.org/ (Accessed: 23 February 2022).

[4] DOI is a unique number comprising a prefix and a suffix separated by a forward slash. More information is available at: https://www.doi.org/ (Accessed: 22 February 2022).

Data findability is also affected by the richness of metadata (FAIR Principle 2). Metadata is information (usually textual) that provides context for published resources. Their primary division includes administrative, descriptive, and structural metadata. Administrative metadata are used for management and contain information about the resource type, origin, and granted rights. Descriptive metadata are used for resource identification and contain information about the title, author, keywords, etc. Structural metadata contains information about components of the resource and its structure. Sometimes, administrative metadata are divided into rights management metadata (copyright and licensing information) and preservation metadata (provenance and technical specifications). The more metadata is provided during publication, the greater the chance that the target audience will find the resource. However, the metadata must be connected to the described resource through an identifier (FAIR Principle 3). This is because metadata are often stored in a separate file, so the system storing the data must provide a link based on the resource identifier. The published resource and its metadata should also be indexed in the search engine (FAIR Principle 4). Indexing involves capturing the essence of the published resource and creating a record in the search engine database with phrases that act as keywords, enabling quick and efficient searches. No one will find data published in an unknown (not machine-readable) repository. Google's search engine automatically updates new web resources, which may not be sufficient for scholarly data. As in the case of paper-based publications, findability can also be enhanced through referencing other resources, which is crucial (5OD 5). This allows the data to be placed in a broader context by the insertion of hyperlinks in documentation materials.

The **accessibility** of published data can be understood as access to virtual surrogates of lost or inaccessible cultural heritage (LC Principle 6.1). Therefore, it is good practice to make scientific data that are not perceived as sensitive available under an open license (5OD Principle 1). However, the model can still be locked by the format used. Many 3D files are proprietary formats, meaning that the way the data are encoded remains undisclosed and specific to particular software. Opening data stored in proprietary format requires commercial software. Therefore, sharing data in open, non-proprietary data exchange formats increases access to the contents of the file (5OD Principle 3). For text files it is the TXT format, for sheets it is the CSV (Comma-separated values) format. 3D files do not have a single open format. The Wavefront (OBJ) format is used by 3D graphic designers, Stereolithography (STL) is used in 3D printing, the Industry Foundation Classes (IFC) format is used by engineers and designers, while Initial Graphics Exchange Specification (IGES) is preferred in mathematical recording of model geometry. Therefore, using open 3D file formats may not necessarily provide access to the data. Meeting this condition requires providing the open exploration of the 3D model using appropriate viewer technology in a web browser. Accessing data published within the model without the need for their downloading and without specialized software benefits a larger audience (LC Principle 6). Accessibility can also be understood as offering methods for retrieving data (FAIR Principle A1). Although most data are available on the web through publicly available protocols such as http(s)[5], this does not mean the data are open and free. However, in the case of protected data, some form of contact (by phone, skype, email, etc.) should be provided to verify the terms of access (FAIR Principle A1.1) It is essential that the communication protocol is standardized, allows user authorization (if required) (FAIR Principle

[5] http stands for The Hypertext Transfer Protocol and is a fundamental method of fetching data on the Internet. The web page that the user sees in the browser is the result of loading the encoded files on the website server (html, css, etc).

A1.2) and is included in the metadata. However, due to rapid technological development, published data can quickly become outdated and useless. Preserving metadata can make it possible to locate the relevant contact to obtain information about the outdated resource (FAIR Principle A2). Therefore, it is necessary to ensure long-term preservation of metadata storage by storing data in official archives or services like Zenodo.

The **interoperability** of the data allows for their interpretation by humans and processing by machines. The first step in this direction is to structure the published resources, for example, by collating the data as an Excel file sheet (5OD Principle 2). A structure can be applied to the created 3D geometry using layers or grouping. Data and metadata should also be compiled in a shared knowledge representation language with broad applicability (FAIR Principle I1, 5OD Principle 4) using a vocabulary that meets FAIR principles (FAIR Principle I2). A knowledge language can encode information in a formal way in order to be readable by machine. For scientific data, standardized knowledge representations are data models, including Resource Description Framework (RDF), Web Ontology Language (OWL) and JavaScript Object Notation for Linked Data (JSON LD). Each of these languages is a file format containing part or all of the documentation of the published resource (the use of the OWL file in the documentation was described with the knowledge graph method in the previous section). Data models also create terms, concepts, and controlled vocabulary databases. The definitions developed there are fixed; each concept is equipped with its unique identifier (URI), thus meeting FAIR requirements. An example of controlled vocabulary for use by the architectural community might be the Getty Art and Architecture Thesaurus[6] (Getty AAT), which defines concepts and terms related to architecture, art, and culture. Interoperability also means ensuring a broader context for the information provided, which can be achieved by referring to relevant external sources on the web (FAIR Principle I3).

The **reuse** of a published resource requires its appropriate adaptation. The 3D model should be available in an open format suitable for the target audience (FAIR Principle R1.3). If this format is not known, the most appropriate method of publication would be to make the model available in a web viewer, allowing a potential audience to examine the reconstruction (LC Principle 4.2). Although the publication should aim at a specific community, it is not always possible to predict the profile of the potential audience. Therefore, the published resource should be enriched with metadata about the resource and the context in which it was created (FAIR Principle R1). The published 3D model should also be accompanied by documentation showing the underlying inquiry process and technical development documentation transparently and understandably (SP Principle 4.7). This will allow the model to be used for validation purposes. Also, usage of published data under legal conditions should be specified by stating the adequate license with an indication if published data could be downloaded, changed, modified, or embedded (LC Principle 6.2, FAIR Principle R1.1). It is also good practice to describe the provenance of the data, the desired method of citation and the acknowledgement (or its lack), and the method of obtaining and processing it (FAIR Principle R1.2).

Preservation of reconstruction models requires ensuring the longevity of the data (LC Principle 5), their storage in appropriate data formats (LC Principle 5.2) and using the most reliable archiving tools (LC Principle 5.1). These questions are still open to interpretation. A significant problem is the

[6] https://www.getty.edu/research/tools/vocabularies/aat/ (Accessed: 05 January 2024)

rapid development of computer visualization technologies, making 3D formats used a few decades ago unusable. Tools for the effective archiving of 3D files have not yet been developed or are not common standardized solutions. This remains a subject of heated discussion among 3D practitioners. However, promising data exchange formats are emerging that use metadata storage along with geometry information, such as IFC and CityGML (Geography Markup Language)[7], which have the potential for 3D files archiving in the CH domain.

The methods of publishing 3D reconstruction models are closely linked to how they are documented and will, therefore, be discussed using the same examples. When a feature of a method meets the requirements of one of the principles, its code from Table 3 will be given in square brackets. A comprehensive analysis of documentation and publication methods to the principles of both topics is presented in Table 4 in the Appendix.

The aforementioned project of New Synagogue in Breslau uses a **Virtual Research Environment (VRE)** for publication [SP 4.7.3]. VRE is an open-source and flexible system that provides a space for collaborative interdisciplinary research, enabling its controlled and secure documentation and publication (Candela et al., 2013). The project uses a documentation system centered around an expanded description of the building's historical context and an analytical approach to source material [SP 4.7]. Data can only be published by authorized project members. The entire project was richly saturated with various metadata [FAIR F2, FAIR R1]. The implementation of the knowledge graph and ontology [FAIR F3] made it possible to describe data through identifiers (URIs) contained in the OWL file [FAIR F1, FAIR I1]. By storing the metadata and paradata in a triple-store [FAIR F4, FAIR R1.3, 5OD 4] separate from the data server, the project data can be retrieved via a SPARQL endpoint[8] [FAIR A1, FAIR A1.1, FAIR A1.2, FAIR A2]. Each database entry also provides different types of access to the 3D model to the original file with which the model was created [LC 4.2], the data exchange format IFC [50D 2, 5OD 3, LC 5.2] and visualization of the model in a web-based 3D viewer [LC 4.2, LC 6, LC 6.1, SP 4.7] provided by a third-party service. All published materials are licensed under the Creative Commons (CC) group [5OD 1, LC 6.2, FAIR R 1.1]. Each model is labeled with information about the creator of the reconstitution and the institutions involved in the project [FAIR R1.2]. The project also uses contextual hyperlinks to external websites [FAIR I3, 5OD 5] and operates with an architectural vocabulary sourced from the Getty AAT [FAIR I2]. The site does not provide information on preserving stored content, presumably tied to the university's funds and project requirements.

SciDoc is an open, institutional documentation system, but does not support the publication of 3D files and the Linked Data technologies. The publication is based on image resources, including screenshots and visualizations. Although the metadata describe the project in detail [FAIR F2, FAIR R1], including information about the origin of the data, the authors of the reconstitutions [FAIR R1.2] and possible contact protocols [FAIR A1.1, FAIR A1.2], the system does not use fixed identifiers or any controlled vocabulary. It is difficult to ascertain the interoperability of published resources when copyright and licenses are not specified. Nor do the images themselves provide a structured format for storing data. Nonetheless, this method of publication helps to ensure transparency [SP 4.7] and

[7] CityGML is an open standardised data model and exchange format to store digital 3D models of cities and landscapes.

[8] A SPARQL endpoint is a quarriable access point on the web that allows users to perform queries on a dataset using the SPARQL language, typically used for retrieving and manipulating data stored in RDF format.

verification of the reconstruction performed [LC 4.2]; the data is easily accessible [LC 6, 5OD 1]. This method does not preserve the 3D data themselves, only derivatives in the form of reconstruction renders [LC 5.2]. There is also no preservation strategy for the data published on the website. Although university servers may have a certain reputation, they do not guarantee the website's longevity.

Sketchfab is an open, commercial repository of web-viewer and 3D data storage services. It is a world leader among 3D model repositories supporting cultural heritage [SP 4.7.3]. The high quality of the visualization, the ease of use and the ability to integrate with other tools (such as Virtual Reality) make publication in this repository synonymous with dissemination of reconstruction models [LC 6, LC 6.1]. Web-visualization also provides the opportunity to critically examine the published model [LC 4.2], but without access to the sources used, it is difficult to perform validation of the reconstruction. Although the published resources are quite poor in metadata and do not have permanent identifiers, copyright issues are made very clear [FAIR R1.1]. It is possible to publish a 3D model under an open license allowing its download and modification [LC 6.2, 5OD 1], but unfortunately only in 3D formats for computer graphics. Published resources are indexed in the repository's search engine [FAIR F4], and a comment function provides the possibility to communicate with the author of the publication [FAIR A1.1, FAIR A1.2]. Despite poor metadata, it is possible to create rich descriptions using hyperlinks to other websites [FAIR F3, 5OD5]. However, Sketchfab does not provide a good tool for data preservation. Its terms of use state clearly that the company reserves the right to shut down its services at one month's notice to users.[9]

The analysis showed that the more principals a publication method fulfils, the more effort it requires from the publisher. Although publishing using VRE fulfils almost all the principals, its creation requires the necessary knowledge in computer science, informatics and data science. The use of ready-made institutional solutions requires a conscious choice in the light of all principals. The example of SciDoc shows that, although it is an excellent and easy-to-use tool for documenting the reconstruction process, it does not provide an adequate infrastructure to guarantee the publication of the 3D model medium itself and does not provide the possibility to structure and index the published data. The example of Sketchfab, used by many renowned cultural heritage institutions, is extremely interesting. Despite its clear policy against data preservation, it is still an unrivalled tool for simple and fast visualization of 3D models.

Metadata set for hypothetical 3D reconstruction

The documentation and publication methods discussed here indicate that there is no single method that fits every reconstruction project and meets all the principles. Therefore, every digital reconstruction project should develop a documentation, publication, and preservation strategy in its initial phase. This requirement is currently not regulated in any way, which may be a major problem in establishing standards for the digital 3D reconstruction. However, the projects and methods of implementation described above may inspire the development of future preservation strategies for this kind of object-related research project.

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[9] Sektchfab's Terms of Use, Point 9. Available at: https://sketchfab.com/terms?utm_source=blog&utm_medium=referral#modifying-service (Accessed: 04 January 2024)

It has also been shown that none of the presented publication methods meets the requirements for archiving published content, which can only be provided by public archives and libraries. However, the requirements and rules for archiving digital resources are not commonly known and are rarely the focus of reconstruction projects. This gap was recognized in the project DFG 3D-Viewer – Infrastructure for 3D Reconstruction[10]. Its goal is to develop an infrastructure for the transfer of 3D reconstruction resources from local repositories directly to archiving institutions. This requires the development of a container that will convey information about the 3D file, as well as the necessary metadata. However, owing to the lack of standardized solutions for transferring 3D data, it is not clear what the basic set of metadata for 3D reconstruction models should comprise. With this challenge in mind, a comparative analysis of the metadata stored by popular commercial and institutional (public) repositories of digital models was conducted (Champion and Rahaman, 2020) to identify a metadata set required to describe digital 3D reconstruction. The metadata was categorized according to two sets of criteria. The first determined five metadata categories, namely data concerning the **Reconstitution Process**, **Object Depicted on the Model**, **Reuse Policy**, **Technical Specification and Relations**. The second set of criteria was based on the metadata types, namely administrative, descriptive, structural, preservation and rights management metadata, as described above. A more detailed analysis is available in Table 5 in the Appendix.

On this basis, two approaches to metadata have been distinguished. The first is to provide a comprehensive description of the published resource, taking into account all metadata appearing in the analysis of repositories presented in Table 5. The schematic diagram of documentation developed in this way formed the basis for creating a test repository for 3D models[11], based on VRE, the OntSciDoc3D ontology and Linked Open Data technology (Figure 4). It also implemented a proprietary solution for a web-viewer based on the Three.js[12]. The repository was to become a solution for institutions looking for an alternative to Sketchfab, while meeting as many of the requirements of the principles in question as possible. It is currently being used in academic seminars as a novel tool for publishing digital 3D reconstruction models (Bajena and Kuroczyński, 2023).

The second approach was based on the extraction of the metadata set necessary to describe the published resource. This set is intended to provide an information base for archiving 3D models. Two main entities requiring description were identified: the **3D model** and the **CH object** depicted in the model. Potential identifiers were also considered to enable data acquisition from external services to minimize the information required for manual entry. For CH objects, the basic information is the **time period** represented on the model and the **object identifier**, which could be the URI of the object's entry in Wikidata. In its absence, the relevant information would be the **object's name**, its **type** (prenatally retrieved from Getty AAT) and the **object's location** (geographic names potentially from Geonames). In the case of a 3D model, the most important information is copyright and the origin of the data, so it includes the type of **license**, the **author** of the reconstitution or **rights holder** (potentially retrieved from ORCID), **publisher** of the model (thus stating that he has the rights to publish it, and the **date of publication** (which makes it possible to track published versions of the

[10] More about DFG 3D-Viewer can be found on the project website: https://dfg-viewer.de/en/dfg-3d-viewer. Accessed: 07 January 2024.

[11] 3D Repository is an open system for publication of 3D models, available at: https://3d-repository.hs-mainz.de. Accessed: 05 January 2024.

[12] Three.js is a JavaScript library and API compatible with multiple browsers, designed for generating and showcasing 3D models in web browsers through WebGL technology.

model). In addition, the set must include information about the **repository** in which the model was published and the location of the **3D file** for archiving and its **preview**. These three pieces of information should be passed as URIs.

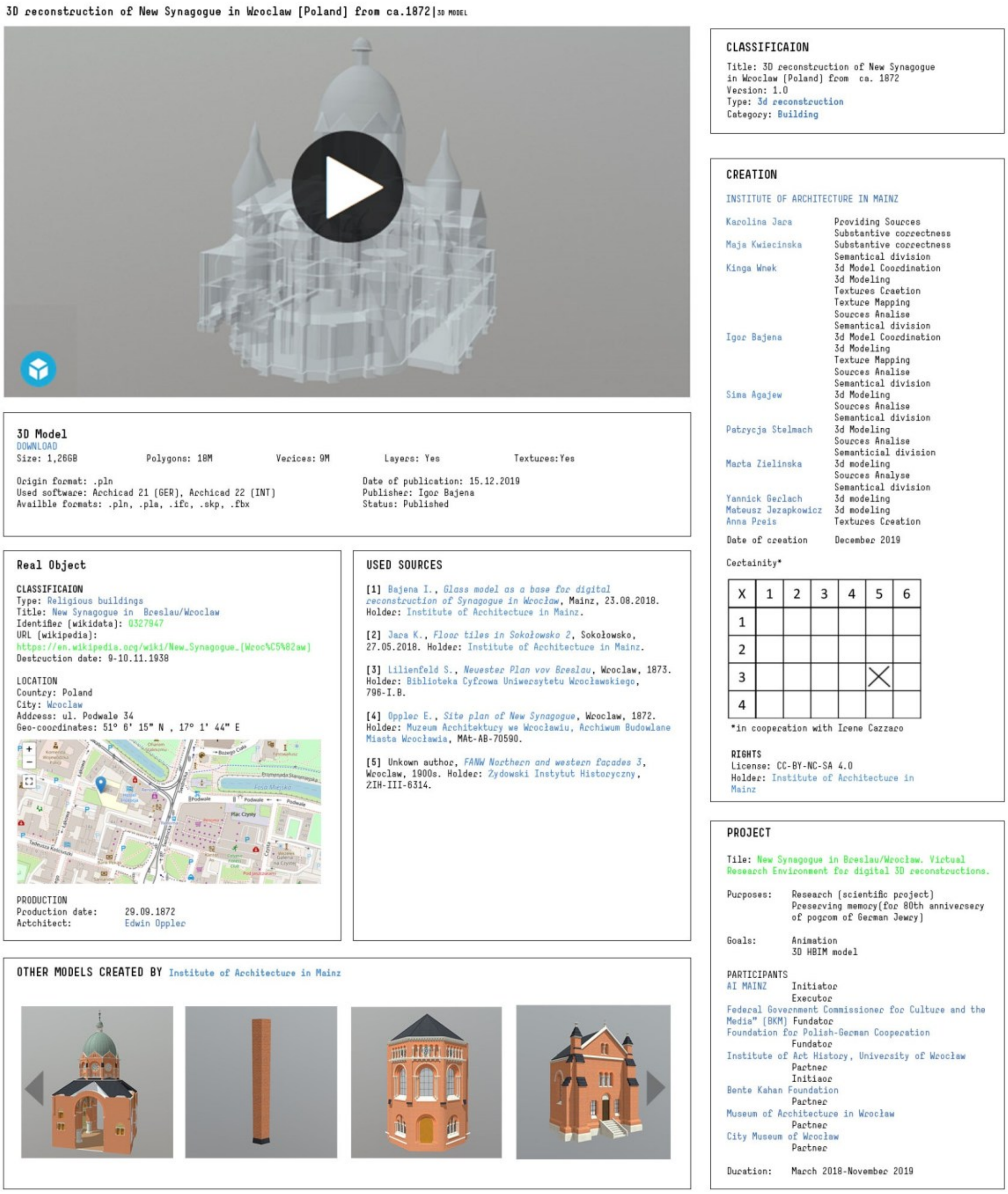

Fig. 4. The example of mock-up of frontend of the extended version 3D repository (© Author, 2021).

Conclusion

3D reconstructions constitute digital heritage. These special resources require adherence to developed guidelines concerning documentation, publication, data visualization and preservation. Scholarly projects often cannot meet all the challenges posed by 3D reconstructions. The developed tools often only focus on selected objectives, as has been demonstrated here. As a result, documentation, and publication in accordance with a wide range of principles can only be achieved by skillfully combining available methods and tools. This is often beyond the digital reconstruction projects. Therefore, it is important that appropriate documentation and publication strategies are developed and enforced top-down by funding institutions. The DFG 3D-Viewer project is pursuing this goal by developing an infrastructure for the publication of 3D models and a strategy for their preservation. In addition, the development of shared practices for the documentation of 3D models requires the collective effort of a wider community. Alongside the DFG 3D-Viewer there are other tools for documentation, publication, and preservation of 3D models currently under development, such as:

- IDOVIR – Infrastruktur zur Dokumentation Virtueller Rekonstruktionen,[13]
- Kompakkt – Semantic annotation for 3D cultural artefacts,[14]
- Europeana,[15]
- Baureka.online – Ein Forschungsdatenportal für die Historische Bauforschung,[16]
- The Platform for Science – FID BAUdigital.[17]

Together with representatives of the above projects, a joint evaluation of the presented solution was undertaken during workshops in Mainz 2022 and Munich 2023 (Bajena and Kuroczyński, 2023a). Further work is expected to include aligning a shared set of metadata for 3D models in the wider community with the assistance of potential users from selected libraries, universities, and data repositories. Despite the many challenges, a collaborative effort may soon yield standardized, comprehensive, and easy-to-use solutions for documentation and publication of digital reconstructions.

Conflict of Interests Disclosure

No potential competing interests have been reported by the authors.

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[13] https://www.dg.architektur.tu-darmstadt.de/forschung_ddu/digitale_rekonstruktion_ddu/idovir/idovir.de.jsp (Accessed: 23 January 2022)

[14] https://kompakkt.de/ (Accessed: 23 January 2022)

[15] https://pro.europeana.eu/ (Accessed: 23 January 2022)

[16] https://baureka.online/ (Accessed: 23 January 2022)

[17] https://www.fid-bau.de/en/home/, Accessed 23 January 2022.

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Appendix

Table 1. A list of guidelines related to the documentation of digital reconstruction extracted from London Charter (LC) and Seville Principles (SP). The yellow color distinguishes the principles for documentation content, the gray color for documentation output, and the green color for visual presentation.

Document	Code	Text of principle	Topic	Group
London Charter	LC 3	In order to ensure the intellectual integrity of computer-based visualization methods and outcomes, relevant research sources should be identified and evaluated in a structured and documented way.	Sources, Structure	Documentation Output
	LC 4.1	Documentation strategies should be designed and resourced in such a way that they actively enhance the visualization activity by encouraging, and helping to structure, thoughtful practice.	Structure	Documentation Output
	LC 4.2	Documentation strategies should be designed to enable rigorous, comparative analysis and evaluation of computer-based visualizations, and to facilitate the recognition and addressing of issues that visualization activities reveal.	Evaluation	Documentation Output
	LC 4.3	Documentation strategies may assist in the management of Intellectual Property Rights or privileged information.	Intellectual Property	Documentation Content
	LC 4.4	It should be made clear to users what a computer-based visualization seeks to represent, for example the existing state, an evidence-based restoration or a hypothetical reconstruction of a cultural heritage objector site, and the extent and nature of any factual uncertainty.	Knowledge Claims	Documentation Content
	LC 4.5	A complete list of research sources used, and their provenance should be disseminated.	Sources	Documentation Content
	LC 4.6	Documentation of the evaluative, analytical, deductive, interpretative, and creative decisions made in the course of computer-based visualization should be disseminated in such a way that the relationship between research sources, implicit knowledge, explicit reasoning, and visualization-based outcomes can be understood.	Paradata	Documentation Content
	LC 4.7	The rationale for choosing a computer-based visualization method, and for rejecting other methods, should be documented, and disseminated to allow the activity's methodology to be evaluated and to inform subsequent activities.	Methodology	Documentation Content
	LC 4.8	A description of the visualization methods should be disseminated if these are not likely to be widely understood within relevant communities of practice.	Methods	Documentation Content
	LC 4.9	Where computer-based visualization methods are used in interdisciplinary contexts that lack a common set of understandings about the nature of research questions, methods and outcomes, project documentation should be undertaken in such a way that it assists in articulating such implicit knowledge and in identifying the different lexica of participating members from diverse subject communities.	Terminology	Documentation Content
	LC 4.10	Computer-based visualization outcomes should be disseminated in such a way that the nature and importance of significant, hypothetical dependency relationships between elements can be clearly identified by users and the reasoning underlying such hypotheses understood.	Levels of Hypothesis	Visualization Presentation
	LC 4.11	Documentation should be disseminated using the most effective available media, including graphical, textual, video, audio, numerical or combinations of the above.	Formats	Documentation Output
	LC 4.12	Documentation should be disseminated sustainably with reference to relevant standards and ontologies according to best practice in relevant communities of practice and in such a way that facilitates its inclusion in relevant citation indexes.	Standards	Documentation Output

Table 1. Continuation

Document	Code	Text of principle	Topic	Group
Seville Principles	SP 4.2	Prior to the development of any computer-based visualization, the ultimate purpose or goal of our work must always be completely clear	Goals	Documentation Content
	SP 4.4	Computer-based visualization normally reconstructs or recreates historical buildings and environments as we believe them to have been in the past. For that reason, it should always be possible to distinguish what is real, genuine, or authentic from what is not. In this sense, authenticity must be a permanent operational concept in any virtual archaeology project.	Authenticity	Visualization Presentation
	SP 4.4.1	Since archaeology is complex and not an exact and irrefutable science, it must be openly committed to making alternative virtual interpretations provided they afford the same scientific validity. When that equality does not exist, only the main hypothesis will be endorsed.	Versioning	Visualization Presentation
	SP 4.4.2	When performing virtual restorations or reconstructions, these must explicitly or through additional interpretations show the different levels of accuracy on which the restoration or reconstruction is based.	Levels of Hypothesis	Visualization Presentation
	SP 4.4.3	In so far as many archaeological remains have been and are being restored or reconstructed, computer- based visualization should really help both professionals and the public to differentiate clearly between: remains that have been conserved “in situ”; remains that have been returned to their original position (real anastylosis); areas that have been partially or completely rebuilt on original remains; and finally, areas that have been restored or reconstructed virtually.	Authenticity	Visualization Presentation
	SP 4.5.1	The historical rigor of any computer-based visualization of the past will depend on both the rigor with which prior archaeological research has been performed and the rigor with which that information is used to create the virtual model.	Historical rigor, Paradata	Documentation Content
	SP 4.5.2	All historical phases recorded during archaeological research are extremely valuable. Thus, a rigorous approach would not be one that shows only the time of splendor of reconstructed or recreated archaeological remains but rather one that shows all the phases, including periods of decline. Nor should it display an idyllic image of the past with seemingly newly constructed buildings, people who look like models, etc., but rather a real image, i.e. with buildings in varying states of conservation, people of different sizes and weights, etc.	Historical rigor, Phases	Visualization Presentation
	SP 4.5.3	The environment, landscape or context associated with archaeological remains is as important as the ruin itself (Charter of Krakow, 2000). Charcoal, paleobotanical, paleozoological and physical paleoanthropological research must serve as a basis for conducting rigorous virtual recreations of landscape and context. They cannot systematically show lifeless cities, lonely buildings, or dead landscapes, because this is an historical falsehood.	Historical rigor, Context	Visualization Presentation
	SP 4.7.1	It is clear that all computer-based visualization involves a large amount of scientific research. Consequently, for the virtual archaeology projects to achieve scientific and academic rigor it is essential to prepare documentary bases in which to gather and present the entire work process in a completely transparent fashion: objectives, methodology, techniques, reasoning, origin, and characteristics of the sources of research, results and conclusions.	Transparency	Documentation Output

Table 2. Summary of selected documentation methods in light of documentation principles extracted from London Charter (LC) and Seville Principles (SP). The yellow color distinguishes the principles for documentation content, the grey color for documentation output, and the green color for visual presentation.

Group	Topic	Code	Knowledge graph using ontology 18	Reconstruction-Argumentation-Method (R-A-M) 19	Web-based visualization with annotations 20
Documentation Content	Intellectual Property	LC 4.3	YES	YES	YES
	Knowledge Claims	LC 4.4	NO in this case, although this method makes it possible	PARTLY by comparing the visualization with a photograph of the current state and argumentation	NO
	Sources	LC 4.5	YES	YES	NO, but it should be possible through annotations
	Paradata	LC 4.6	YES	NO in this case, although this method makes it possible	NO
	Methodology	LC 4.7	YES	YES	NO
	Methods	LC 4.8	YES	YES	NO
	Terminology	LC 4.9	YES	NO	NO
	Goals	SP 4.2	YES	YES	NO
	Historical rigor, Paradata	SP 4.5.1	YES	YES	NO
Visualization Presentation	Levels of Hypothesis	LC 4.10	YES	YES	NO
	Authenticity	SP 4.4	NO in this case, although this method makes it possible	PARTLY by comparing the visualization with a photograph of the current state and argumentation	NO
	Versioning	SP 4.4.1	NO in this case, although this method makes it possible	YES	NO
	Levels of Hypothesis	SP 4.4.2	NO in this case, although this method makes it possible	NO	NO
	Authenticity	SP 4.4.3	NO in this case, although this method makes it possible	PARTLY by comparing the visualization with a photograph of the current state and argumentation	NO
	Historical rigor, Phases	SP 4.5.2	NO in this case, although this method makes it possible	NO in this case, although this method makes it possible	NO
	Historical rigor, Context	SP 4.5.3	YES	YES	YES

[18] on the example of VRE for reconstruction of the new Synagogue in Wroclaw: https://www.new-synagogue-breslau-3d.hs-mainz.de/ (Accessed: 05 January 2024)

[19] on the example of the Tell Halaf reconstitution entry from the SciDoc: http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=20 (Accessed: 05 January 2024)

[20] on the example of the Bar Hill Fort Reconstruction from Sketchfab: https://sketchfab.com/3d-models/bar-hill-fort-reconstruction-antonine-wall-6d04c19858b8421ebd034ba13abf4831 (Accessed: 05 January 2024).

Table 2. Continuation

Group	Topic	Code	Knowledge graph using ontology 21	Reconstruction-Argumentation-Method (R-A-M) 22	Web-based visualization with annotations 23
Documentation Output	Sources, Structure	LC 3	YES	YES	PARTLY, because the annotation introduces a structure, but does not include sources
	Structure	LC 4.1	YES	YES	YES
	Evaluation	LC 4.2	YES	YES	YES
	Formats	LC 4.11	YES	YES, given the legal restrictions	YES
	Standards	LC 4.12	YES, in terms of ontological solutions	YES, referring to local standards used at TU Darmstadt	NO
	Transparency	SP 4.7.1	YES	YES	NO

Table 3. A list of guidelines related to the publication of digital reconstructions extracted from London Charter (LC), Seville Principles (SP), FAIR Principles (FP) and 5-star Open Data scheme (5OD). The blue color distinguishes rules for findability, yellow for availability, orange for interoperability, green for reuse, and purple for preservation.

Document	Code	Text of principle	Topic	Group
London Charter	LC 4.2	Documentation strategies should be designed to enable rigorous, comparative analysis and evaluation of computer-based visualizations, and to facilitate the recognition and addressing of issues that visualization activities reveal.	Evaluation	Reuse
	LC 5	Strategies should be planned and implemented to ensure the long-term sustainability of cultural heritage-related computer-based visualization outcomes and documentation, in order to avoid loss of this growing part of human intellectual, social, economic and cultural heritage.	Long-term Sustainability	Preservation
	LC 5.1	The most reliable and sustainable available form of archiving computer-based visualization outcomes, whether analogue or digital, should be identified and implemented	Archiving	Preservation
	LC 5.2	Digital preservation strategies should aim to preserve the computer-based visualization data, rather than the medium on which they were originally stored, and also information sufficient to enable their use in the future, for example through migration to different formats or software emulation.	Data Formats	Preservation
	LC 6	The creation and dissemination of computer-based visualization should be planned in such a way as to ensure that maximum possible benefits are achieved for the study, understanding, interpretation, preservation, and management of cultural heritage.	Dissemination	Accessibility
	LC 6.1	The aims, methods and dissemination plans of computer-based visualization should reflect consideration of how such work can enhance access to cultural heritage that is otherwise inaccessible due to health and safety, disability, economic, political, or environmental reasons, or because the object of the visualization is lost, endangered, dispersed, or has been destroyed, restored or reconstructed.	Access	Accessibility

[21] on the example of VRE for reconstruction of the new Synagogue in Wroclaw: https://www.new-synagogue-breslau-3d.hs-mainz.de/ (Accessed: 05 January 2024)

[22] on the example of the Tell Halaf reconstitution entry from the SciDoc: http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=20 (Accessed: 05 January 2024)

[23] on the example of the Bar Hill Fort Reconstruction from Sketchfab: https://sketchfab.com/3d-models/bar-hill-fort-reconstruction-antonine-wall-6d04c19858b8421ebd034ba13abf4831 (Accessed: 05 January 2024).

Table 3. Continuation

Document	Code	Text of principle	Topic	Group
London Charter	LC 6.2	Projects should take cognizance of the types and degrees of access that computer-based visualization can uniquely provide to cultural heritage stakeholders, including the study of change over time, magnification, modification, manipulation of virtual objects, embedding of datasets, instantaneous global distribution.	Licensing	Reuse
Seville Principles	SP 4.7	All computer-based visualization must be essentially transparent, i.e. testable by other researchers or professionals, since the validity, and therefore the scope, of the conclusions produced by such visualization will depend largely on the ability of others to confirm or refute the results obtained.	Transparency	Reuse
	SP 4.7.3	In the interests of scientific transparency, it is necessary to create a large globally accessible database with projects that offer optimum levels of quality (Art 8.4), without undermining the creation of national or regional databases of this type.	Database	Findability
FAIR Principles	FAIR F1	(Meta)data are assigned a globally unique and persistent identifier	Persistent Identifiers	Findability
	FAIR F2	Data are described with rich metadata (defined by R1 below).	Metadata	Findability
	FAIR F3	Metadata clearly and explicitly includes the identifier of the data they describe.	Metadata, Persistent Identifier	Findability
	FAIR F4	(Meta)data are registered or indexed in a searchable resource.	Indexing	Findability
	FAIR A1	(Meta)data are retrievable by their identifier using a standardized communications protocol.	Retrievability	Accessibility
	FAIR A1.1	The protocol is open, free, and universally implementable	Retrievability	Accessibility
	FAIR A1.2	The protocol allows for an authentication and authorization procedure where necessary	Retrievability	Accessibility
	FAIR A2	Metadata is accessible, even when the data are no longer available.	Preservation	Accessibility
	FAIR I1	(Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.	Data Format	Interoperability
	FAIR I2	(Meta)data use vocabularies that follow FAIR principles.	Vocabulary	Interoperability
	FAIR I3	(Meta)data include qualified references to other (meta)data.	Referencing	Interoperability
	FAIR R1	(Meta)data are richly described with a plurality of accurate and relevant attributes	Metadata	Reuse
	FAIR R1.1	(Meta)data are released with a clear and accessible data usage license.	Licensing	Reuse
	FAIR R1.2	(Meta)data are associated with detailed provenance.	Data Provenance	Reuse
	FAIR R1.3	(Meta)data meet domain-relevant community standards.	Standards	Reuse
5-star Open Data Scheme	5OD 1	Available on the web (whatever format) but with an open license, to be Open Data.	Licensing	Accessibility
	5OD 2	Available as machine-readable structured data (e.g. excel instead of an image scan of a table).	Data Format	Interoperability
	5OD 3	as (2) plus a non-proprietary format (e.g. CSV instead of Excel).	Data Format	Accessibility
	5OD 4	In addition to all the above, use open standards from W3C (RDF and SPARQL) to identify things so that people can point at your stuff.	Data Format, Standards	Interoperability
	5OD 5	All the above, plus: Link your data to other people’s data to provide context.	Referencing	Findability

Table 4. Summary of selected documentation methods in light of documentation principles extracted from London Charter (LC), Seville Principles (SP), FAIR Principles (FP) and 5-star Open Data scheme (5OD). The blue color distinguishes rules for findability, yellow for availability, orange for interoperability, green for reuse, and purple for preservation.

Group	Topic	Code	Closed Virtual Research Environment (VRE) [24]	Open, institutional repository for projects documentation: SciDoc[25]	Open, commercial repository for 3D models: Sketchfab [26]
Findability	Database	SP 4.7.3	PARTLY, published database is searchable worldwide	NO	YES
	Persistent Identifiers	FAIR F1	YES	NO	NO
	Metadata	FAIR F2	YES	YES	NO
	Metadata, Persistent Identifier	FAIR F3	YES	NO	NO
	Indexing	FAIR F4	YES	NO	YES
	Referencing	5OD 5	YES	NO	YES
Accessibility	Dissemina-tion	LC 6	YES	PARTLY because the system does not support 3D content	YES
	Access	LC 6.1	YES	YES	YES
	Retrievability	FAIR A1	YES	NO	NO
	Retrievability	FAIR A1.1	YES	YES	YES
	Retrievability	FAIR A1.2	YES	YES	YES
	Preservation	FAIR A2	YES	NO	NO
	Licensing	5OD 1	YES	NO	YES
	Data Format	5OD 3	YES	NO	NO
Interoperability	Data Format	FAIR I1	YES	NO	NO
	Vocabulary	FAIR I2	YES	NO	NO
	Referencing	FAIR I3	YES	NO	YES
	Data Format	5OD 2	YES	NO	NO
	Data Format, Standards	5OD 4	YES	NO	NO
Reuse	Evaluation	LC 4.2	YES	YES	PARTLY, it is not possible to display the model with the sources
	Licensing	LC 6.2	YES	YES	YES
	Transparency	SP 4.7	YES	YES	NO
	Metadata	FAIR R1	YES	YES	NO
	Licensing	FAIR R1.1	YES	NO	YES
	Data Prove-nance	FAIR R1.2	YES	YES	NO

[24] on the example of VRE for the reconstruction of the new Synagogue in Wroclaw: https://www.new-synagogue-breslau-3d.hs-mainz.de/ (Accessed: 05 January 2024)

[25] on the example of the Tell Halaf reconstitution entry from the SciDoc: http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=20 (Accessed: 05 January 2024)

[26] on the example of the Bar Hill Fort Reconstruction from Sketchfab: https://sketchfab.com/3d-models/bar-hill-fort-reconstruction-antonine-wall-6d04c19858b8421ebd034ba13abf4831 (Accessed: 05 January 2024)

Table 4. Continuation

Group	Topic	Code	Closed Virtual Research Environment (VRE) [27]	Open, institutional repository for projects documentation: SciDoc[28]	Open, commercial repository for 3D models: Sketchfab [29]
Reuse	Standards	FAIR R1.3	YES, in terms of ontological solutions	YES, referring to local standards used at TU Darmstadt	NO
Preservation	Long-term Sustainability	LC 5	NO	NO	NO
	Archiving	LC 5.1	NO	NO	NO
	Data Formats	LC 5.2	YES	YES	NO

Table 5. Analysis of the metadata used by the most popular 3D repositories from commercial and institutional offers.

Category	Type of metadata	3D Repository		3D Warehouse[30]	Europeana[31]	Kompakkt[32]	Sketchfab[33]	Smithsonian[34]	Turdbosquid[35]	Blend Swap[36]
Reconstruction data	Descriptive	Name		x	x	x	x	x	x	x
	Descriptive	Description		x	x	x	x	x	x	x
	Descriptive	Type		-	x	x	x	-	-	-
	Descriptive	Categories		-	x	-	x	-	x	x
	Administrative	Version of model		-	-	-	-	-	-	-
	Descriptive	Creators	Name	-	-	-	-	-	-	x
	Descriptive		Institution	x	x	x	x	-	x	-
	Descriptive		Role	-	-	x	-	-	-	-
	Administrative	Date	of creation	-	-	-	-	-	-	-
	Administrative		of publication	-	x	-	x	-	x	x
	Administrative		of the last update	x	x	-	-	-	-	-
	Descriptive	Tags		-	-	-	x	-	x	x
	Administrative	Made in project	Name	-	-	-	-	-	-	-
	Administrative		Duration	-	-	x	-	-	-	-
	Administrative		Cooperation	-	-	-	-	-	-	-
	Administrative		Funders	-	-	-	-	-	-	-
	Administrative		Website	-	x	-	-	-	-	-
	Descriptive	Level of certainty		-	-	-	-	-	-	-
	Descriptive	Used sources		-	x	-	-	x	-	-

[27] on the example of VRE for the reconstruction of the new Synagogue in Wroclaw: https://www.new-synagogue-breslau-3d.hs-mainz.de/ (Accessed: 05 January 2024)

[28] on the example of the Tell Halaf reconstitution entry from the SciDoc: http://dmz-39.architektur.tu-darmstadt.de/reconstruction/?ac=project&cm=view&project_id=20 (Accessed: 05 January 2024)

[29] on the example of the Bar Hill Fort Reconstruction from Sketchfab: https://sketchfab.com/3d-models/bar-hill-fort-reconstruction-antonine-wall-6d04c19858b8421ebd034ba13abf4831 (Accessed: 05 January 2024)

[30] https://3dwarehouse.sketchup.com/ (Accessed: 23 January 2022)

[31] https://www.europeana.eu/en (Accessed: 23 January 2022)

[32] https://kompakkt.de/home (Accessed: 23 January 2022)

[33] https://sketchfab.com/feed (Accessed: 23 January 2022)

[34] https://3d.si.edu/ (Accessed: 23 January 2022)

[35] https://www.turbosquid.com/ (Accessed: 23 January 2022)

[36] https://www.blendswap.com/ (Accessed: 23 January 2022)

Table 5. Continuation

Category	Type of metadata	3D Repository		3D Warehouse[37]	Europeana[38]	Kompakkt[39]	Sketchfab[40]	Smithsonian[41]	Turdbosquid[42]	Blend Swap[43]
	Descriptive	Identifier		-	x	-	-	-	x	-
Object data	Descriptive	Identifier		-	-	-	-	x	-	-
Object data	Descriptive	Name		-	-	-	-	-	-	-
Object data	Descriptive	Type		-	-	-	-	-	-	-
Object data	Descriptive	Style		-	x	x	-	x	-	-
Object data	Descriptive	Producer	Name	-	-	-	-	x	-	-
Object data	Descriptive	Producer	Role	-	-	-	-	-	-	-
Object data	Descriptive	Producer	Institution	-	-	-	-	x	-	-
Object data	Descriptive	Location	of creation	-	x	x	-	x	-	-
Object data	Descriptive	Location	current	-	x	x	-	x	-	-
Object data	Descriptive	Date	of creation	-	x	-	-	-	-	-
Object data	Descriptive	Date	of destruction	-	-	-	-	-	-	-
Object data	Descriptive	Date	others	-	-	-	-	-	-	-
Object data	Descriptive	Condition (existing, demolished, etc.)		-	-	-	-	x	-	-
Object data	Descriptive	Materials		-	-	-	-	x	-	-
Object data	Descriptive	Dimensions		-	-	-	-	x	-	-
Reuse data	Administrative Rights Management (ARM)	License		-	x	x	x	x	x	x
Reuse data	Administrative Rights Management (ARM)	Rights	Information	-	x	x	x	x	x	-
Reuse data	Administrative Rights Management (ARM)	Rights	Owner	-	x	x	-	-	-	-
Reuse data	Administrative Preservation (AP)	Contact	Creators	-	-	x	-	-	-	-
Reuse data	Administrative Preservation (AP)	Contact	Institution	-	-	x	-	x	x	-
Reuse data	Administrative Preservation (AP)	Contact	Right Owner	-	-	x	-	-	-	-
Reuse data	Administrative Preservation (AP)	Available file formats		-	-	-	x	x	x	x
Reuse data	structural	Related models		-	x	-	-	x	x	-
Technical data	Administrative Preservation (AP)	Origin format		-	-	-	x	-	x	x

[37] https://3dwarehouse.sketchup.com/ (Accessed: 23 January 2022)
[38] https://www.europeana.eu/en (Accessed: 23 January 2022)
[39] https://kompakkt.de/home (Accessed: 23 January 2022)
[40] https://sketchfab.com/feed (Accessed: 23 January 2022)
[41] https://3d.si.edu/ (Accessed: 23 January 2022)
[42] https://www.turbosquid.com/ (Accessed: 23 January 2022)
[43] https://www.blendswap.com/ (Accessed: 23 January 2022)

Table 5. Continuation

Category	Type of metadata	3D Repository		3D Warehouse[44]	Europeana[45]	Kompakkt[46]	Sketchfab[47]	Smithsonian[48]	Turbosquid[49]	Blend Swap[50]
Technical data	Administrative Preservation (AP)	Data capture	Technique	-	-	-	-	-	-	-
	Administrative Preservation (AP)		Equipment	-	-	-	-	-	-	-
	Administrative Preservation (AP)	Used software		x	-	-	-	-	x	x
	Administrative Preservation (AP)	Version of software		-	-	-	-	-	x	x
	Administrative Preservation (AP)	Possible formats		-	-		x	x	x	-
	Administrative Preservation (AP)	Type of model (points cloud, polygonal, etc.)		-	-	-	-	-	-	-
	Administrative Preservation (AP)	Geometry type		-	-	-	-	-	-	-
	Administrative Preservation (AP)	Number of	Polygons	x	-	-	x	-	x	-
	Administrative Preservation (AP)		Vertices	-	-	-	x	-	x	-
	Administrative Preservation (AP)		Layers	x	-	-	-	-	-	-
	Administrative Preservation (AP)		Textures	x	-	-	x	-	x	-
	Administrative Preservation (AP)	Size		x	-	-	x	-	-	-
	Administrative Preservation (AP)	Units		x	-	-	-	-	-	-
	Administrative Preservation (AP)	PBR		-	-	-	x	-	-	-
	Administrative Preservation (AP)	Rigged geometries		-	-	-	x	-	x	-
	Administrative Preservation (AP)	Morph geometries		-	-	-	x	-	-	-
	Administrative Preservation (AP)	Scale regulations		-	-	-	x	-	-	-

[44] https://3dwarehouse.sketchup.com/ (Accessed: 23 January 2022)
[45] https://www.europeana.eu/en (Accessed: 23 January 2022)
[46] https://kompakkt.de/home (Accessed: 23 January 2022)
[47] https://sketchfab.com/feed (Accessed: 23 January 2022)
[48] https://3d.si.edu/ (Accessed: 23 January 2022)
[49] https://www.turbosquid.com/ (Accessed: 23 January 2022)
[50] https://www.blendswap.com/ (Accessed: 23 January 2022)

Table 5. Continuation

Cate-gory	Type of metadata	3D Repository	3D Ware-house[51]	Euro-peana[52]	Kom-pakkt[53]	Sketch-fab[54]	Smith-sonian[55]	Turdbos-quid[56]	Blend Swap[57]
Technical data	Administrative Preservation (AP)	Vertex color	-	-	-	x	-	-	-
	Administrative Preservation (AP)	Animation	-	-	-	x	-	-	-
	Administrative Preservation (AP)	Bounds	x	-	-	-	-	-	-
Relations	Structural	Similar items	-	x	-	x	-	x	-
	Structural	Models created by author	x	-	-	-	-	x	-
	Structural	External relations	-	x	-	x	x	-	-

[51] https://3dwarehouse.sketchup.com/ (Accessed: 23 January 2022)
[52] https://www.europeana.eu/en (Accessed: 23 January 2022)
[53] https://kompakkt.de/home (Accessed: 23 January 2022)
[54] https://sketchfab.com/feed (Accessed: 23 January 2022)
[55] https://3d.si.edu/ (Accessed: 23 January 2022)
[56] https://www.turbosquid.com/ (Accessed: 23 January 2022)
[57] https://www.blendswap.com/ (Accessed: 23 January 2022)