

# Virtual Research Environment for Digital 3D Reconstructions: Standards, Thresholds, and Prospects

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Since the 1990s, the application of digital 3D reconstruction and computer-based visualization of cultural heritage has increased. Virtual reconstruction and 3D visualization have revealed a new “glittering” research space for object-oriented disciplines such as archaeology, art history and architecture. Nevertheless, the scientists concerned with the new technology soon recognized the lack of documentation standards in the 3D projects, leading to the loss of information, findings and the fusion of knowledge behind the digital 3D representation. Based on the methodological fundamentals of digital 3D reconstruction, the potentials and challenges in the light of emerging Semantic Web and Web3D technologies is introduced here. The presentation describes a scientific methodology and a collaborative web-based research environment followed by crucial features for these kinds of projects. As the groundwork, a human- and machine-readable “language of objects” and the implementation of these semantic patterns for spatial research purposes on destroyed and/or never realized tangible cultural heritage will be discussed. Using examples from the practice, the presentation explains the requirements of the Semantic Web (Linked Data), the role of controlled vocabularies, the architecture of the VRE and the impact of a customized integration of interactive 3D models within WebGL technology. The presentation intends to showcase the state-of-the-art steps on the way to a digital research infrastructure. The focus lies on the introduction of scholarly approved and sustainable digital 3D reconstruction, compliant with recognized documentation standards and following the Linked Data requirements.

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## Key words:

Digital hypothetical 3D reconstruction, 3D modeling, data modeling, Linked Data, Virtual Research Environment

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## 1. THE THREE-DIMENSIONAL MODEL AND DIGITAL 3D RECONSTRUCTION

The three-dimensional model has been used as a simplified representation of reality for a long time in architecture, the fine arts, art and architectural history and archaeology. The model can serve different purposes: to represent an existing original or to communicate a creative vision. Especially

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in historical subjects, it is also of great interest as a way of creating a hypothetical representation of ruined and unrealized works of art and buildings, reducing these to an essential and effective communication of the space. In academic publications, however, two-dimensional images of models are usually used to support text-based argumentation.

In contrast to analogue models, digital models can also be used to communicate historical research. As a result of the rapid development of information technology, digital 3D reconstruction projects have been increasingly used in academic research since the 1990s. In the German-speaking world, the early digital models of destroyed synagogues at the TU Darmstadt and TU Vienna deserve mention [Grellert et al. 2004, Martens and Peter 2009]. This type of model, virtual reconstruction, has become very popular; it attracts a great deal of publicity, bringing lost cultural heritage back to life. Derivatives of these models, starting with animated films, have become a regular feature of historical documentaries and museum exhibitions. Upon closer examination, the increasing use of photorealism and computer-generated images is striking. This is powered by technological development on the one hand, and by the growing social influence of the gaming and film industries on the other. Researchers are therefore justified in criticizing the hyper-realistic representation of hypothetical constructions in digital models and their derivatives [Bentkowska-Kafel 2013]. The more realistic the representation is, the more likely it is that the hypothesis is not scientifically documented, and the more skeptical the recipient is likely to be.

A new methodology and range of possible applications are involved in the virtual reconstruction of digital models, henceforth called digital 3D reconstruction [Kuroczyński 2012]. All historical computer reconstructions base their hypothetical three-dimensional replica of a destroyed work of art or building on historical sources and their interpretation. Digital 3D reconstruction is supported by interdisciplinary processes, in which the sources are collected, the objects identified and classified, in order to then be modeled on the computer and textured. During modeling, the geometry of an object is digitally reconstructed and its materiality expressed through the texturing of bare structure (figure 1).

Modeling in the virtual space provided by simulation and animation software has several advantages: a holistic (free) approach to the models, lightweight versioning and representation of variants arising from ongoing consultation with specialists, and the variety of secondary applications that can be used with it. The possible applications range from established technologies like animation films, exportation into the interactive environment of a game engine, and implementation within an immersive virtual reality installation or augmented reality application in physical space, to re-materializing the digital models using rapid prototyping.

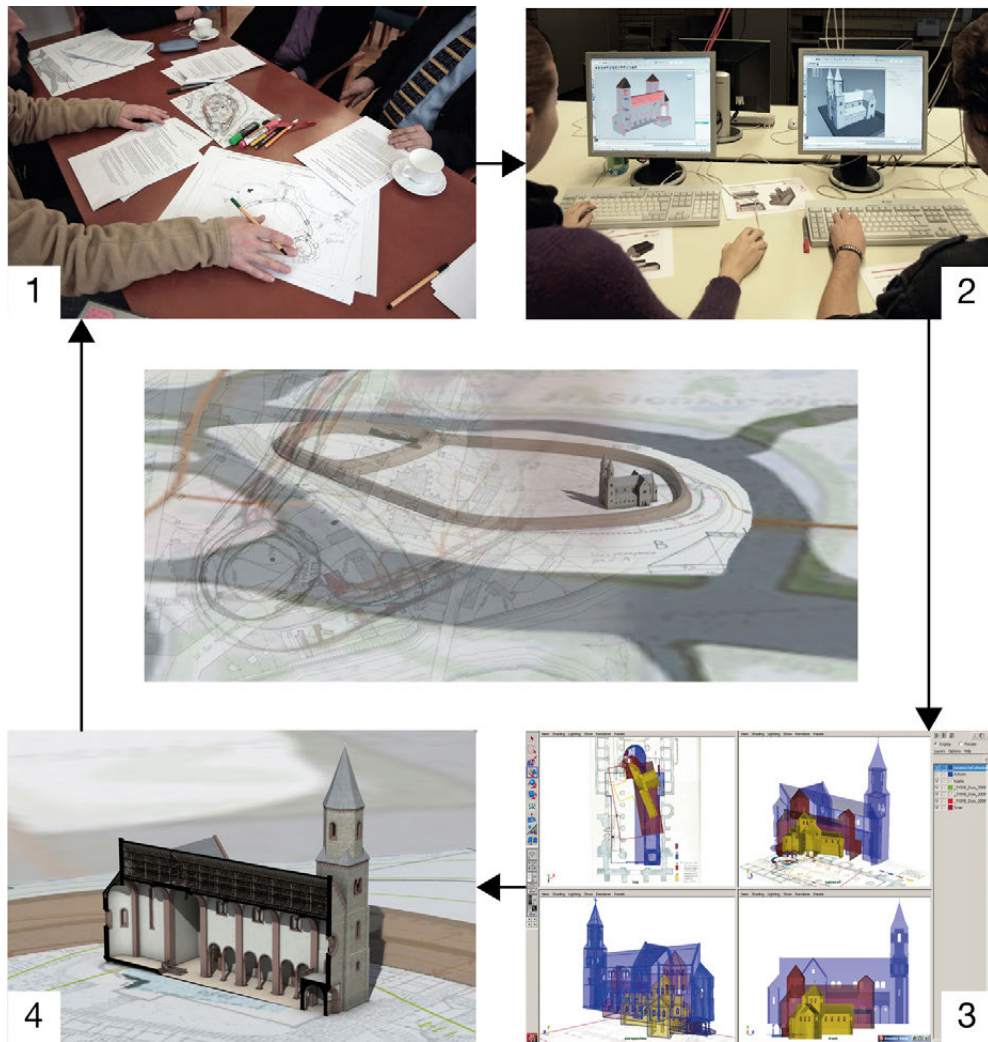


Figure 1. Example of a digital 3D reconstruction process – the architectural history of Wrocław Cathedral. 1) Review and evaluation of the sources, 2) 3D modeling based on the sources, 3) integrated view of the reconstructed phases, 4) textured 3D computer visualization (copyright TU Darmstadt, 2010).

The holistic approach, process orientation and knowledge fusion of digital 3D reconstruction is an asset to architectural historical research, as Diane Favro stresses:

A comprehensive historical digital reconstruction model requires the same amount of information as a new building, compelling scholar modelers to study every single aspect, not solely a parsed segment. The holistic approach reveals valuable information especially during model creation, as scholar modelers must deal with the interrelationships between wall thicknesses, materials, building techniques, engineering, and other architectural aspects. Published 2-D historical reconstruction drawings of façades and floor plans in black and white do not infrequently elide significant aspects of the design that are readily evident in 3-D

depictions, such as the need for ground-level support for upper floors, or accessibility from one section to another. [Favro 2012]

The *bright side* of digital modeling masks the *dark side* of digital 3D reconstruction. This manifests itself primarily in the unresolved issues of traceability and documentation in processes based on interpretation and the (long-term) availability of results. The key challenge is lack of communication between experts within the community about digital documentation standards and sustainable file formats, both 3D and in general. This is compounded by generally observed irregularities regarding rights and licensing issues, which prevent the open access publication of 3D models, and is further hampered by a lack of digital infrastructure to support sustainable archiving and adequate publication. To put it plainly, it shows a lack of academic rigor and is a waste of public funds if the 3D models and the knowledge behind them eke out their existence after the projects are completed in ever-expanding *digital cemeteries*.

The new virtual research facilities arising from the implementation of 3D modeling software (computer-aided design, CAD) in art and architectural history have been studied and documented since the second half of the 1990s. A number of influential members of the German-speaking art historical research community have called for verifiable traceability, including *Footnotes to the Model* [Hoppe 2001] and *Critical Computer Visualization* [Günther 2001]. At a same time, on the international level, the *London Charter for the Computer-based Visualization of Cultural Heritage* was developed from a number of EU projects. "The Charter defines principles for the use of computer-based visualisation methods relating to intellectual integrity, reliability, documentation, sustainability and accessibility." [The London Charter 2006]

The 2006 London Charter highlights the interpretive creative process of digital 3D reconstruction and the subsequent 3D visualization. The *documentation of this process (paradata)* is declared as a central tenet: "Documentation of the evaluative, analytical, deductive, interpretive and creative decisions made in the course of the computer-based visualisation, should be disseminated in such a way that the relationship between research sources, implicit knowledge, explicit reasoning, and visualization-based outcomes can be understood." [The London Charter 2006]

*Paradata*, a widely-used neologism of the *London Charter*, extends the concept of metadata, or information about the digital records themselves, to include information on the creative development (artistic creation) of a computer-based visualization. Guidelines based on the original charter also deserve a mention here [The Seville Principles 2011], as does fundamental research into digital 3D reconstructions [Pfarr 2010], which is setting trends for medium-term research on and in digital models.

## 2. THE NEW DATA CULTURE: THE TOP-DOWN AND BOTTOM-UP APPROACHES

The digital revolution and the associated development of information technology can generally be associated with a *democratization of knowledge*, because access to digital information via the internet is virtually unlimited, regardless of location. The exponential growth of information in the digital age is favored by the fact that, globally, more and more people are participating in the creation and delivery of content on the World Wide Web (Web 2.0). The issue is no longer whether it makes

sense to digitize everything. Rather, the question is now *when* our own personalities, our analogue environment and all the knowledge of the past millennia will be fully digitized. The order chosen here probably reflects the chronological progress of digitization. This raises another question: In what form must the data be available so that people can take advantage of this flood of information, which has already been heralded as the *democratization of knowledge*?

The digital research data are key here as the main raw material of the information society, which we will address below. Digital research data raises a variety of new challenges in terms of quality assurance. The human and computer oriented documentation of knowledge, focused on openness and integrity, puts a *new culture of data* on the agenda [Information Infrastructure Council 2016].

An essential building block for ensuring the readability and usability of digitized information in an academic context is the formalization of knowledge. Formalization aims to represent the linguistically composed translation and formally ordered representation of knowledge in a form that can be read by humans and machines. The concepts (classes or entities) and relevant relationships to be researched are classified by discipline and defined. In the language of computer science, *data modeling* gives rise to *ontologies*, which represent a field of research. A distinction is drawn between *application ontologies*, covering a specific sub-field of a subject, for example specific issues relating to the portraits of the Renaissance, and the overlying *reference ontologies*, which enable an exchange of data in a larger context, for example general issues relating to art history. In the field of cultural heritage, the reference ontology CIDOC Conceptual Reference Model (CRM), developed between 1996 and 2006, has become the *lingua franca*. As an internationally recognized ISO standard, ISO 21127:2014 describes about 90 entities and 150 relations based on events, all the key areas of the daily business of cultural institutions, but primarily focusing on museum work (figure 2).

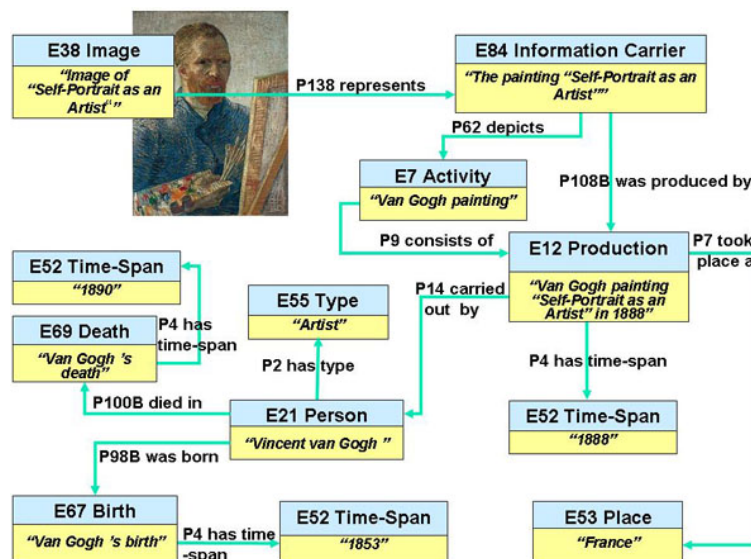


Figure 2. Illustration of the entities and relations with the CIDOC CRM, using a self-portrait by Vincent van Gogh as an example (copyright Martin Doerr).

The importance of adequately preparing information for digital documentation, computer-based research and interchangeability of data was declared as early as 1983 by Lutz Heusinger, the Director of the German Documentation Centre for Art History – Bildarchiv Foto Marburg, in his eight theses of art history and computer science: "Since electronic data processing is mechanical, it forces us to give it our research results in a consistently formalized form. This presupposes a set of rules which will be much more extensive than the famous 'Prussian instructions' for the cataloging of books, or the 'Anglo-American Rules of Cataloguing'" [Heusinger 1983].

The formalization and associated determination of *core fields* of archival documentation (card index principle), raises the question of who has the right to make such a far-reaching decision in advance. Are the *fine arts information professionals*, who Heusinger says need to be retrained, qualified enough to redefine lasting boundaries for a subject? Hardly.

Nevertheless, formalization driven by specialists plays an important role in the development and provision of information online. The goal of this top-down knowledge processing is to publish structured data sets that both humans and machines can read. One notable example, *Europeana*, the European digital library, is worth mentioning here [www.europeana.eu]. This contains records from the libraries, archives and museums of all EU member states. *Europeana* must provide a link to these, which refers to the relevant institutions and the delivered content (its original online presence).

In the case of *Europeana*, records are exported in the Lightweight Information Describing Objects (LIDO) data format, an XML Interchange format that delivers the metadata about collection objects to portals [http://network.icom.museum/cidoc/working-groups/lido/what-is-lido/]. LIDO was developed to be event-oriented and to support the integration of unique identifiers. As a consequence, objects are better described based on events, analogous to the CIDOC CRM principle. In the digital documentation and digital research data, identifiers are understood as especially unique attributions of a person, an object or a location. These are called standard data, as they ensure disambiguation of the information, which supports targeted searching with unambiguous results. A well-known example from the German-speaking countries is the Integrated Authority File (Gemeinsame Normdatei, GND), which was originally created and maintained by the German National Library. In order to meet the growing challenges, retrieval and maintenance is increasingly done in cooperation with multiple cultural institutions. On the international level, the Virtual International Authority File (VIAF) is used for personal data.

Complementary to this, the free encyclopedia Wikipedia (cf. DBpedia) and the supportive, freely editable database Wikidata are developing into an important reference file, or authority file. Their citizen science and crowdsourcing based records are increasingly referred to (2,018,694 German articles on Wikipedia on 9 January 2017) because of their topicality, multilingualism and fascinating amount of information.

The standard files are complemented by controlled vocabularies (thesauri), which index terms semantically, following a hierarchical structure. The best-known are the Getty vocabularies, which were created in the 1980s for the electronic information system of the John Paul Getty Trust for art history [https://www.getty.edu/research/tools/vocabularies/]. The Getty Research Institute today offers four referencing vocabularies: The Art & Architecture Thesaurus (AAT), The Cultural Objects Name Authority (CONA), The Union List of Artist Names (ULAN) and The Getty Thesaurus of

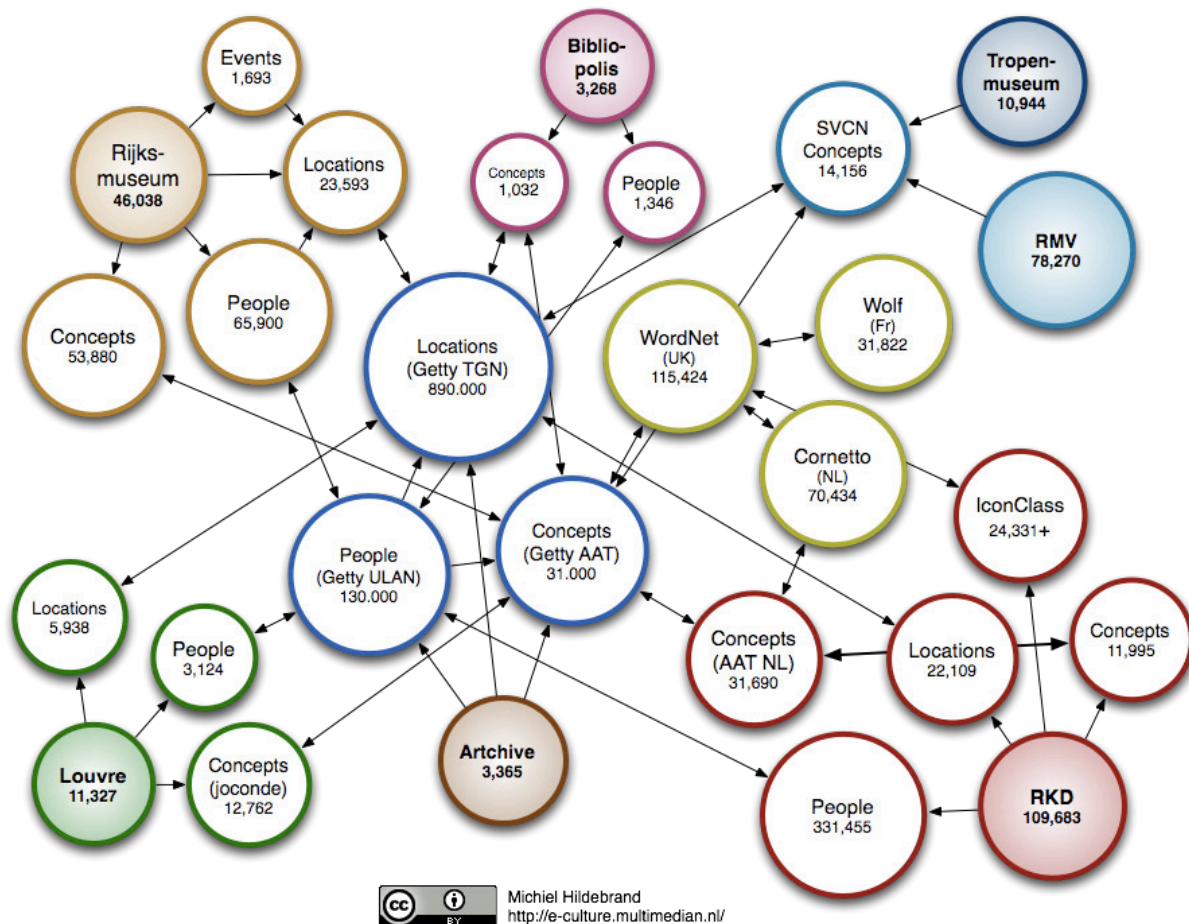


Figure 3. Networking the internal identifiers within the museum scene with other Linked Data resources (Copyright Michiel Hildebrand).

Geographic Names (TGN). The Getty vocabularies are significant because of their ongoing translation into multiple languages and increasing use by a large number of renowned cultural institutions (the Louvre, Rijksmuseum, etc.) to index their own object-related records (figure 3).

One digital technology that is increasingly being used for globally networking semantically enriched data is based on an idea by Tim Berners-Lee: the Semantic Web. In his article in *Scientific American* in 2001, he postulated that the internet needed to be developed in such a way as to ensure the legibility and readability of digital data:

The Semantic Web is not a separate Web but an extension of the current one, in which information is given well-defined meaning, better enabling computers and people to work in cooperation. The first steps in weaving the Semantic Web into the structure of the existing Web are already under way. In the near future, these developments will usher in significant new



functionality as machines become much better able to process and “understand” the data that they merely display at present [Berners-Lee et al. 2001].

The basic building blocks for this development are based on familiar technologies, *eXtensible Markup Language* (XML) to create your own tags and annotate Web content, and a *Resource Description Framework* (RDF) to represent the meaning within a semantic syntax (triples). An RDF triple follows the usual sentence structure (subject-predicate-object), and can be written using XML tags. An RDF provides documents with the ability to express assumptions in the form of entities (e.g. a capital) and their relations (e.g. is part of) with certain values (e.g. an architectural column).

In the concept of *Semantic Web*, also called Web 3.0, each subject and object is identified by persistent *Universal Resource Identifiers* (URIs), analogous to an internet address (URL, Uniform Resource Locator). Each predicate also receives a URI, which enables the definition of a concept (or a new verb). At the moment, where objects and subjects of a record from repository A web-based links are made to other similarly structured data records from repository B, C, D, and so on, this is called *Linked (Open) Data*. The application of ontologies to index the semantic elements of triples, accompanied by the integration of authority files and controlled vocabularies, enables deeper, more human and machine-readable cataloguing of digital information (figure 4).

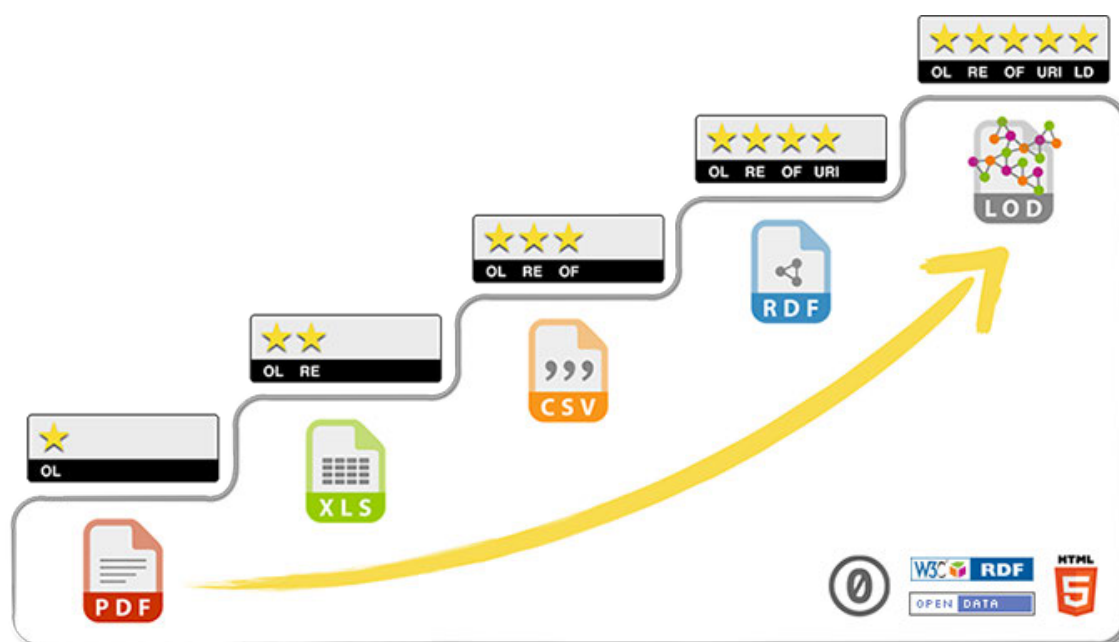


Figure 4. The 5-star model for open data by Tim Berners-Lee (<http://5stardata.info/en/>). ★ make your stuff available on the Web (whatever format) under an open license, ★★ make it available as structured data (e.g., Excel instead of an image scan of a table), ★★★ make it available in a non-proprietary open format (e.g., CSV as well as Excel), ★★★★ use URIs to denote things, so that people can point at your stuff, ★★★★★ link your data to other data to provide context.



A negative side effect of the institutionally-led formalization of knowledge as a result of digitization is the confusing number of documentation standards for different subject cultures. This hampers interoperability between data sets and restricts the level of utilization by potential users.

The institutionalized *top-down approach* is understandable, given the increasing challenge of evaluating the immense flood of data, algorithmic analysis and analysis of large, heterogeneous data sets (Big Data). The complementary *bottom-up approach* is increasingly used to evaluate data by major search engine companies like Google, as well as industry and intelligence services, such as the CIA. Another background technology that is of interest to the humanities is *computer vision*, which is characterized by multi-layered structures consisting of a variety of algorithmic nodes. Each node specializes in the detection of certain values, such as following a contour line in the analysis of digital images, or the geometric conditions of a digital 3D model. The special feature of *computer vision* is that it processes data similarly to the human brain, continually producing more accurate results. This is called *Deep Machine Learning*. The computer-based auto-detection of objects is already being tested, for example by the automotive industry, to use in self-driving vehicles. The computer-generated creation of another Rembrandt portrait shows us the future possible applications of this technology [www.nextrembrandt.com].

### 3. DIGITAL CULTURAL HERITAGE AND THE DIGITAL CONTINUITY OF 3D MODELS

A computer-supported and scientifically-based 3D reconstruction model is the result of a process of source gathering, interpretation and creative replication of a non-existent (or no longer existing) object. The original digitally generated model is a unique source for research and should be viewed as a *born-digital* equivalent of the cultural heritage it emulates. One example is the digital 3D models of the construction and developmental phases of St. Peter's Basilica in Rome (figure 5).

The outstanding importance of the digital sources described above, but also the danger that they would not survive owing to lack of maintenance and access strategies were recognized as early as 2003 in the *UNESCO Charter on the Preservation of Digital Heritage*. This charter coined the term "digital continuity" and urged the development of the necessary digital (research) environments and infrastructures:

Continuity of the digital heritage is fundamental. To preserve digital heritage, measures will need to be taken throughout the digital information life cycle, from creation to access. Long-term preservation of digital heritage begins with the design of reliable systems and procedures which will produce authentic and stable digital objects [UNESCO 2003].

In the field of history of art, the mass digitization of objects from museum collections and the digitization of many monuments from national monument authorities, while it has increased the number of 3D data sets, has not led to the establishment of digital documentation standards. Instead, only isolated solutions for representing the documentation of digitization in metadata schema can be observed.

With the expansion of the CIDOC CRM data model to CRM<sub>dig</sub>, the 3D retrodigitization process (e.g. a 3D scan of a museum artifact) can be made human and machine readable, together with records of the objective, measures, software and set parameters used.

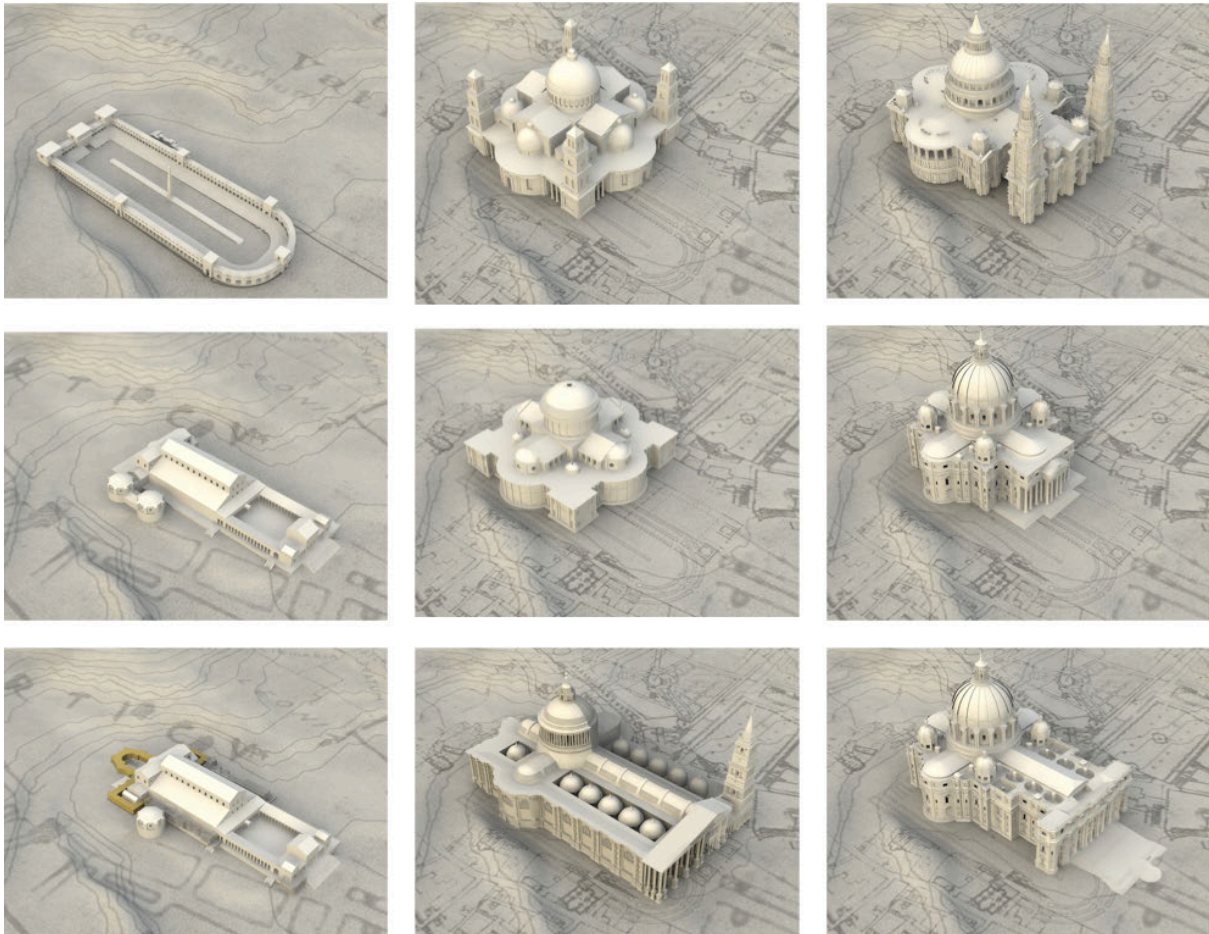


Figure 5: Representation of the different construction and developmental phases of St Peter's Basilica in Rome, proprietary file formats of Maya v. 6.5 (Copyright TU Darmstadt, 2005).

Paola Ronzino designed a CIDOC CRM<sub>BA</sub> extension for creating a data model for documenting different building types, time periods and styles, to enable comprehensive digital research using archaeological sources [Ronzino 2015]. Ina Blümel is researching and developing a metadata model for digital libraries based on 3D architectural models for targeted structuring and further networking of information [Blümel 2013]. This mainly concerns documenting and archiving contemporary architectural projects and their 3D models [www.duraark.eu].

Significant projects on the European level include *3D Icons* and the attempt to develop a metadata scheme to enable the publication of 3D models in *Europeana* [www.3dicons-project.eu]. The CARARE 2.0 scheme consists of four top-level classes to describe a digital object:

*Heritage asset* – holds the metadata for a monument, building or cultural object including printed materials and born-digital objects, including descriptive and administrative metadata.

*Digital resource* – holds the metadata about a digital resource including its online location.

*Activity* – holds the metadata about an event or activity.

*Collection information* – holds the collection-level description.

Heritage assets are “first-class” citizens in the CARARE schema and it is mandatory for each CARARE record to include one heritage asset and at least one digital resource – in this way the schema provides for the description of cultural objects including historical images whose exact location is no longer certain and born-digital cultural objects” [Ferne et al. 2013].

In contrast to CARARE 2.0, in which recording the activity (processes) is not a key requirement, another concept that is ten years older is *Cultural Heritage Markup Language* (CHML). CHML was introduced in 2003 by Oliver Hauck and Andreas Noback at the CeBIT stand of the Department of Architecture of the TU Darmstadt. It is an XML-based markup language for scientific documentation of the built cultural heritage and computer-aided 3D reconstructions:

Concerning our built heritage, we use CAD to create nice pictures ... What about research? What about science? Working scientifically means linking 3D models with historical sources and scientific findings to make them comprehensive and revisable. XML is the most powerful tool to create these links and to enhance communication between the shareholders of our built cultural heritage [Hauck and Noback 2003].

Based on this, a sustainable data model for storing human and machine-readable digital models of ruined cultural heritage was developed within a research project on digital 3D reconstructions of East Prussian baroque palaces, conducted at the Herder Institute of Historical Research on East-Central Europe in Marburg from 2013 to 2016 [Kuroczynski et al. 2016]. The project was primarily dedicated to the manifold issues surrounding *digital continuity*, including the formalization of knowledge within an application ontology, an adequate *Virtual Research Environment* (VRE), the necessary digital tools and web-based 3D visualization. Ruined East Prussian baroque palaces provided a prime example of the multilingual, cross-border and interdisciplinary cooperation in digital 3D reconstruction.

#### 4. THE DATA MODEL BEHIND THE 3D MODEL

The general findings regarding the data model, based on the published CHML ontology (Version 1.1), are presented below. The data model forms the basis for the digital research data produced within a VRE. A detailed description of the project can be found on the project page of the Herder Institute [[www.herder-institut.de/go/Q-338d9c2](http://www.herder-institut.de/go/Q-338d9c2)]. At the heart of any digital 3D reconstruction and its models is the variety of human-led research activities, henceforth simply called *activities*. The authors, heterogeneous sources, and the types and versions of the digital models are grouped around these activities. The knowledge collected and interpreted by the art historian is used for 3D modeling on a computer. The interpretation of knowledge and 3D modeling gives rise to the born-digital 3D models. The results of this creative act on the computer are made available for art historians to discuss. This process is cyclical and encourages the creation of several versions or, if necessary, variants of a model. In this way, human-led *digital (hypothetical) 3D reconstruction* differs significantly from the machine-driven *3D retrodigitization* of existing artifacts, such as 3D data of a laser scan (figure 6).

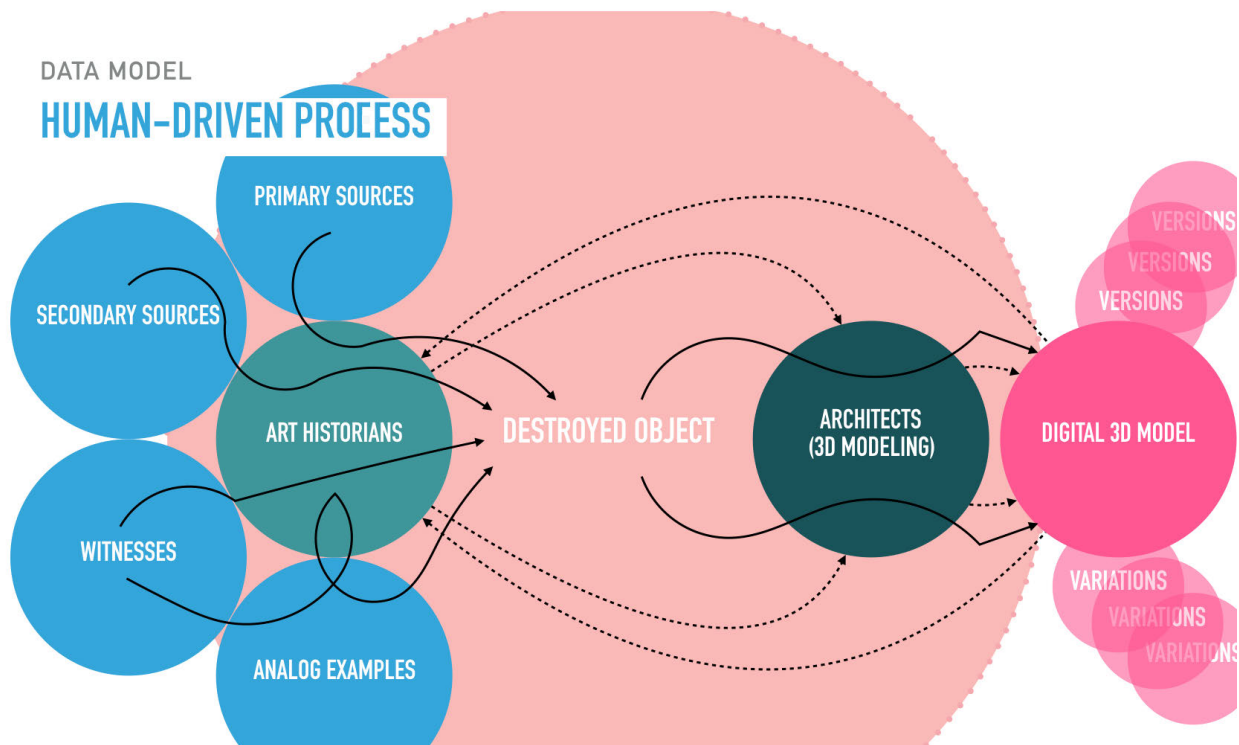


Figure 6. Cyclical workflow of a digital 3D reconstruction (Copyright Piotr Kuroczyński, 2016).

The top-level classes in the data model are therefore the *activities*, the *sources*, the *objects* and, to some extent, the *authors*. The time and location information is primarily attached to the activities. The data model or the application ontology is CIDOC CRM referenced. It integrates the relevant standard data (GND, Wikipedia), controlled vocabularies (the Getty vocabularies) and the IDs from Openstreetmap.org to the unique identification of elements in terms of the *Semantic Web*.

A TYPE system that uniquely identifies the meaning of each entry is proposed for the required classification of all entries. Uniqueness is ensured, on the one hand, through integration (linking) with relevant standard data and controlled vocabularies, and on the other, by the user's own annotation, evidenced by links to online articles and the literature (figure 7).

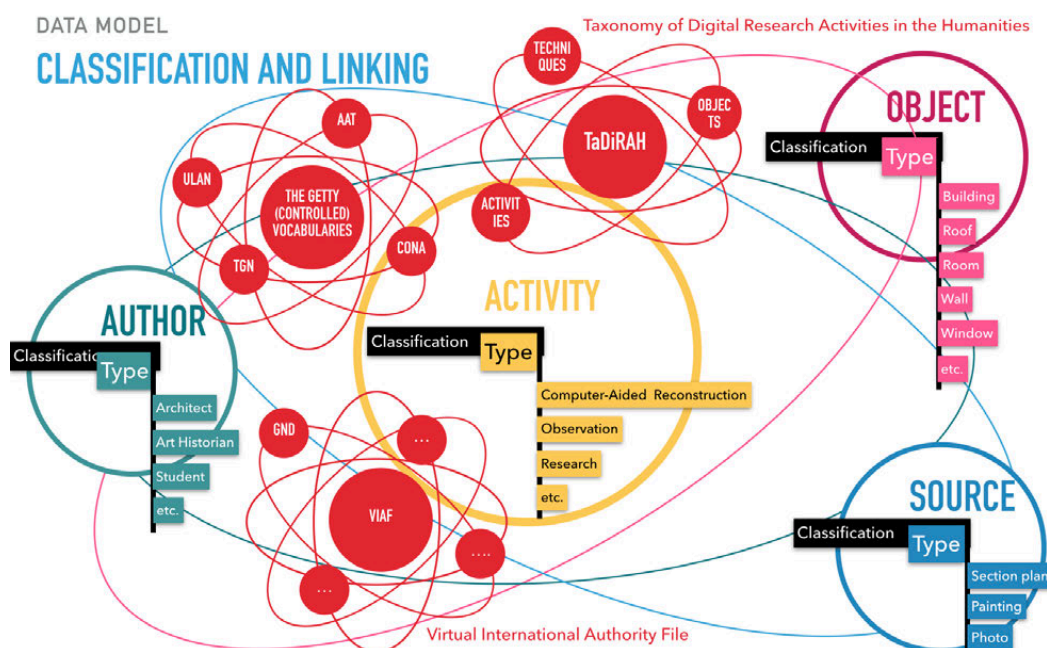


Figure 7. The classification of entries using the TYPE system and networking with other linked data resources (copyright Piotr Kuroczyński, 2016).

Experience has shown that the currently available controlled vocabularies, such as the Getty Art & Architecture Thesaurus (Getty AAT), are not mature enough for the comprehensive academic exploration of architectural and art-historical issues and will probably remain so. It is therefore very useful to create one's own TYPES and design an internal project thesaurus. This approach is also taken by other digital humanities projects, and is called *labelling systems* [Thiery and Engel 2015]. Since key authority data and controlled vocabularies are available in Linked Open Data Format, this type of classification is an important building block for sustainable, unique and semantically enriched digital research data.

The strength of the data model is that data fields can be expanded as required for specific issues. The starting point for representing the main features of a digital 3D reconstruction in terms of scientific methodology is the activity, which describes the process of knowledge generation and modeling.

The basic structure of the data fields used to record research activity (activity) consists of a classification field (Type), a multilingual and/or extensible identification (Title Set), an extensible representation of the relationships and administrative data. The top-level classes of the data model and their mandatory (core) fields are presented in more detail below (figure 8).



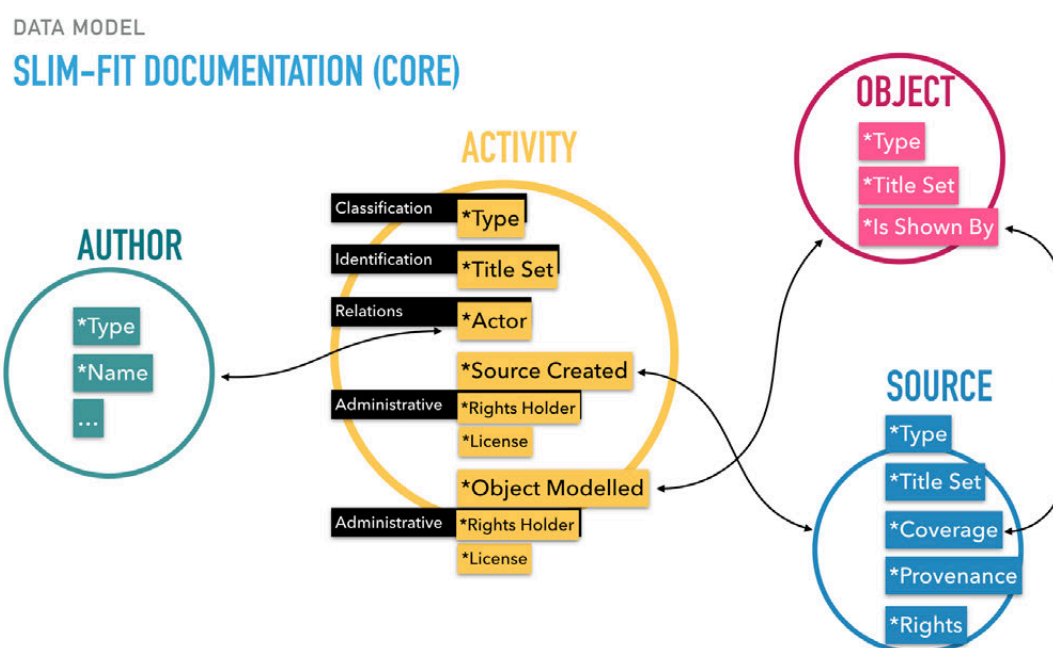


Figure 8. Top-level classes and mandatory fields for minimum level documentation (copyright Piotr Kuroczyński, 2016).

The top-level class activity (*H1 research activity*) is a subclass of CIDOC CRM *E7 Activity*. It represents the activity of creating a source for 3D reconstruction or a model as a result of 3D reconstruction. Its core fields consist of the classification (*Type*: Computer-Aided Reconstruction), assigning the identifying name (*Title Set*: 3D reconstruction of XYZ), the relationship to persons involved (*Author*), the relationship to utilized sources (*Source Used*: XYZ) and to the created object (*Object Modeled*: XYZ).

When a source is created, the classification of the entry in TYPE changes (e.g. *Source Creation*). Instead of entering it under *Object Modeled*, a relationship to the core field *Source Created* is generated. In both cases, it is essential to state the rights to the created digital resources and digital models, making note of the rights holders and the license.

Historical events are a special case. In the context of the digital 3D reconstruction, they are secondary to the documentation of the reconstruction processes, the sources and discussion. The data model was extended at the highest level by the addition of another top-level class, *H20 Historic Event*, and subclass, CIDOC CRM *E5 Event*. This is important, for instance, if the event of planning and/or implementing a building and/or work of art needs to be represented in the data model. In contrast to the (research) *activity*, the people participating in an event are specified as historical *actors*, while the *authors* are the people who create the sources or models.

The top-level class object (*H5 Material Object*) is a subclass of CIDOC CRM *E71 Man-Made Thing*. Here each modeled object is treated as a material object, whether it is certain that it never existed or not.



The (mandatory) core fields consist of the classification (*Type*), identification (*Title Set*), and the reference to a source (*Is Shown By*).

The top-level class object (*H4 Source*) is a subclass of CIDOC CRM *E71 Conceptual Object*. Within the scope of the digital 3D reconstruction, the source is explicitly treated as an object in an art-historical context. From the perspective of the digital 3D reconstruction, it is a conceptual representation (manifestation) of the object to be reconstructed.

Data modeling in the Semantic Web requires the structuring of data in a triple architecture (subject-predicate-object). As a result, chains of *triple paths* are concealed behind the presented data fields. The core field Source Used is composed of the chain *H1\_Action* > *P16\_used\_specific\_object* > *H4\_Source* > *R32\_has\_preferred\_appellation* > *H76\_Title*. The (semantic) meaning behind the fields is human and machine-readable (figure 9).

Data modeling provides a basis for solid digital research data, which can then be made available for further research. Ideally, modeling, customization, and extension should be supported by information experts who are specialists in artificial intelligence.

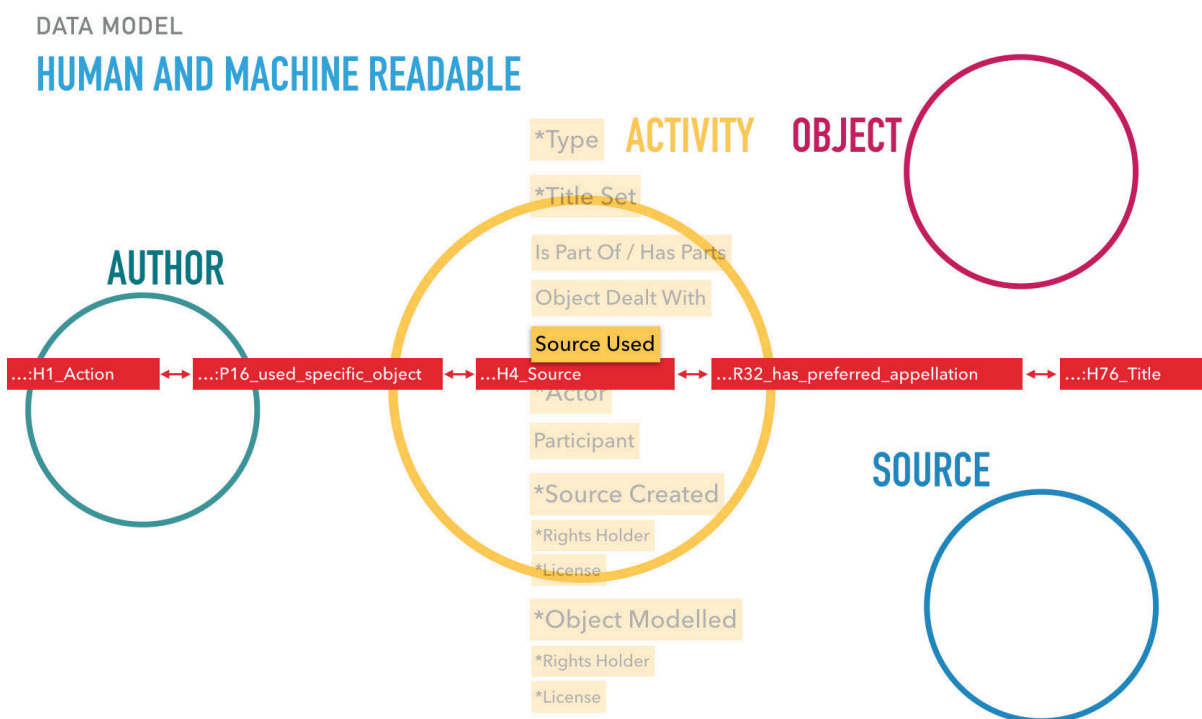


Figure 9. The triple path behind the core field Source Used (copyright Piotr Kuroczyński, 2016).

## 5. VIRTUAL RESEARCH ENVIRONMENT

The requirements for a virtual research environment (VRE) should be formulated clearly from the perspective of the digital 3D reconstruction. The VRE is a web-based application that enables collaboration between specialists in historical fields (archaeology, art and architectural history) and especially the geospatial subjects (geospatial analysis, construction and architecture). The prerequisite is the use of open source applications, taking into account the requirements of the Linked Data technology, to provide networked and web-based digital research results (*Open Science*). In addition, the 3D data sets must be integrated and visualized within the VRE as part of the research data.

In this context, the project to digitally reconstruct ruined baroque palaces in former East Prussia is pioneering and a model for other projects in German-speaking countries [www.drematrix.de/projects/dokuvis-a-documentation-system-for-digital-reconst/ and www.fiz-karlsruhe.de/forschung/projekte/toporaz-topographie-in-raum-und-zeit.html]. During this project, a VRE with digital tools and web-based visualization strategies was developed in addition to the CIDOC CRM referenced data modeling, providing a foretaste of potential new areas of research in art history (figure 10).

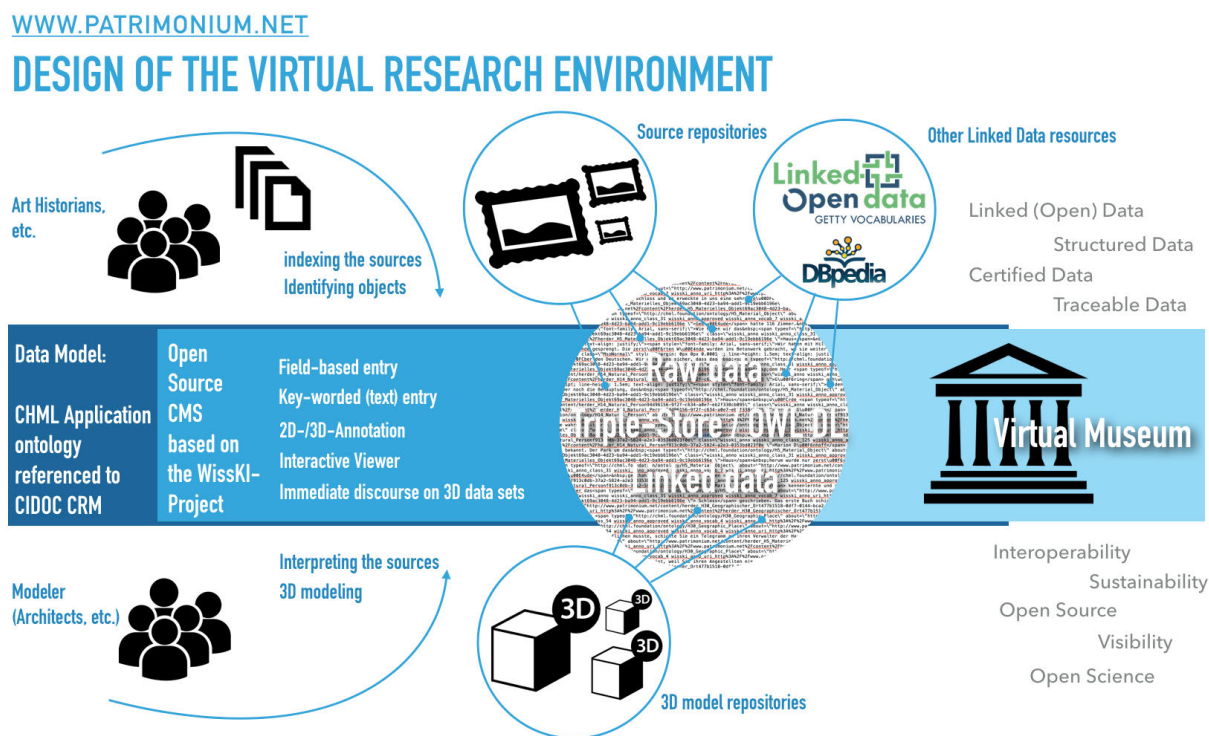


Figure 10. Graphic of the concept of a virtual research environment for digital 3D reconstruction (copyright Piotr Kuroczyński, 2016).

The VRE is an extension and adaptation of the academic communication infrastructure WissKI [http://wiss-ki.eu]. The DFG-funded project WissKI is a flexible research environment based on the open-source content management system (CMS) Drupal. The ability to upload ontologies into WissKI is particularly interesting. Based on this, the WissKI environment makes it easy to create pages (input screens) and data fields. The triple path is constructed based on the uploaded ontology using a *Path Builder* for each data field (see figure 9).

In addition to data field input/recording, free-text annotation is also possible, which can be useful for argumentation and discussion in the humanities. An essential feature of text annotation is hypertext linking and indexing based on semantic instances of the system-internal research data. One of two input modes can be used for this: *Full HTML* or *WissKI Annotated HTML*.

The 3D models are integrated via a WebGL window within the HTML architecture. The open source WebGL technology supports the web-based interactive visualization of 3D models. Many browsers now offer this as a pre-installed plugin. The 3D models can be created in various software programs. The formats used for 3D visualization in the VRE are OBJ for the geometry and MTL, a tried and tested 3D text-based format, for the texture (materiality). Freely viewable models are a basic requirement for direct academic debate in a virtual environment. In addition to 3D reconstruction models, point cloud models of 3D retrodigitizations can also be visualized.

Based on WebGL technology, 2D and 3D annotation can be used. Selected locations on the model and the sources can be annotated by selecting these areas (picking by face) or drawing polygons freehand. Each area is linked to a new *activity*. Thus, for the first time, it is possible to conduct an academic discourse directly on the 3D data sets, which can be seen as an extension of the *digital footnotes*. WebGL can also be used for 2D annotation of sources, but *Scalable Vector Graphics* (SVG) provide a more elegant solution (figure 11).

The front end of the VRE conforms to the processes and top-level classes in the data model. It enables the creation of an object, a source, an event or activity, a legal or natural person, and the location. The exception here is the TYPE editor, which can be used to manipulate the project's internal classification, for disambiguation and linking to other Linked Data repositories. Qualified project staff can use the editor to create the ID, the full name (*Title Set*) and the connections to referenced standard data and controlled vocabularies (*Identifier Set*). The hierarchy of classes needed for architectural and art-historical analysis is as follows: *Broader Term* (mandatory field), *Narrow Term*, *Can Be Part of* and *Can Have Part*.

The data is structured and semantically developed behind the field and text-based input. The resulting research data are stored in a semantic graph database in Linked Data format (OWL DL / RDF Triple Store), and can be externally manipulated and evaluated using the query language for RDF (SPARQL). The 3D data sets are linked with the entries and are freely available for download onto the data server under the *Creative Commons license* CC-BY-NC-SA.

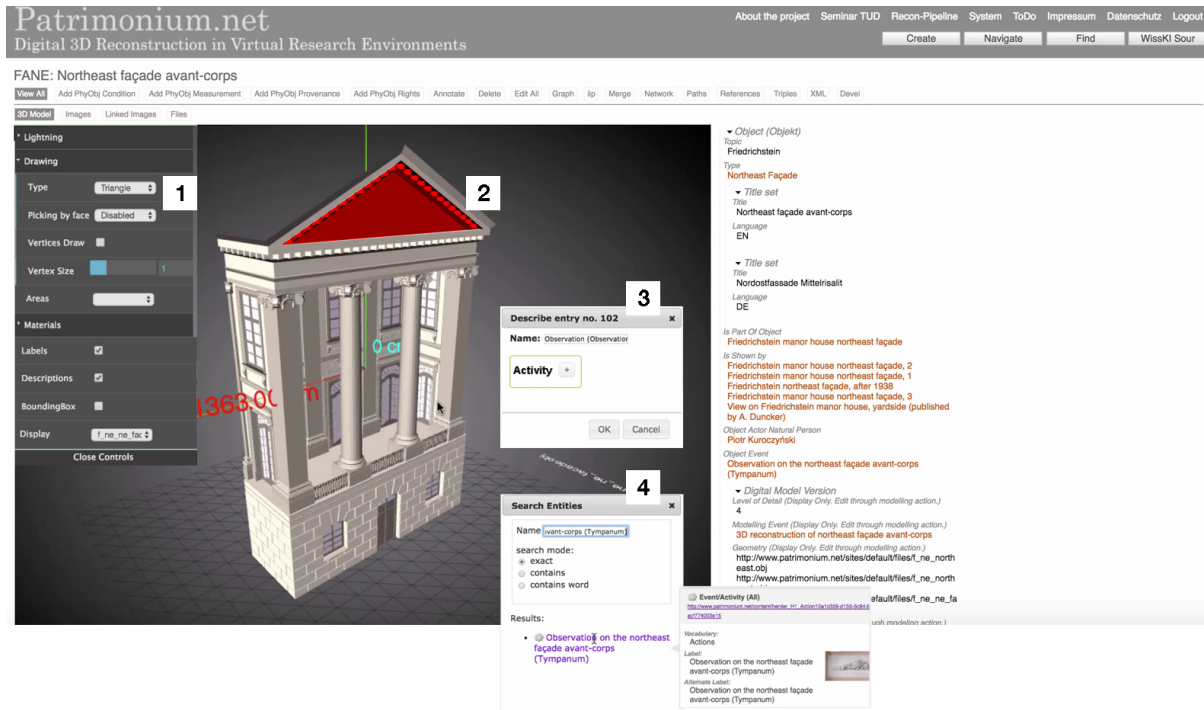


Figure 11. 3D annotation within the virtual research environment on [www.patrimonium.net](http://www.patrimonium.net), 1) control window of WebGL-enabled visualization with active Triangle shown, 2) field shown on the geometry, 3) pop-up window to link the field to a semantic instance activity, 4) pop-up window to search for a semantic instance within the database with which the subscribed field should be associated (Copyright Herder Institute, 2016).

## 6. COMPUTER-AIDED VISUALIZATION

This is a development in conjunction with WebGL technology towards web-based content delivery in three-dimensional virtual space. The internet is moving into 3D – the annual SIGGRAPH Web3D conference is a good place to observe developments in this direction. As free, but not open source, 3D repositories, such as Trimble's *3D Warehouse* or *Sketchfab* become better established, a growing community of content providers are able to publish their models. Research institutions are increasingly recognizing the potential of this technology. For example, digitized archaeological finds or entire architectural monuments can be uploaded to *Sketchfab* with annotations. It is only a matter of time before digital libraries such as *Europeana* will start enabling 3D publication services like this.

It will also become possible to link and publish interactive 3D models in academic publishing. As *Studies in Digital Heritage* attests [[www.studiesdh.org](http://www.studiesdh.org)], this vision is already becoming reality – researchers publish interactive models that not only *illustrate* the content of their article, but also mediate this knowledge in a *holistic* and *understandable* way. In the near future, it will be possible to draw on the development of virtual reality, *head-mounted displays* and *caves*, to work collaboratively and immersively, on and in heterogeneous sources within a digital 3D reconstruction. The project *Photoportals: Shared References in Space and Time* at the Bauhaus University in Weimar is a good example of this (figure 12) [Kunert et al. 2014].

However, one issue related to computer-based visualization remains pressing. The question of how to represent a hypothesis is largely unresolved. In their paper, Dominik Lengyel and Catherine Toulouse take an aesthetics-led approach to the representation of knowledge blurring [Lengyel and Toulouse 2015]. The choice of suitable colors for hypothetical areas has been discussed for some time. It is interesting to follow conceptions of a parametric value scale for visualizing the hypothesis depending on the density of information in the available sources compared to the resulting model [Apollonio 2016]. The concepts can only provide serious solutions, however, if their applicability can be proven on a larger scale.

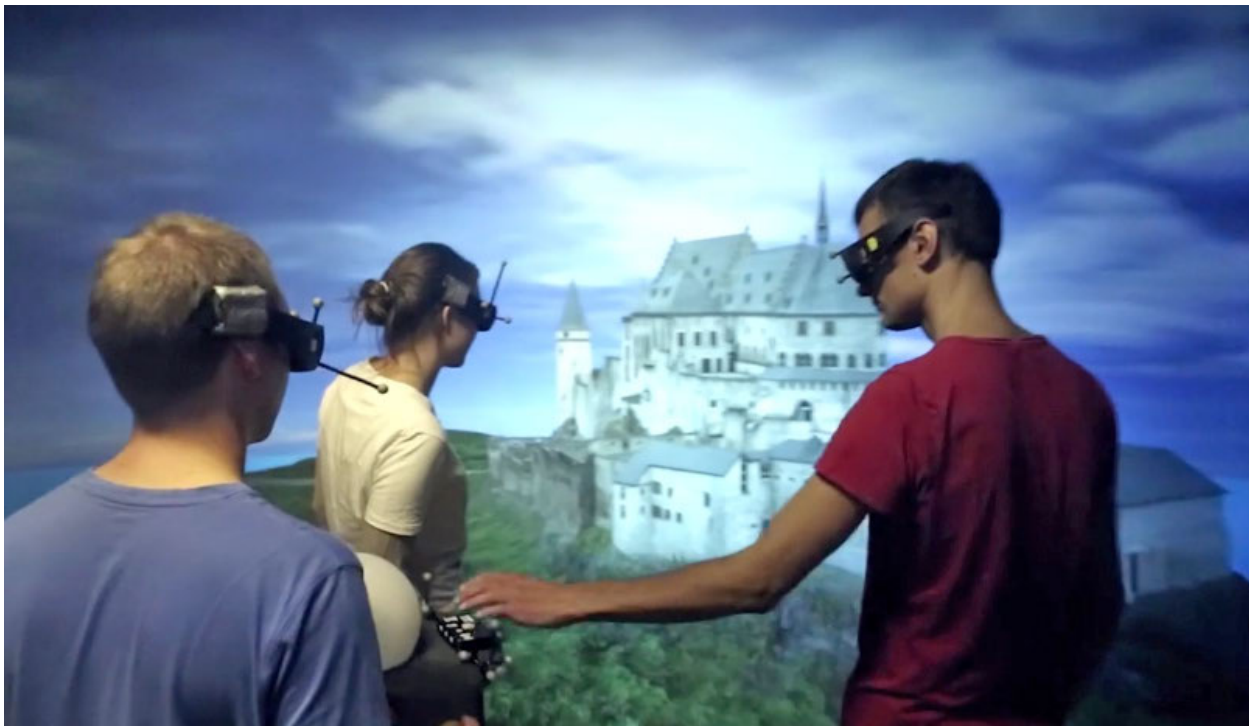


Figure 12. *Interaktive und kollaborative Begehung des Schlosses Vianden in einer Virtual Reality Anwendung [Interactive and Collaborative Tour of Vianden Palace in a Virtual Reality Application]* (Copyright Bauhaus-Universität Weimar, 2014).

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