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Virtual Reconstruction as a Scientific Tool:
The Extended Matrix and Source-Based Modelling Approach

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Abstract. The focus of this paper is to highlight what are the major theoretical issues of virtual reconstruction in archeology (black-box effect, palimpsest-effect, role of accuracy) and explain how the Extended Matrix approach was designed to respond to these specific needs. The Extended Matrix (EM) is a tool that extends the stratigraphic approach to the recording and managing of the *re-constructive record*: one of the goals of this research is to prove that the stratigraphic method, intended as chronological reading of a spatial context, is able to compose a complete and multidimensional *re-constructive record* through the EM. This approach can improve the quality of virtual reconstructions non only for scientific purposes but also in the industry of Virtual Museums and Digital Libraries.

1 Introduction

Sometimes the virtual reconstruction is used as a final phase that synthesizes the results of an archaeological research. In other cases, it is considered an effective solution for the communication of the intermediate steps of an ongoing project. Finally, it is even carried out without a complete and accurate scientific study because sometimes a suggestive representation of the past seems to be considered "sufficient" for a "general public of non-experts". These scenarios, despite the fact that they can result in very different outputs from a scientific point of view, can generate confusion if they are not correctly recognized. This situation contributes to a widely diffuse perception of the virtual reconstruction as an "aesthetic" endeavor more than a scientific tool (*see* Sect. 3.2).

The focus of this paper is to highlight what are the major theoretical issues of virtual reconstruction in archeology (black-box effect, palimpsest-effect, role of accuracy, *see* Sect. 3) and explain how the Extended Matrix (EM) approach was designed to respond to these specific needs. The EM offers a standardized work-flow and visual tools for analysis, synthesis, data visualization, and publication that are based on the stratigraphic method (temporal reading of a spatial context), and it can be a convenient solution to compose a *re-constructive record* (*see* Sect. 4).

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2 Related Work

Despite the fact that the practice of virtual reconstruction has a long tradition [17] (*see* Sect. 3.1) and that different digital tools and approaches to record the data provenance have been proposed in the last few years[1] [1,14–16], there is not a shared standard for the documentation of the *re-constructive record* in archeology. There is an approach based on CIDOC-CRM that uses the Cultural Heritage Modeling Language (CHML) [9,10]: unfortunately the CIDOC-CRM has some limitations because it is implemented to describe physical objects and is not intended to describe more abstract and fuzzy concepts like in the case of virtual reconstruction. Other approaches are based on the CHARM abstract reference model and use the ConML language [2,7]. The Extended Matrix language [3,4] is similar to the ConML but is specifically intended to organize data along a time-line, is focused in a meta-data drawing approach trying to simplify the ingestion steps, and is specifically oriented to include the granularity of the stratigraphic record into the *re-constructive* one.

3 Theoretical Issues of Virtual Reconstruction in Archaeology

3.1 The Problem of Reconstruction

Virtual reconstruction is an archaeological/architectonic matter that began a digital matter only in the last decades. Virtual (from the Latin term *virtus*), is a synonym for "potential" and expresses the likelihood of a certain artifact having existed in the past. The reconstruction is not only a digital matter: it started long before the introduction of the computer [17]. The theory of reconstruction in archeology/architecture is well testified by the *Envois de Rome de la Académie de France* (*see* Fig. 1).

The reconstruction pipeline (Fig. 3) starts with the collection on the field of all the information about a monument (survey or excavation). Alongside the activity on the field, all the sources available (ancient drawings, photos, information from very similar contexts) are collected. All these information are stored and organized in a convenient way in the so called *dossier comparatif* [8, p. 322]. The next step is the use of the *dossier comparatif* for the creation of the *eidotipi* (sketches or technical drawings on paper or by means of digital tools [13]) where the hypotheses in the mind of the researcher can be fixed before starting to model in 3D space. The 3D model, in this schematic, seems to be the last step, the output of the whole process. The introduction of digital techniques in archeology stimulated some interesting improvements allowing to use the modeling step as a simulation of the reconstruction. Let us have an example (Fig. 2) from an archaic temple [11]: in the case of the *simae* on the top of the temple, it is possible to make a digital anastilosys using real objects acquired during the 3D

[1] For a critical review about data provenance strategies and data granularity in archaeological virtual reconstruction *see* [3, pp. 43–44] and [4, pp. 501–502].

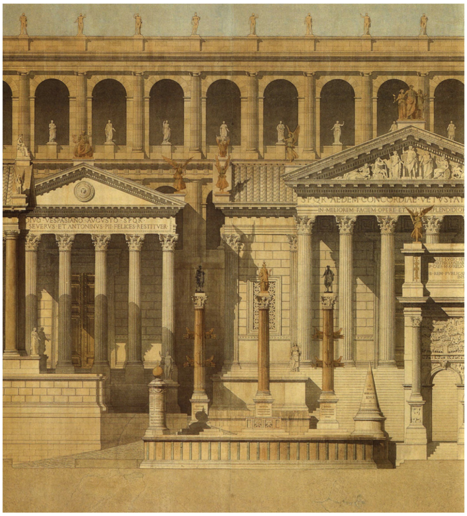


Fig. 1. Virtual reconstruction of the Tabularium in Rome from the XIXth century (Envois de Rome de la Académie de France).

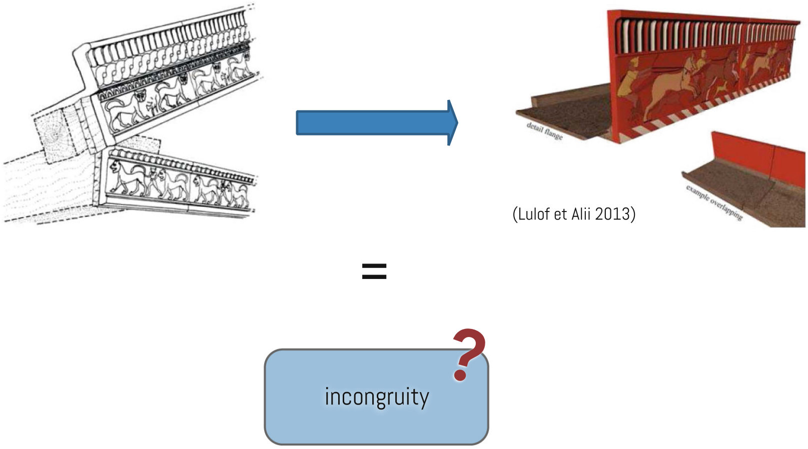


Fig. 2. Example of incongruity occurence during a 3D reconstruction (*see* [11]).

survey. These elements are placed inside a source based model as a reference during the 3D content creation. During this simulation, something "goes wrong": it is not possible to place it inside the 3D model. It simply does not fit in place like a "wrong" block of a 3D puzzle. Here there is an "incongruity" and, as a result, the 3D reconstruction hypothesis has to be changed. The simulation acts like a test of the quality of the reconstruction: the researcher has to modify something in the *dossier comparatif*, the *eidotipi* or just has to search more (or different) sources.

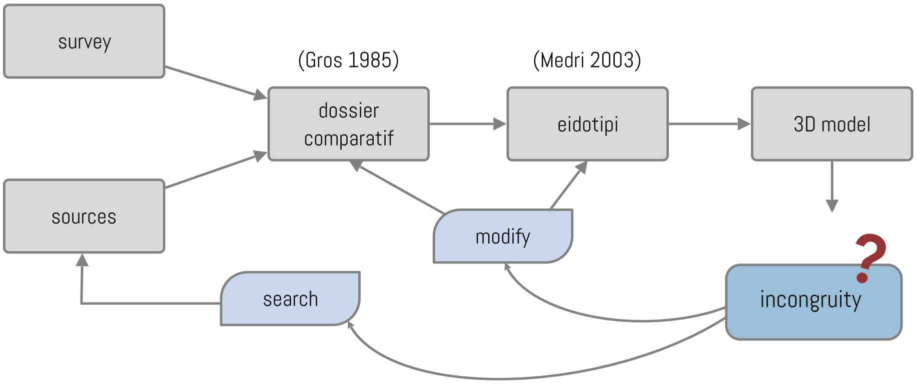


Fig. 3. Archaeological theory in virtual reconstruction.

3.2 Reconstruction is Part of a Scientific Research

When a researcher is dealing with a lacunose system (i.e. a broken ionic capital), it is impossible to interpretate it (and, in some cases, even to describe it) without visualizing in the mind the intact, original object. The reconstruction is part of the research from the earliest stages; it influences the reasoning, the interpretation, and the generalizations which will emerge in the synthesis of the research. For that reason, the reconstruction can be considered a scientific tool able to improve the understanding of a context or phenomenon. A scientific reconstruction is first of all a matter of creating a validated content.

A transparent publication of a re-constructive study can improve the scientific quality of a research and can enable the possibility of the re-use of the "raw" *re-constructive record* in future scientific researches as well as a standardized adoption in several digital outputs like the Virtual Museums or the Digital Libraries.

3.3 The Black-Box Effect (Gap in the Communication of the Reconstruction Process)

In the case of the reconstruction of the *Templum Pacis* at Fig. 4 the link between the archaeological remains and the source-based model is not easy to figure out.

The process behind the reconstruction is unreadable, it results in a *black box effect*: looking to a 3D reconstruction, several doubts emerge about what is real and what is an invention. It is not clear what is sure, certain and what is just an hypothesis or an "evocative" representation. This happens because in archaeological research, the 3D model is often considered a tool with which to synthesize and convey different elements, each with varying degrees of reliability.

Fig. 4. Templum Pacis, Rome (reconstruction E. Demetrescu, CNR-ITABC).

3.4 The Palimpsest-Effect and the Complexity of an Archaeological Context

Every archaeological/architectonic context shows a stratification of changes and modifications on its surfaces that represents its "history". This phenomenon is the *palimpsest* effect (*pàlin-* again *pseptòs* wrote: wrote again, re-wrote). Let us take an example: it is not enough to take in consideration "a building" in the heritage domain. There are, in the same construction, remains of different "buildings" from different epochs (*see* Fig. 5). In order to enable a reconstruction of a specific epoch it is mandatory to ideally remove all the non coeval physical elements. The same process has to be done with a 3D reality-based model: it is a *digital palimpsest* and has to be segmented using the stratigraphic approach in order to make a virtual reconstruction of a given epoch.

3.5 Scientific Accuracy and 3D Digital Content in Cultural Heritage

As in Fig. 6, the 3D content in cultural heritage can be divided, according to the creation process, into *reality-based modeling* (the digital acquisition through 3D survey of existent archaeological contexts [18]) and *source-based modeling* (virtual reconstruction of "lost" archaeological contexts [3, p. 43]). In the first case the "accuracy" of the model has a *quantitative approach* and can be expressed in real units of measure (i.e. 2 mm) while in the second case the accuracy has a *qualitative approach* and can *not* be expressed in real units of measure since it derives from a blending of different sources (with different reliability degree). In this two scenarios, the digital provenance follows completely different paths.

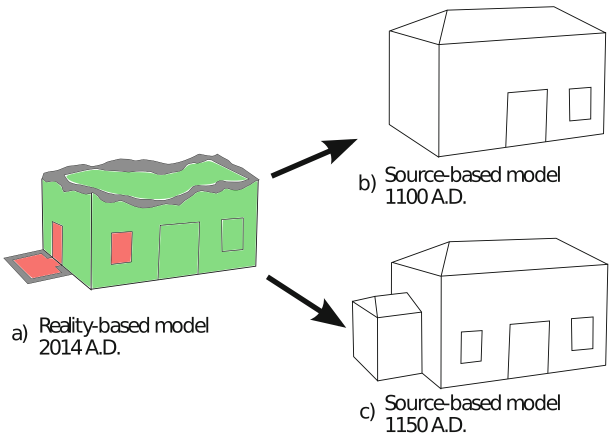


Fig. 5. Palimpsest effect. Every reality-based model can result in different virtual reconstructions, one for each epoch identified in the Extended Matrix.

Meta-Data for Reality Based and Source Based Models. A widely recognized way to annotate the processes behind the creation of 3D models is through a meta-data description. There are however some differences between the reality-based and the source-based approach (*see* Fig. 7). In the first case the steps follow discrete scenarios and has a objective, "closed output" which is not intended to be modified in the future. In the second case, the process is iterative and results in an "open output" that will be likely re-discussed in the future.

In the last fifteen years, several tools have been developed in order to track and manage the information connected to the reality-based models creation. Solid semantic tools like CIDOC CRM or CHARM are present and several shared meta-data schema permit interoperability and dissemination of information.

Some solutions can be derived from these robust 3D survey annotation tools but it is important to take in mind that they are meant to track mainly the digital life of the models, not the archaeological interpretation processes behind the

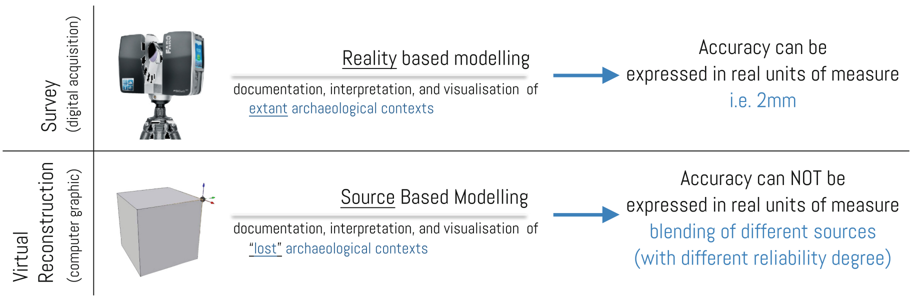


Fig. 6. Accuracy in reality and source based models.

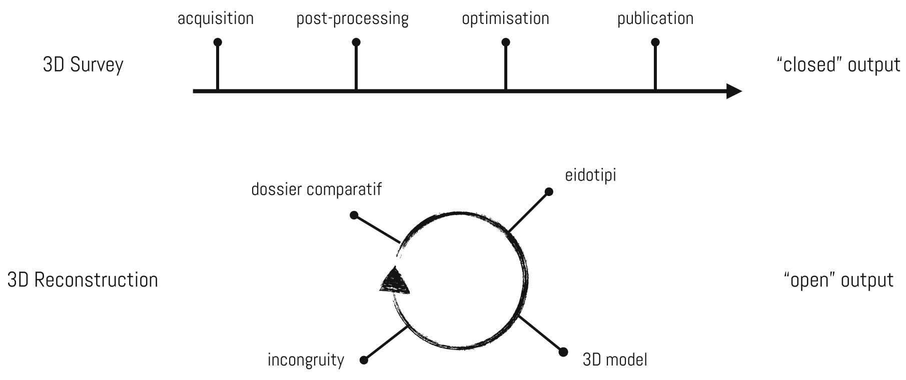


Fig. 7. Metadata from a work-flow point of view

reconstruction: in the case of the annotation of the file creation work-flow, we are able to describe life-cycles of 3D models but there are not standards to annotate the sources used (and the way they are combined together) in order to describe the processes of reconstruction. CIDOC CRM is intended to describe physical collections more than abstract concepts like "virtual" (potential) presence.

It is important to take in mind that in the field of meta-data annotation there are two parallel approaches: (a) the description and

> "*[..] management of the life cycle of digital resources, from data creation and management to data use and rights management*" ([6, p. 124])

(b) the creation of the re-constructive record (or description of the virtual asset) that is digital-agnostic.

In the first case, the digital source chain description describes events that happen at the time of the research (day of creation of a 3D model using a 3D

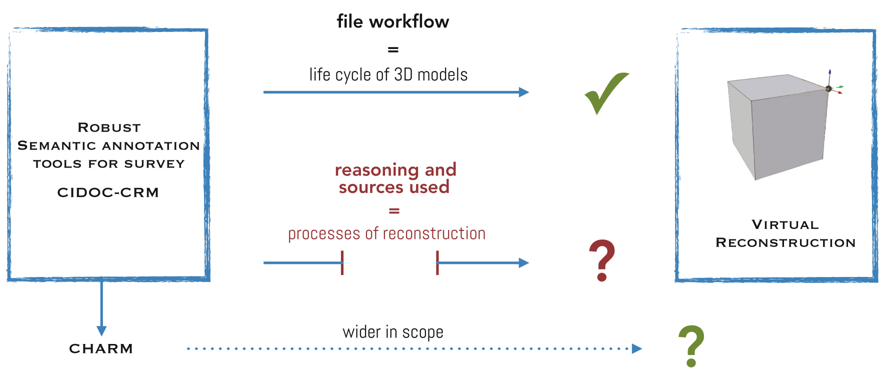


Fig. 8. Semantic tools for reality based models and their applicability to virtual reconstruction

software, the model has been created by the researcher X, etc.). In the second case the historical content chain describes potential (virtual) events happened in the past (construction of a wall, destruction of part of the same wall, first restoration of the wall) (Fig. 8).

4 The Use of the Extended Matrix for the Virtual Reconstruction

The Extended Matrix [3–5] is a formal language with which to keep track of virtual reconstruction processes. It is intended to be used by archaeologists and heritage specialists to document in a robust way their scientific hypothesis. It organizes 3D archaeological record so that the 3D modeling steps are smoother, transparent and scientifically complete. The EM offers a standardized work-flow (*see* Fig. 10) and visual tools for analysis, synthesis, data visualization, and publication. Starting from a stratigraphic reading of masonry (Building Archeology), all the sources used in the reconstruction are provided along (and integrated) with the 3D model. Considering the stratigraphic record as a starting point for the reconstruction process, it is possible to maintain coherence with the level of documentation used during the excavation or the interpretation steps in Building Archeology. The EM (Extended Matrix) has its specific 3D reference in the so-called proxy model, along with the "representation model" (*see* Fig. 9). EM, in combination with 3D models, stores the stratigraphic relations, and enables data-driven representation through computer graphic techniques. All the metadata are stored in an XML compliant format (GraphML) that permits a graphical data modeling approach and human readable representation of relations and properties (a difficult aspect in meta-data creation is the ingestion process). The XML stores all the reconstruction steps, both the sources used (3D models provenance) and the reasoning involved. It enables a convenient dissemination of the whole 3D reconstruction process for scientific publications, belonging 3D models released as Digital Libraries or inside Virtual Museums.

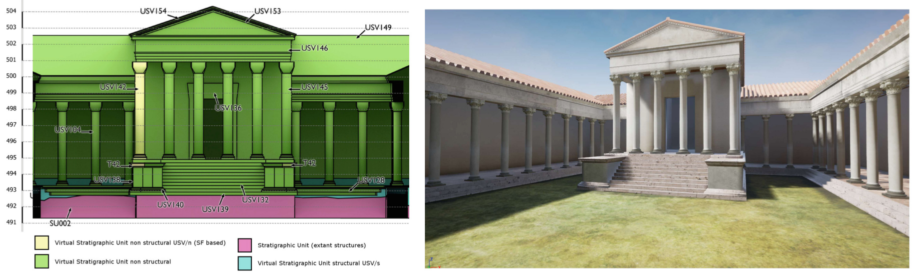


Fig. 9. Proxy model and representation model related to the II century AC epoch of the Great Temple at Sarmizegetusa.

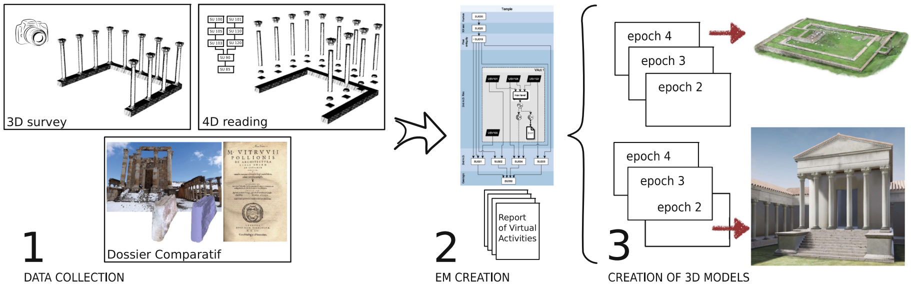


Fig. 10. Production work-flow, from data collection to 3D visualization.

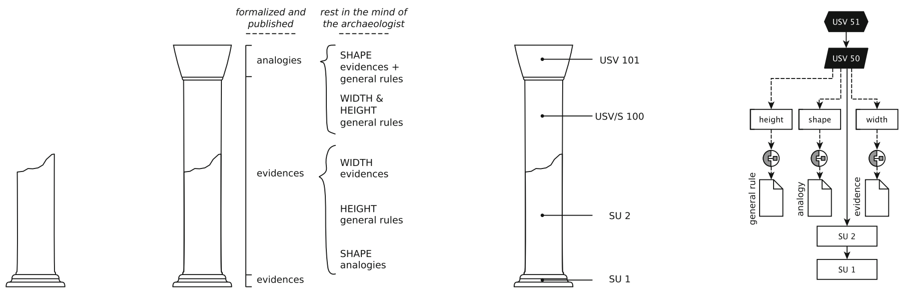
The EM is continuously in development and used in several archaeological researches inside the VHLab of the CNR-ITABC Institute in order to be validated against different scenarios and expanded in its functionalities. Recently, the version 1.1 [4] has introduced a complete support for 3D representation of the validation workflow. Next releases will include software tools (in development) and new solutions for semantic data integration (Open Linked Data, Thesauroi, etc.) and Graph-DB solutions.

4.1 Filling the Black Box Effect Through a Finer Data Granularity and a Standard for Publication

The complexity of the evidences and reasoning behind a virtual reconstruction is a challenge for the standardization of annotation tools.

In literature, one of the most common solution in the management and visualization of reliability is what is generally known as the "generative layers with query-able elements". This approach consists in the segmentation of the model based on the typology and the supposed "degree of certainty" of the sources used in the reconstruction (usually represented with a color scale). It has been tested with different solutions and terminologies, but has not resulted in the creation of a common standard (for a critical state of the art about the methods to validate virtual reconstructions, *see* [3, pp. 43–44] and [4, pp. 501–502]).

All these approaches have a common granularity: the source typology used for the reconstruction hypothesis. Current limitations in the annotation of virtual reconstruction mainly concern this data granularity: in the "source-granularity approach", a reconstruction hypothesis (Fig. 11(a)) is usually segmented (Fig. 11(b)) according to a single source typology (i.e. evidences, analogies - in square brackets). It is a fact that each segment of a reconstruction is not based on a single source but on different sources blended together (i.e. evidences + analogies + general rules - in curly brackets). More, it is possible to state that every source is connected to and validates a specific property (height, width, shape, etc.) of a virtual stratigraphic unit. In Fig. 11(c) and (d) the "property-granularity approach" of the EM provides the details of the sources (and corresponding properties) for each SU.



(a) Survey (b) Actual granularity (c) EM granularity (d) EM

Fig. 11. Current limitations in virtual reconstruction granularity and the EM approach

Publishing a Reconstruction Using the EM. The publication of the reconstructive record involve standardized tools inside the EM work-flow (Fig. 10). The dataset can include more than one reconstructed phase (i.e. roman times, medieval times, etc.). Every epoch is described as a section or chapter and inside this timespan, the Stratigraphic Units and the Virtual Stratigraphic Units are explained as part of Virtual Activities. Every Virtual Activity comes along with a Report of virtual activity, a discursive text that puts into words the reasoning behind the stratigraphic reading and the hypothesis (*see* the Great Temple of Sarmizegetusa in the II century AC at Fig. 12). Every virtual activity is presented with the corresponding portion of EM graph, sections and plans illustrating the *proxy model* and the *representation model* (*see* Fig. 13). The description of virtual activities focuses on portion of the monument/context as likelihood was in the past. They can be integrated with the standard description of activities in the classical publication of an archaeological excavation. In Fig. 14, the site of the great Roman basin found during the excavation for the new Underground of Rome (Metro C) under the scientific direction of Rossella Rea (Superintendence of Rome), is documented both as an excavation (remains found in green) and as a reconstruction hypothesis (in red).

4.2 Managing the Palimpsest Effect: The Stratigraphic Approach and the Matrix of Harris

A very common equivocacy about stratigraphy is that it concerns just earth strata or remains. *Stratigraphy is the grammar used by the Time to write itself on physical elements.* The importance that archaeologists grant to the stratigraphy is directly connected to the need to have a tool as much "wide" as possible in term of semantic representation: dealing with a brush stroke on a canvas (painting stratigraphic annotations from an x-ray image), trees on a landscape, deposits of earth, architectonic elements or graffiti carved in a painted wall, the tool used is the same: the SU. It has a wide scope: it means "result of an action"

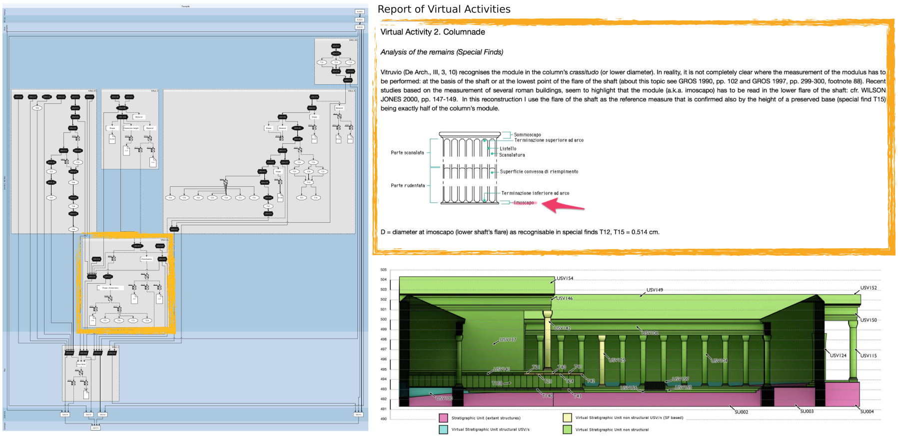


Fig. 12. Extended Matrix with virtual activities (highlighted in grey), report of virtual activities, and proxy model of the Great Temple at Sarmizegetusa in the II century AC.

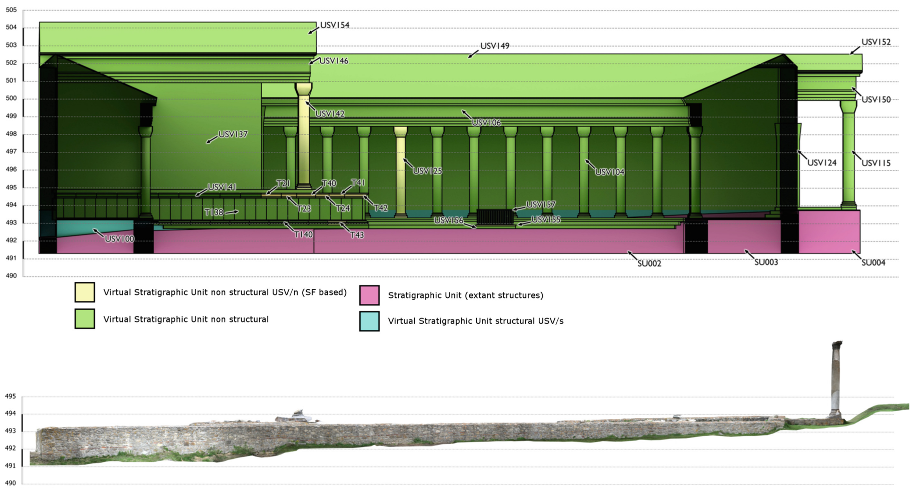


Fig. 13. Proxy model (II century AD) and 3D survey of the Great Temple at Sarmizegetusa.

and it is intended to be applied to every cultural element on a chronological timeline (*see* Figs. 15 and 16). These actions can be natural (earthquake interface of destruction, a tree, an interface of a flooding from the near river) or anthropic (a foundation, a lintel, the decoration of a lintel etc...). An interesting thing is that the SU, despite the fact that it can refer to different objects, can have always a precise and actual 4D representation (time and geometry).

When a stratigraphic system results to be intricate, an important step is to reduce its complexity without loosing information.

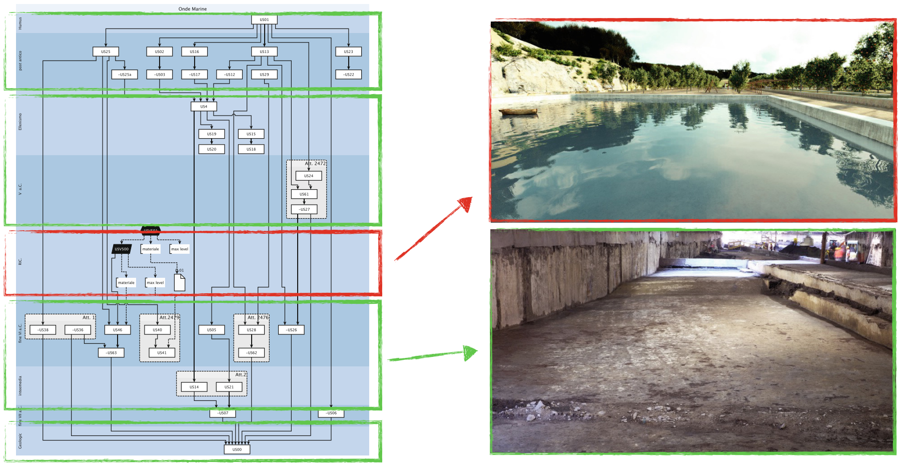


Fig. 14. Extended Matrix, representation model (red) and the state of the site at the time of the excavation. (Color figure online)

A very common way to do this is through the use of the Matrix of Harris, an oriented graph that annotates the chronological relationships between elements (after-before). In the archaeological domain, this is the finest level of granularity about a monument/context.

4.3 Visualize Data Through Graph Based Structures (EM)

In the last years there is and increased adoption of graph databases, especially in scenarios where the connections between the information is a valuable aspect. The visualization of data through graph-based visual structures is the main approach used in data visualization, but has been scarcely involved in the field

Fig. 15. Scenarios of application of the stratigraphic reading.

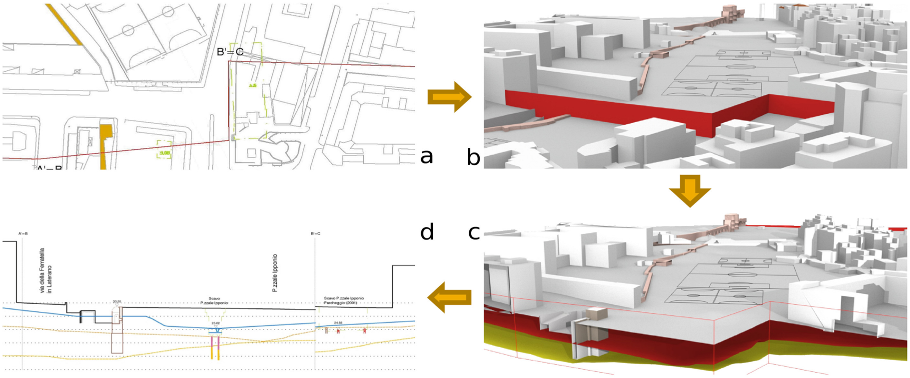


Fig. 16. Extensive reconstruction of stratigraphies at urban scale, Rome

of cultural heritage. Apparently in this domain the elements have a better and more compact representation in forms and tables. When it comes to representing strongly interconnected information (linked data), such as in the case of virtual reconstructions, visual graph databases allow for better adherence to the scientific record [12], better visual appeal, improved effectiveness (for the aesthetic principles for information visualization [19]), and reduced complexity. According to the Steno's vision, every complex system "written" in the historical language of nature has to be studied in its smaller parts and in their mutual relationships. The reciprocal connections between sources, reasoning, and virtual hypothesis can be stored and analyzed within a graph database framework. Unfortunately, a widely diffuse approach to graph databases involves liquid data visualization without the use of a codification for the spatial distribution of the nodes (like in the case of the EM where the y axis is the time-line).

A Schema-Less Database Approach. The Extended Matrix is a semantic graph that leads to a schema-less data model: the reconstructed objects and their descriptive elements are heterogeneously fitted into space and time, in a way that better suits the incompleteness of the historical record. The descriptive elements (EM nodes, *see* [3]) are used as a modular grammar to compose the final description of the reconstruction process (data-driven re-construction). Let's look at an example: I could describe a USV using just the property "material" (i.e. a wooden lintel) because it is the only re-constructive value I am confident in. Meanwhile, in the case of other USVs I may declare more properties, each of which can be validated by different sources. There is no predetermined schema: each USV has its own unique node tree (whiting a common EM data structure) which describes and validates the USV itself.

5 Conclusions

This paper presents a stratigraphic approach to the scientific validation of the virtual reconstruction: the Extended Matrix work-flow. The stratigraphic reading enables the collection of a coherent re-constructive record while the paradata nodes of the EM allow the annotation of the re-constructive process. This approach can improve dramatically the use of virtual reconstruction non only for scientific purposes but also in the industry of Virtual Museums and Digital Libraries. In order to better define the innovations of the EM, some key concepts about the classical archaeological theory in virtual reconstruction (black-box effect, palimpsest-effect, role of accuracy) and about the connections between technologies and cultural heritage (meta-data, digital formats, and granularity) are highlighted.

6 Future Works

The Extended Matrix is under active development and has recently reached the 1.1 version with full support to 3D representation.

- In the future, a support for different, self excluding reconstruction hypotheses will be added. In the case where there are more than one possible hypothesis, the EM will help to represent and compare them.
- The scenarios of use of the EM will be categorized with the aim to clarify the limits of applicability in certain typologies of context.

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