# Archaeological Stratigraphy as a formal language for virtual reconstruction. Theory and practice.

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**Abstract**

In recent years there has been a growing interest in 3D acquisition techniques in the field of cultural heritage, yet, at the same time, only a small percentage of case studies have been conducted on the virtual reconstruction of archaeological sites that are no longer in existence. Such reconstructions are, at times, considered "artistic" or "aesthetic" endeavors, as the complete list of sources used is not necessarily provided as a reference along with the 3D representation. One of the reasons for this is likely the lack of a shared language in which to store and communicate the steps in the reconstruction process. This paper proposes the use of a formal language with which to keep track of the entire virtual reconstruction process. The proposal is based on the stratigraphic reading approach and aims to create a common framework connecting archaeological documentation and virtual reconstruction in the earliest stages of the survey. To this end, some of the tools and standards used in archaeological research have been "extended" to taxonomically annotate both the validation of the hypothesis and the sources involved.

*Keywords:* 3D virtual reconstruction, archaeological stratigraphy, 3D reconstruction methodology, 3D modelling in archaeology, Virtual Stratigraphic Unit, Extended Matrix

## 1. Introduction

The goal of this paper is to propose a theoretical and practical *framework* with which to keep track of, manage, and publish the steps in the archaeological reconstruction process. The primary approach (*see infra* sec. 3) is based on the same formal language already in use to create archaeological stratigraphic records during excavation and survey[1], and makes use of its consistency and standardization. The stratigraphic method is based on the laws of the geological stratification (*see infra* par. 3.1) and is characterized by a taxonomic approach and data consistency (*see* Barker 2003, Carandini 1981, Giuliani 1976, Medri 1988, Medri 2003). There are several examples of institutionally defined standards (*see* ADS - Archaeological Data Service "http://archaeologydataservice.ac.uk/" and Parise Badoni and Ruggeri 1988.).

In order to fulfill this statement, a subset of the "classic" archaeological record-keeping concepts and tools – such as the *Stratigraphic Unit* (or *Context*)[2], the *Activity*, and the *Matrix of Harris* – have been "extended" (*see infra* sec. 4) to include and define not only re-constructive elements (like "lost" columns, friezes, capitals, etc.), but the sources on which they are based as well. The primary tools used are (1) the Virtual Stratigraphic Unit (or USV) organized into a diagram; and (b) the Extended Matrix (EM)[3].

Archaeological stratigraphy, intendend as the study of the actions' sequence made in the past, provides a robust methodology to acquire and manage data (segmentation and annotation of the context in small parts) that can be applyed to archaeological excavations, extant buildings, objects and other contexts where it is possible to distinguish different phases of construction (4D data).

The objective of this paper is *not* to propose solutions for the visualization of the 3D model's degree of reliability (such as, gradient colors), but is rather to formalize the

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[1]In this paper, with the term *survey*, I mean not only the acquisition of the shape (laser scanner, drawings, photogrammetry) of extant buildings, objects and other archaeological contexts but also the examination and data recording of its stratigraphy (phases of construction). It results in a "4D survey" with data collection about geometries and chronological sequence (*see infra* sec. 5).

[2]Despite the fact that nowadays the stratigraphic method is the most common approach used in archaeological excavation, some discrepancies still exist in the naming of its basic unit: in English speaking countries it is called "Context", in Italy "Unità Stratigrafica" (US), in some excavations (i.e. Villa Magna, *see* www.villamagna.org) "Stratigraphic Unit" (SU), in still other instances "locus", and so on and so forth. For the purposes of this paper, the abbreviation "SU" has been arbitrarily chosen so as to remain consistent with the "USV" abbreviation of the proposed Virtual Stratigraphic Unit.

[3]*See infra* sec. 4.1

steps involved in each reliability evaluation and visualization: *which* sources have been chosen and *how* they have been used in the virtual reconstruction.

Virtual reconstruction, sometimes confused with post-processing of digital acquisition (*mesh reconstruction*, like in Kazhdan et al. 2006), is a series of steps which includes the documenting, interpretation, and visualization of "lost" archaeological contexts (for a critical approach to the terminology *see* Golvin 2003, Golvin 2005 and Seville Principles, p. 3, *"definitions"*). Despite the fact that this application's potential for use by the scientific community has been widely recognized (Ryan 2001, Ryan et al. 2002, Hermon et al. 2005, Hermon and Nikodem 2007, p. 1, Hermon 2008, Niccolucci 2012 and Cerato and Pescarin 2013), only a small percentage of case studies regarding reconstruction exist in scientific literature, and furthermore its contributions to the integration of 3D modeling in archaeological research methods are fairly uncommon. According to Münster 2013, p. 198 and Münster and Köhler (in print) in recent years only 20% of papers written about the use of 3D technology in archaeology focus on the 3D reconstruction of lost contexts. A recent survey (Cerato and Pescarin 2013, p. 290), based on 686 publications, reports that only 1% of contributors propose methods to be used in the validation of models. 3D reconstruction is most often used in communications (Internet, museum installations, etc.).

As a result, virtual reconstruction, as a field of archaeological research, is an as yet undefined discipline, one that is still largely fragmented when it comes to methodology, both in terms of data transparency and common standards (for a critical review with bibliography on the lack of scientific accuracy and methodological consistency in the practice of virtual reconstruction *see* Beacham et al. 2006, sec. 4 and, recently, Denard 2012, p. 57, footnote 2).

In recent years several initiatives within the community, like the *London Charter*[4] and the *Sevilla Principles*[5], have highlighted the principles of scientific visualization and the need for the formalization of re-constructive processes, but they are intended as guidelines and not as norms or standard solutions. This is primarily due to the complexity and variety of technologies involved in virtual reconstruction: digital acquisition, spatial-enabled databases, metadata enrichment, and 3D modeling. The scientific aspects, like archaeological record fragmentation and context diversity, are, however, the hardest to deal with (on the need for a multidisciplinary approach *see* Bakker et al. 2003, for ontological aspects, see Doerr 2003, p. 79..

Indeed, a major problem with the current methodology is the difficulty of representing and dealing with uncertainty. This issue, however, is not only related to digital-based reconstruction, but is, first of all, a "classic" core topic (Gros 1985, p. 185 and Medri 2003, pp.186-192) of archaeological record management and interpretation, as the practice of archaeological reconstruction began long before the advancement of computers (Manacorda 2007, p. 102).

It is for this reason that this paper takes an "archaeological approach", aiming to define: a) a formal language based on existing archaeological standards; and b) an annotation system with which to document reconstruction processes that is capable of linking them to both the survey and interpretation procedures within the same framework (*see infra* sec. 3, 4).

A review of related works is outlined in section 2. Sections 3 and 4 explore the theoretical aspects of the proposed approach and the definition of the tools involved. The paper ends with an examination of "applicability and definition of uses "(*see infra* sec. 5) and conclusions (see *infra* sec. 6).

## 2. Related works

### *2.1. Current connections between 3D survey and 3D reconstruction*

The awareness that the creation of a 3D model for scientific purposes requires a solid semantic enrichment, has led, in recent decades, to the search for formal solutions with which to link the model to its sources. Thus, what is needed is an arrangement of tools and standards that is able to manage complex datasets and that is based on shared ontologies like the CIDOC-CRM (Doerr 2003, Binding et al. 2008) or, more recently, CHARM (González-Pérez and Parcero-Oubiña 2011 and Gonzalez-Perez et al. 2012).

Over the past few years, more and more projects in this field of research have focused on a "visual approach" to semantic enrichment, with a data-granularity more similar to that of the archaeological stratigraphic record (Fiorini and Archetti 2011, Drap et al. 2012, Micoli et al. 2013, p. 245-246, Cappellini et al. 2012, Stefani et al. 2011). In some cases 3D technology is used as a tool in the management and tracking of processed data at the stratigraphic level (Apollonio et al. 2012, p. 1273) while, in other cases, complex monuments are represented with acyclic graphs (Gaiani et al. 2011, p. 59 fig. 17, Apollonio et al. 2012, p. 1277 and p. 1283 fig. 12 and Apollonio et al. 2013).

In the 1980s, the stratigraphic approach, initially used exclusively in archaeological excavation, began to be applied to architecture as well, as a tool for identifying phases of construction through stratigraphic readings of the masonry (Parenti 1985, Parenti 1988, Hoggett 2000 and Bianchi et al. 2004). In just a short time this approach became a common standard in documentation methods.

At present, however, a major topic in the visual approach is the segmentation of the 3D model, in which the solutions span from a real-time, interactive approach

[4] *See* "www.londoncharter.org".

[5] *See* "www.arqueologiavirtual.com/carta/".

(Serna et al. 2012, p. 37) to a pre-calculated, fully geometric segmentation of the model based either on the archaeological record or on the typology of the architectonic elements (Apollonio et al. 2012).

These approaches are used exclusively for the creation of 3D models of monuments as they appear in the present day, based on a survey of the existing remains ("reality-based" models). In recent years, the use of the term "reality-based model" (Remondino and Rizzi 2010) has become fairly common in geomatics applications to indicate 3D models obtained from a survey, as opposed to those created through a *computer graphics* approach, which is intended to be hypothetical. In archaeological theory, reconstruction is based on sources that have been reorganized according to hypotheses and characterized by varying degrees of certainty. As a result, a possible term for scientifically accurate 3D models could be "source-based models" (models obtained from "source-blending" during the reconstruction process).

In recent years the survey activities of many archaeological excavation projects have expanded with the introduction of "digital born" (De Felice et al. 2008b, p. 278) documentation created directly in 3D (De Felice et al. 2008a, Katsianis et al. 2008, Fiorini 2008, Fiorini and Archetti 2011, Forte et al. 2012, Dellepiane et al. 2013). The introduction of precise and/or low-cost 3D acquisition techniques (Remondino 2011) in the archaeological field has not only challenged and improved the efficiency of some of the standards used in the record-keeping process (D'Andrea 2006, Bianchini 2008, De Felice et al. 2008a, De Felice et al. 2008b and Fiorini 2008), but has also led to the implementation of modeling methods used for virtual reconstruction purposes that are directly related to the 3D survey (Balletti et al. 2007 and Dell'Unto et al. 2013). In this way the reality-based model is used as a "spatial reference" in modeling, and the 3D reconstruction metrics are consistent with the archaeological remains, thus "inheriting" their geometrical accuracy.

### *2.2. An in-depth look at 3D reconstruction: current limitations in virtual reconstruction granularity*

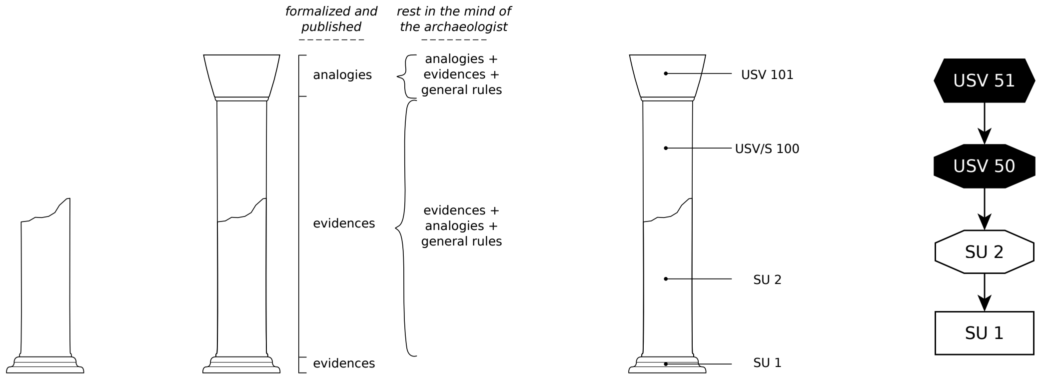
In archaeological research, the 3D model is often considered a tool with which to synthesize and convey different elements, each with varying degrees of reliability. As a result, the process behind the reconstruction is unreadable. To avoid this "black box" effect, a wide range of tactics for managing and visualizing reliability and uncertainty have been implemented in an effort to establish a "model validation" process. Some methods are proposed to represent uncertainty in reconstructions (Kensek 2007), chronological uncertainty (Zuk et al. 2005 and Pang et al. 1997), typological details of the image sources (Dudek and Blaise 2004 and Blaise and Dudek 2009), uncertainty charts representing ambiguity in virtual reconstructions (Pollini et al. 2005) and interactive visualization solutions (Bakker et al. 2003, Borra 2004, Bonde et al. 2009). But these tactics lack a common and agreed-upon standard.

However, one of the most common solutions in the management and visualization of reliability is what is generally known as the "generative layers with query-able elements" approach. 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. In some cases the validation of the model passes through "gradients of consistency" and is based on documentary sources (*see* Borra 2004, Vico López 2012, p. 117). In other cases such sources may be grouped according to "levels" and "classes" (*see* Viscogliosi 2006, pag. 213) or simply according to "typologies" (*see* Dell'Unto et al. 2013).

In these approaches the data granularity relies on the sources and not on the stratigraphy. In other words, the segmentation adheres to the typology of the sources used for the reconstruction (i.e. ancient drawings, literary sources, etc.), while the processes used to create the 3D model from its sources are known only to the archaeologists (cfr. Figure 1). In fact, there is a discrepancy between the archaeological record and the visual representation of the reliability.

This problem has been partially dealt with in a few case studies (Hermon et al. 2006, Hermon and Nikodem 2007) based on quantitative methods (fuzzy logic, etc.), such as the Roman Theater of Paphos (Georgiou and Hermon 2011), in which the validation of the model is calculated numerically as an "Index of Reliability" (IR). In this approach, based on the "Level of Existence" (LOE) and on the "Level of Geometrical Reality" (LOGR), the granularity of the 3D model's semantic annotation is object-based and not source-based. Nonetheless, the indexes are assigned only upon individual approval by the archaeologists: there is no explicit link to the archaeological data (as stratigraphic record), nor to the available sources which are the basis for the index assignments. At the same time, no annotation tool for the reconstruction process is provided for. Other case studies show a connection between the archaeological sources and the detail of the 3D model, but only in terms of elements like the architecture's static aspects (Vico López 2012), and without any specific connection to the stratigraphic record. Meanwhile, others focus on an "experimental approach" in which 3D reconstruction modeling is used to verify a hypothesis and results in a cyclical validation process (Viscogliosi 2006, pp. 214-217, Lulof et al. 2013). Finally, still others highlight the importance of workflow standardization (Baldwin and Flaten 2011), but do not propose tools capable of formalizing the reconstruction processes.

A qualitative different approach is followed by Cyber Archaeology, with the aim to go beyond the reconstruction processes and focus in a wider, systemic simulation




(a) Survey. (b) Actual granularity. (c) Proposed granularity. (d) Extended Matrix.

Figure 1: Current limitations in virtual reconstruction granularity: (a) the model obtained from the survey, or "reality-based model", (b) the "source-granularity approach": the model is divided according to a single source typology (square brackets), but each segment is actually based on different sources blended together (curly brackets). In this approach, the process used to obtain the the stratigraphic unit from its sources is known only to the archaeologists. (c) The proposed "SU-granularity approach": it is possible to provide the source details for each SU. (d) The Extended Matrix regarding the previous Figure c (for details *see* sec. 4).

of the past (Forte 2014). The authenticity of the reconstruction is rightly considered as a "false dilemma" since the reconstruction is always an approximation of the past: the real core-topic is to make transparent the full process of model creation. To achieve this goal a primary tool is represented by the collaborative environment possibilities. The importance of making transparent the reconstruction processes and the wider systemic approach results in an acceleration and simplification of the interpretative processes through collaborative environments. Even though no shared standards or technical solutions have been proposed to formalize and make the reconstruction processes part of the archaeological modeling language (Harris Matrix) and documentation (stratification description) as it is used by archaeologists.

Despite the progress made in recent years in the annotation and semantics of 3D surveys, since the analysis of the London Charter, the situation in the virtual reconstruction field of research has not changed dramatically.

## 3. Main approach and theoretical aspects

As discussed in the previous paragraphs, the virtual reconstruction field currently lacks: 1) a methodology that is consistent with archaeological records in terms of data granularity; and 2) a tool with which to document the re-constructive process. How can such an approach be established? What are the necessary elements involved ?

### *3.1. Nicolas Steno and stratigraphical gaps: a starting point for archaeological reconstruction*

The need for a virtual reconstruction arises when, in an archaeological context, certain gaps appear (due to damage or transformation). Nicolas Steno's categorization of gaps and laws of stratigraphy make it possible to extract information useful in the archaeological reconstruction directly from the gaps themselves. When Nicolas Steno theorized the principles of stratigraphy in the 17th century (Ascani et al. 2002), he defined the historical language (as opposed to the mathematical language) of the "Book of Nature". This approach led to the distinction between so-called "readable pages" (those objects visible to the observer) and "unreadable pages" (contexts and objects from the past which have been lost).

Steno based his theory primarily on the fundamental importance of the "gap" in the reconstruction of the sequence of events[6] (Hansen 2002). An important characteristic of gaps in nature is that, paradoxically, *they provide assertions which would otherwise not appear in non-lacunous systems.* Due to the physical absence of existing structures, gaps create discontinuous systems, such as a bite taken from an apple. This broken structure allows us to make two assumptions: 1) the bite from the apple is more recent than the creation of the apple, because it is discontinuous in relation to the apple; and 2) the bite is an external influence on the apple. It follows that one can say much more about the bitten apple than about the whole one. An example of this property of lacunous systems can be observed in the Meta Sudans in the Colosseum valley in Rome. One can make assumptions about the Meta Sudans' Augustan stage (*see* Figure 2) only because of the subsequent destruction of the Flavian stage over the course of centuries, and especially at the beginning of the twentieth century (*see* Panella 2001). In the following sections we will examine the theoretical implications of gaps in archaeological reconstructions and how to semantically

[6]This methodological awareness, however, did not bring about the expected results until the 19th century, mainly because Descartes' reductionist paradigm triumphed (as demonstrated by the famous quarrel between Descartes and Steno).

Figure 2: The Flavian Meta Sudans (dotted line), built over the previous one (solid line). The gaps produced over the years make it possible to “read” the complete stratigraphy.

annotate these assumptions by taking advantage of their “known” degree of certainty (*see* sec. 4.1.1).

### *3.1.1. Structural gap/non-structural gap*

According to Steno, history is full of *structural gaps* which provide us with assertions that can be inferred from the logic of natural history. At the same time, history is also full of *non-structural gaps*, the existence of which we are only indirectly aware of due to analogous conclusions, and the meaning of which can only be understood intuitively or extrapolated indirectly from the logic of natural history and mathematics. It is important therefore to differentiate between:

1. specific data (certain): structural gaps allow us to obtain this information from that which has been preserved;
2. general data (uncertain): preserved remains can provide information about that which has been lost or destroyed, through analogous conclusions and calculations.

How is this taxonomy related to archaeological reconstructions? The field of 3D architectural survey is usually focused on that which has been preserved and considers gaps to be “lost data”. Despite the fact that the “lack of information” concept itself is not explicitly defined in standard archaeological documentation, the stratigraphic approach places particular emphasis on the causes of damage (anthropic or natural such as cuts, spoliations, smoothing, etc.) and formalizes them as a “negative stratigraphic unit”[7] or “-SU” (the process of *subtracting* material from the stratification, *see* Carandini 1981).

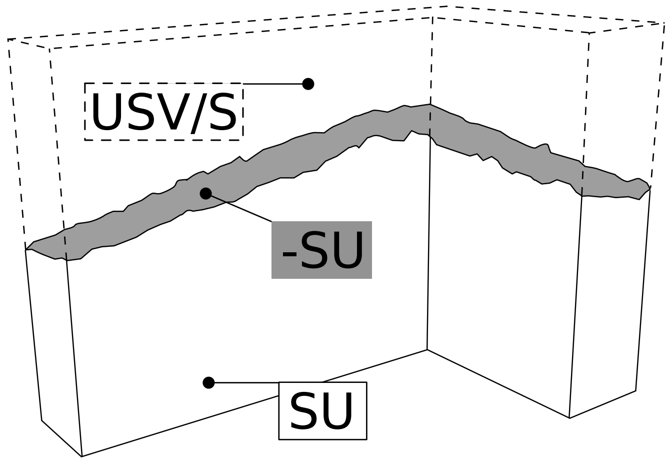
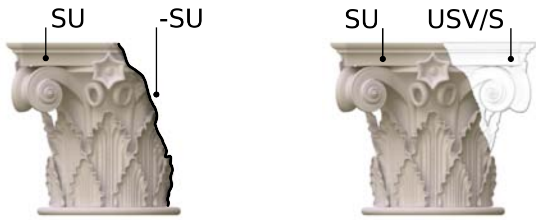



Figure 3: Example of a structural gap: remains of a wall. The wall (SU) has experienced a cut (-SU) that testifies to a structural gap filled in by a reconstruction hypothesis (USV/S). For technical terminology *see* sec. 4.

This information is represented as an interface which affects other, positive SUs. It is the “evidence of an absence”, a surface which indicates a missing volume, a detail of a surviving object, and, as a result, substantiating evidence for a reconstruction hypothesis (*see* Figure 3 and Figure 4).




(a) (b)

Figure 4: (a) The model resulting from the survey or the “reality-based model”, (b) the “source-based model”. The remains of the capital (SU) have undergone a cut (-SU) that can be filled in by a reconstruction hypothesis (USVs). For technical terminology *see* sec. 4.

It follows that the negative stratigraphic unit testifies to the existence of a *structural gap* (*see* Steno’s definition above) and is a reliable starting point for archaeological reconstruction.

Practical aspects and methods for the extraction of “gap-based” data for virtual reconstruction will be examined in sec. 4.1.

[7]The concept of removed stratigraphy (or negative stratigraphic unit) is not a common standard used worldwide despite the fact that has been theorized from the beginnigs of the stratigraphic approach (*see infra* sec. 3.1). Examples of use of -SU can be found in the Italian archaeological school.

### 3.2. The reconstruction process as part of the archaeological survey and excavation

For archaeologists, the survey and the excavation are both records of measurements and exercises in interpretation. It is nearly impossible to look at a fragment and understand what it is without mentally reconstructing the shape of the complete original object (*see* Manacorda 2004, p. 7). Furthermore, the documentation of the negative stratigraphic unit as a testimony of lost elements facilitates re-constructive processes as data is obtained. Therefore, one could say that the first step in virtual reconstruction actually occurs during archaeological documentation (especially in terms of the "involuntary" reintegration of *structural gaps*).

According to Steno's terminology (*see infra* sec. 3.1.1), such re-constructive processes can be divided into two types:

1. Reintegration of the *structural gap* represented by the negative stratigraphic unit (-SU) at the time of survey documentation: the absence of an object is recorded and it is possible to make a series of assumptions regarding its position, material, geometry, shape, and size with a high degree of certainty. There is a direct relationship with the documentation process.
2. Reconstruction of *non-structural gap*: the reintegrated element has no physical continuity with the remains, therefore the archaeological documentation becomes an indirect source alongside other external sources (like paintings, historical maps, photos, etc.). There is an indirect relationship with the documentation process.

### 3.3. A synoptic and synchronic representation of virtual reconstruction

The division of the reconstruction processes into groups is only the first step. It is then necessary to create a visualization of the structured information. In "classic" archaeological research, the representation of the stratigraphy is performed through the so-called Matrix of Harris (Harris 1979), technically an acyclic, oriented graph in which the nodes represent stratigraphic units or "actions"[8] and the arcs represent the chronological relationships between them (upper is newer, lower is older). This graph is a "holistic" description of the archaeological context: each element is considered individually (the node) and in relation to the others (the relative position of the node in the graph). The elements are identified and organized by archaeologists during the documentation phase and the laws of stratigraphy provide reliable reference points in terms of chronological order (i.e. the cut to the wall is always more recent than the wall itself).

The Matrix of Harris presents all of the archaeological elements in a single document and in a two-dimensional space. Consequently, its representation is *synoptic* (all of the elements and their relationships to one another are included in the same document "under the eye of the observer") and *synchronic* (all of the archaeological phases are a part of the same, unique sequence) with reliable benefits in terms of human-readability and data management/overview. The visualization of the 3D reconstruction, on the other hand, lacks both synoptic and synchronic representations of virtual reconstructions:

- *No synoptic representation.* It is not possible to visualize all of the aspects of a monument in a single image unless one performs complex operations in order to create an exploded view of the model (Kensek 2007). This is necessary because the reconstructed model usually obstructs the view of the original remains, as these are volumetrically smaller (*see* Figure 5 at page 7). As a result, it is not possible to unambiguously and simultaneously represent the presence of archaeological remains and their proposed reconstruction, nor the relationship between them. An interactive approach is usually used in this type of situation, giving the observer the ability to explore the model three-dimensionally (3D GIS). In this way, however, the advantages of the synoptic representation are lost.
- *No synchronic representation.* A reality-based model is the representation of an archaeological context *as it appears at the exact moment of the 3D survey*, and requires a stratigraphic segmentation in order to uncover previous phases. Such a model may be considered a palimpsest of all of the changes made over the centuries (raised walls, new windows, porticoes that have been filled in or replaced, etc.). Consequently, every reality-based model theoretically results in as many different 3D reconstructions as time-periods identified in the stratigraphy (*see* Medri 1988 and Figure 6 at page 7). Unfortunately it is not possible to synchronously represent all of a monument's various phases with a 3D visualization unless one uses hard-to-read methods, like transparent surfaces and materials.

Computer-based 3D visualization is not necessary the most appropriate means of addressing all communication aims in Cultural Heritage research (*see* London Charter, principle 2.1, p.6.). It is for this reason that the following paragraph (sec. 4.2) introduces a modified version of the Matrix of Harris, the "Extended Matrix" (EM), as a tool with which to annotate and complete the 3D modeling processes.

## 4. Definition of norms, tools and practical aspects (ver. 1.0)

As mentioned earlier, both the typology of the gap and the stratigraphic granularity are fundamental to a coherent

[8]The SU, in stratigraphic terms, is also called an "action", referring to an action that happened in the past.

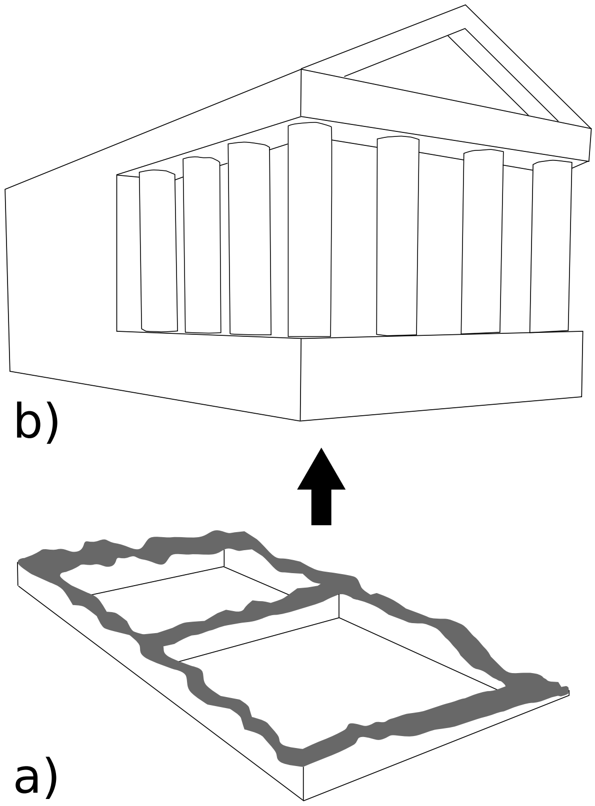



Figure 5: Limits of 3D visualization and exploded views of the model. Without this device, the source-based model (b) would obstruct the visibility of the corresponding reality-based one (a).

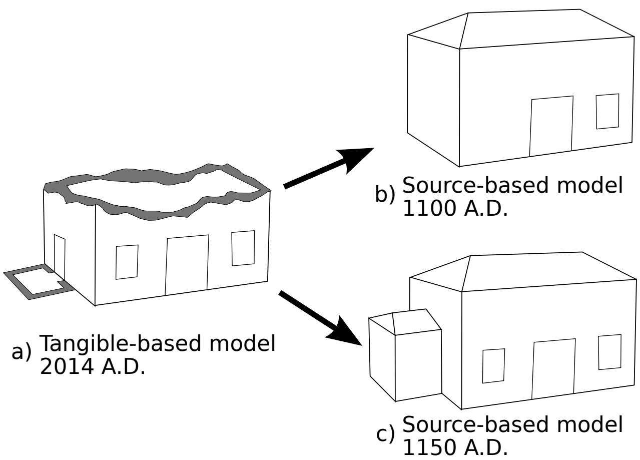



Figure 6: A reality-based model (a) is equivalent to n source-based models from $n$ time-periods (i.e. *b*, *c*). Note how the different solutions are not alternatives, but rather consecutive versions.

and taxonomic annotation of the reconstruction process. In practice, these concepts require norms and symbols for the visualization and management of data that are as similar as possible to the common modeling language in use by archaeologists, particularly the SU (Stratigraphic Unit) and the Matrix of Harris. The aim of the following terms is to propose definitions for these "working tools".

### *4.1. Proposal for the Virtual Stratigraphic Unit (USV)*

The virtual stratigraphic unit (USV) is a re-constructive hypothesis regarding a specific SU that is no longer in existence due to the occurrence of a gap at some point in the history of the archaeological context (i.e. the destruction of a building's roof). The hypothetical presence of a column atop the remains of a temple's podium is an example of a virtual stratigraphic unit relating to a specific SU (the column) which is no longer in existence. The term "virtual" is here considered a synonym for "potential" (from the Latin term virtus), and expresses the likelihood of a specific SU having existed in the past.

#### *4.1.1. USV typology*

USV typology can be determined according to the gap from which it is derived[9]:

- *structural gap based USV* (**USV/S**): the USV/S is directly related to a tangible SU that proves "the presence of an absence". An example is an interface of destruction -SU (negative Stratigraphic Unit) which affects an SU wall (*see* Figure 3) and testifies to the missing upper part of the wall (the USV/S). There is evidence supporting the stratigraphic connection between the -SU and the USV/S and, according to Steno's definition, at least *some of the information is certain.* Some of the properties of the SU affected by the -SU can indeed be passed on to the USV/S (*directly inheritable properties*): in the example at Figure 8, a marble fragment of a frieze automatically indicates that the same material was used in the corresponding USV/S - uncut frieze. At the same time, properties like size, shape, and position must be combined with other data in order to be identified (Figure 8): i.e. a fragment of a frieze (SU) must be combined with a general rule[10] in order to transmit the total height to the corresponding USV/S - uncut column (non-directly inheritable properties). The symbol to represent the USV/S is a parallelogram (*see* Figure 7(b)).

  Sometimes the USV/S can be based on variations of the -SU, like *footprints.* In this case there is physical proof of an absence as well. An example of this is the

[9] For details *see* Steno's gap classification (*infra* sec. 3.1.1) and the derived reconstruction processes (*infra* sec. 3.2).

[10] By "general rule" I here mean an assumption made about a recognizable "trend" or typology in a given time-span (i.e. the proportions of the column vary according to the expected total height).

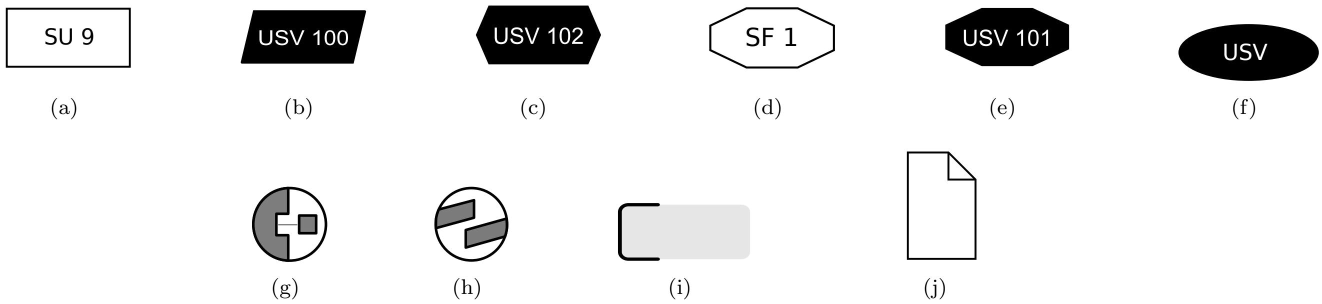



Figure 7: Examples of symbols used in the Extended Matrix: (a) Stratigraphic Unit or "SU"; (b) Virtual Stratigraphic Unit or "USV/S", related to a structural gap (see sec. 4.1); (c) USV/N related to a non structural gap (*see* sec. 4.1); (d) SF (Special Find) not *in situ* (*see* sec. 4.4); (e) USV serving as a representation of an SF not *in situ* (*see* sec. 4.4); (f) Seriation node (*see* sec. 4.5.1); (g) Extractor node, capable of extracting specific information from the sources and transforming them into properties of the USV (*see* sec. 4.3.2); (h) Combination node, useful in combining two or more extractor nodes (see sec. 4.3.4); (i) Property node, validates the USV it is connected to (see 4.3.3); and (j) source useful for the reconstruction (text, image, etc., see sec. 4.3.1)..

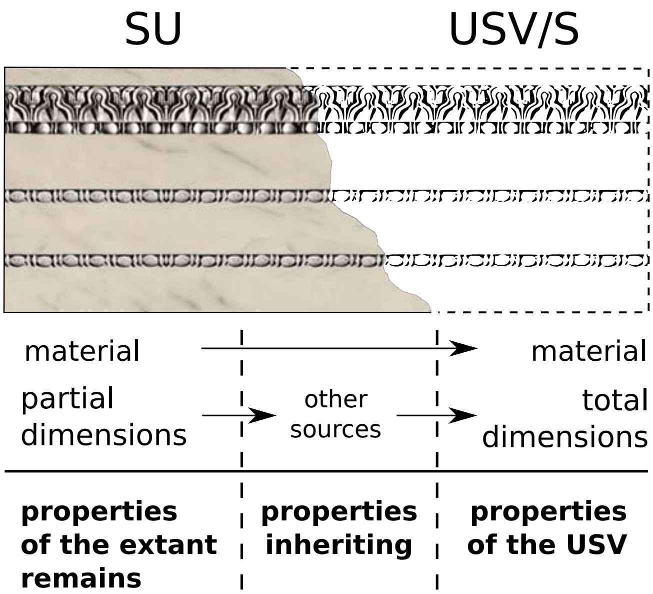



Figure 8: Example of a directly inheritable property and a non-directly inheritable property.

central square of Trajan's Forum, where the signs left in the mortar of the floor provide an accurate idea of the missing marble slabs (*see* Figure 9).

- *non structural gap based USV* (**USV/N**): the USV/N is primarily connected to another USV (USV/S or USV/N), but the stratigraphic connection is uncertain and based only on sources. The symbol used to represent a USV/N is a hexagon (*see* fig. 7(c)).

This typology has significant repercussions in the way multiple USV/Ss can be connected with one another in the Extended Matrix, as well as in the way that their "validation" is defined.

Figure 9: The floor of the central square of Trajan's Forum in Rome. The footprints in the mortar are proof of USV/S lost marble slabs (Virtual Stratigraphic Unit based on a structural gap).

### *4.2. Integration of the USV in the Matrix of Harris: the Extended Matrix*

The Matrix of Harris helps archaeologists to navigate their way through complex systems like that of stratification, where hundreds of units must be managed at the same time. Furthermore, elements with different purposes (lints, columns, etc.) and from different time periods (Roman, Medieval etc.) can be meaningfully connected to one another, with the entire "graph" serving as a "mind map" (*see* Figure 20) of relative chronology. In fact, the Matrix of Harris can also be considered a semantic annotation of the archaeologist's thoughts, expressed as a time-line representing a sequence of SUs (or *actions* which happened in the past).

The USV can be represented as part of the tangible SU (archaeological remains), in a modified version of the matrix of Harris: the "Extended Matrix". Here the USV can have a stratigraphical relationship to: a) one or more SUs; or b) one or more USVs. The hypotheses that a lintel existed on top of a conserved column (a USV on an SU) and that a wooden beam existed on top of this lintel (a USV on a USV) are both examples of relationships which are represented in the Extended Matrix (see Figure 10).

### *4.2.1. General graphic notation in EM*

Every element is constructed from bottom to top. The black lines connecting the nodes indicate the stratigraphic relationship, while the dotted lines indicate chains of data transformation (paradata). The visual representation of the nodes makes use of the symbols introduced in Figure7.

### *4.2.2. Hybrid aspects of the Extended Matrix*

The SU and the USV display the same behavior within the matrix. Nevertheless, the Matrix of Harris represents the documentation of tangible contexts (from the archaeological survey) while the Extended Matrix also includes the representation of objects which are no longer in existence, and which are modeled from other sources (*see* Figure 11 for a schematic representation of the Extended Matrix's hybrid nature). This difference requires the introduction of additional elements (*see* Figure 7), like the "source" node and a subset of paradata (Denard 2012, p. 66,Baker 2012, p. 169) nodes, which are used to *validate* the USV/S (for details *see* sec. 4.3). These nodes can also be considered *data metamorphosis nodes*: the proposed paradigm is similar to the DIKW hierarchy (Data → Information → Kwnowledge → Wisdom, *see* Zeleny 1987 and Ackoff 1989.). Figure 12 shows an example of a validation workflow, from source node to USV. The information is collected from the source node by the extractor node and, subsequently, a property is passed along which is used to validate the USV.

## *4.3. Validation nodes for the USV: sources and paradata*

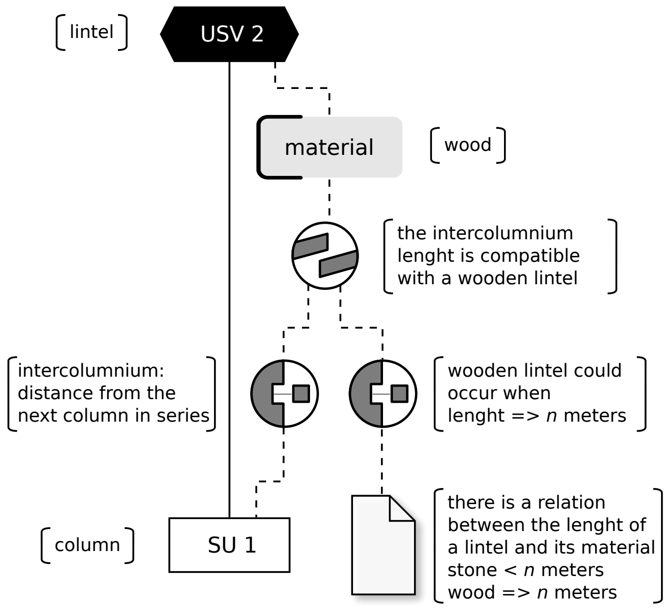
### *4.3.1. Source node*

In the approach presented in this paper, sources are elements of the Extended Matrix and are involved in the USV validation process. The symbol used to represent the source is a "blank document", as shown in Figure 7(j). Examples of *sources* are:

- digital or tangible media (drawings, photos, texts, 3D models, etc.);
- tangible objects (archaeological discoveries, etc.);
- abstractions like general rules[11] or archaeological typologies.

An SU or a USV can also be a source for another USV. In Figure 8 the dimensional properties of the SU act as a source for the dimensional properties of the USV lintel. Thus every element within the EM (Extended Matrix)


(a)




(b)

Figure 10: Examples of a stratigraphic sequence of tangible and source-based actions: (a) a wooden beam on a wooden lintel (USV3 on USV2) and, again, a wooden lintel on a preserved column (USV2 on SU1); (b) detail of the EM in relation to figure "a" representing the validation of USV2 (*see* sec. 4.3.4).

[11] *See* footnote 10.

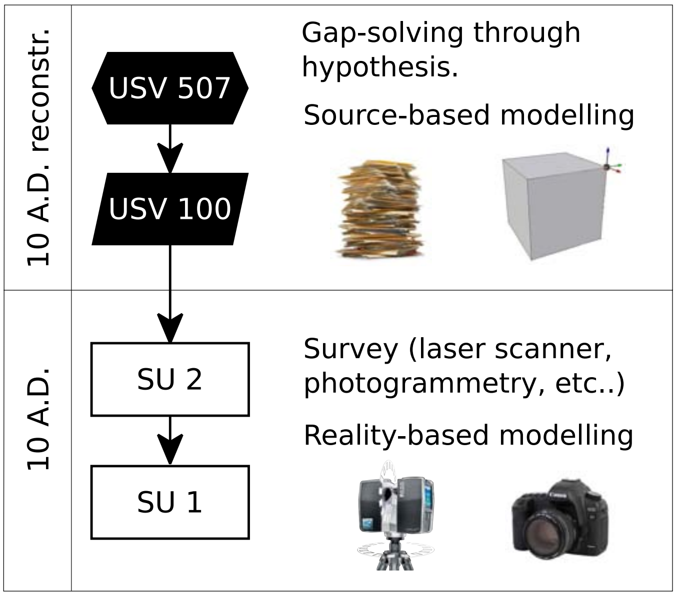



Figure 11: The hybrid nature of the EM.

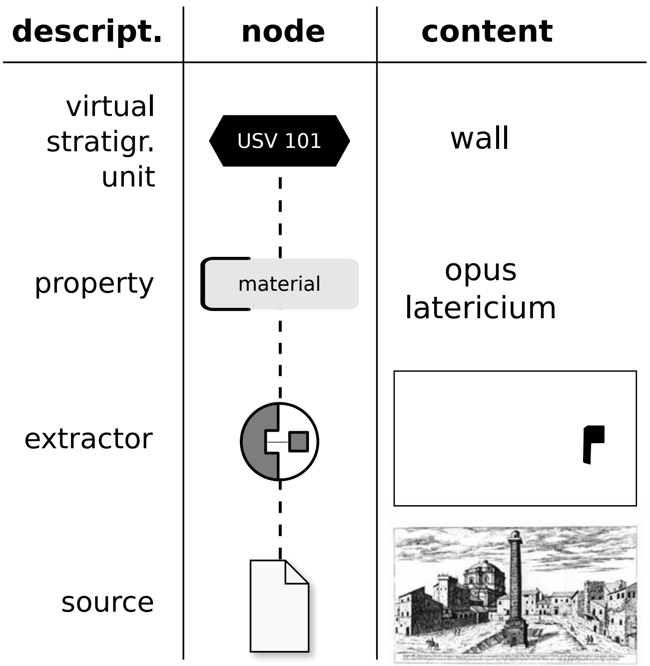



Figure 12: Summary of the USV validation workflow, from the source to the USV/N (example of Du Perac's drawing.).

Figure 13: Trajan's Column by Etienne Du Perac, 1575 (The arrow points to the remains of the "library" near Trajan's Column).

can be used as a source, which means that archaeologists must identify and keep track of the important relationships which they are aware of.

Let us now take a look at an example from a case study: the goal is to reconstruct Trajan's Forum using the perspective of the Trajan Column found in Du Perac's drawing (Figure 13) as a source. This image provides a lot of information about the state of the buildings in the 16th century. Furthermore, the right side of the drawing reveals an interesting detail, indicated with a black arrow. This outline can be interpreted as the remains of the former wall of the east library in Trajan's Forum (for our purposes, a USV/N). To make use of this record, it is important to distinguish between the source and the content that it provides: the source is the whole document (Du Perac's drawing) and acts as a container of information, while the content (the outlined element) is the result of extrapolated data (see Figure12). In the EM this action is represented with the "Extractor node".

#### *4.3.2. Extractor node*

In the Extended Matrix, the source is processed by an "extractor node" that performs the following functions:

1. uniquely identifies the detail "captured" by archaeologists in the source;
2. transforms the detail into a property of the USV to which it is connected (*see* sec. 4.3.3).

From a practical standpoint, the extractor node can be an image, written text, or anything else that may be used to uniquely highlight something in the source. For instance, in Figure 12, Du Perac's drawing (source node) is connected to an extractor node that is a B/W mask highlighting the remains of the large wall in Trajan's Forum.

The symbol used to represent an extractor node is shown in Figure 7(g).

*4.3.3. Property node (USV)*

The property node is directly related to the USV and is the result of one or more sources transformed by paradata nodes (extractor, combination, etc.). The basic qualities of the property node are:

- position, placement;
- shape, material;
- dimensions, proportions;
- style.

This is not a finite list: other qualities may be added. The symbol for the property node is represented in Figure 7(j).

In the example of Du Perac's drawing (*see* Figure 12), the extractor node transmits a material property (*opus latericium*) to the USV.

*4.3.4. Combine node*

When two or more extractor nodes feed a property, it is necessary to combine them. In Figure 10, USV 2 is validated by a "known" property: the material. This property comes from two sources: the placement value of SU 1 (distance between the SU 1 column and the other columns) and a general rule regarding the relationship between a lintel's length and its material. In other words, the reconstruction process is, in this case, based on the following statement: *the intercolumnium length is compatible with a wooden lintel*. The symbol for the combination node is represented in Figure 7(h).

| Source | Extractor | Property |
|---|---|---|
| image | image | location |
| text | text | shape |
| 3D | 3D | dimension |
| 2D | 2D | material |
| .... | .... | placement |
| | | style |
| | | ..... |

Figure 14: Schematic of the paradata workflow nodes and their values.

*4.4. The anastylosis of Special Finds*

During the reconstruction process, one may also have to deal with objects that have been displaced from their original context. The position of these objects can be restored by establishing a reconstruction hypothesis. An example of this type of situation is a column found in the destroyed level of a temple, such as in Figure 15(a). This fragment, known as a *special find* (SF) in excavation taxonomy, can be restored to its position on top of SU1 (stratigraphic unit in its original place) in accordance with a hypothesis. The information available regarding SF1 is incomplete: the material, shape, style, and dimensions are known, but no data is available regarding other properties like position and placement. However, reviewing the steps in the validation process is not the purpose of this section (*see* sec. 4.3), so, for the sake of brevity, it is enough to say that a validation process must be formalized, the same as for a USV. The symbol used to represent a special find is a white octagon (see Figure 7(d)).

Once an SF has been placed in the Extended Matrix, a hypothesis can be created for a USV with which to reintegrate it. In this case, however, the USV has a lower degree of certainty as compared to other USV/Ss that are based on "normal" SUs (see Figure 16). The symbol used to represent this type of USV is a black octagon (*see* Figure 7(e)).

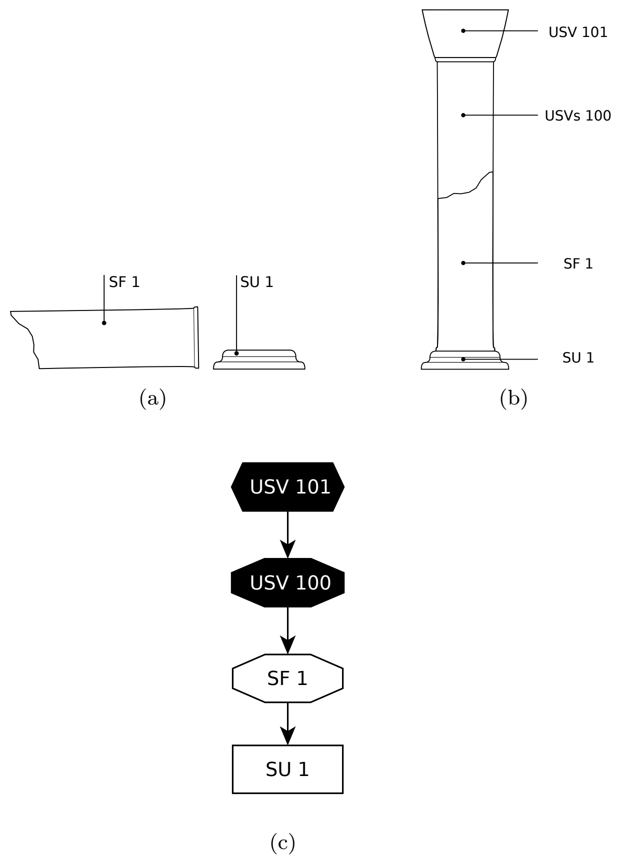



Figure 15: Example of anastylosis: a) Special Find - SF1 (fragment of a column) found in a secondary position, and a base of column *in situ*; b) reconstruction proposal for the column; c) EM of the previous figure (b).

*4.5. Avoiding redundancy and improving readability in the EM*

The EM can be a very complex graph, especially when dealing with hundreds of SUs and USVs. For that reason,

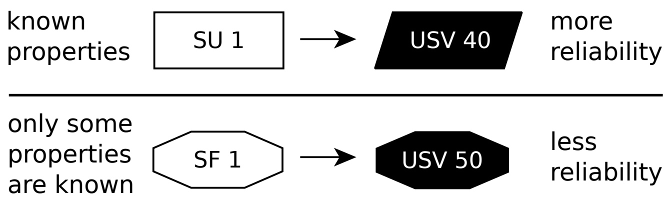



Figure 16: Comparison between SU-based and SF-based USVs

some rules can help to avoid redundancy and improve data readability.

### *4.5.1. Seriation of the USV*

Sometimes groups of USVs can be considered as a whole. This is the case for a series of objects like a colonnade or a sequence of *acroterion.* In these cases the Extended Matrix provides a seriation node that acts like a proxy for the entire group, like the USV 2000 in Figure17. Hopefully the seriation node can be validated by some of the known SUs and USVs included within the "proxy" itself (for instance, the remains of one or two columns can contribute to the validation[12] of an entire colonnade). The seriation node acts like a "whole" and simplifies the stratigraphic relationship with the earlier (upper) SU (i.e. a *lintel* USV connected to a lower seriation node *colonnade*).

The symbol used to represent a seriation node is a black ellipse (*see* Figure 7(f)).

### *4.5.2. Avoiding redundancy in SU-USV/S-USV/N triplets*

As with the Matrix of Harris, the EM is not a representation of the physical chain of events, but rather a non-redundant chronological sequence. Furthermore, each USV/S, both from the point of view of the stratigraphic relationship and as a source for other USVs, becomes a "proxy" for the corresponding SU/SU, and indicates the object as a whole (i.e. in Figure18, the USV/S 504 wall becomes a *proxy* for the USM[13] 30 with respect to the extraction node above).

## *4.6. Virtual Activities (AV)*

To improve readability, it is possible to group different actions within *Virtual Activities*, as happens in the Matrix of Harris' archaeological sequence. This approach is particularly important for complex EMs and results in a tagging of the nodes involved (both USV, sources and paradata). In Figure19 the elements that make up the lintel (AV 3), the decoration (AV 4), and the roof (AV 5) are grouped in such a way as to improve readability and provide a model for a solution which may be reused in other contexts.

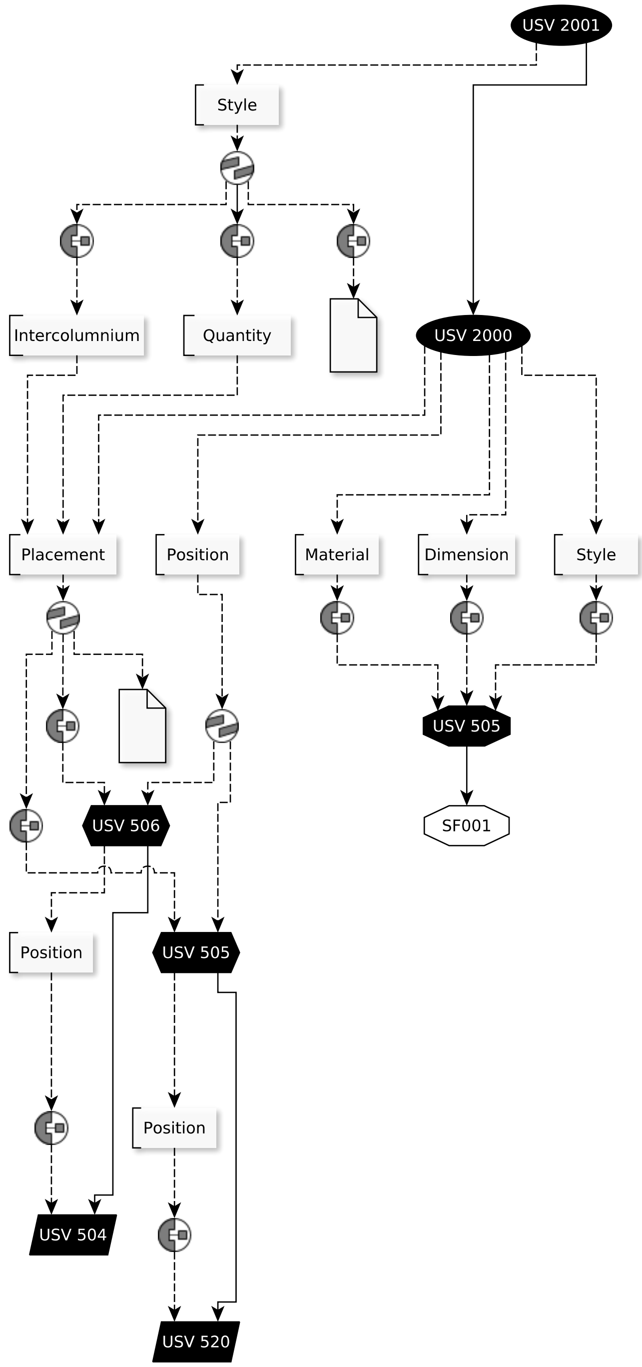



Figure 17: Extract from the EM of the Temple (Figure20) representing the temple's USV 2000 colonnade and USV 2001 capitals.

[12]The "validation" process of a USV is based on the connections between one or more properties.

[13]USM stands for Unità Stratigrafica Muraria (masonry stratigraphic unit), *see* Parenti 1985.

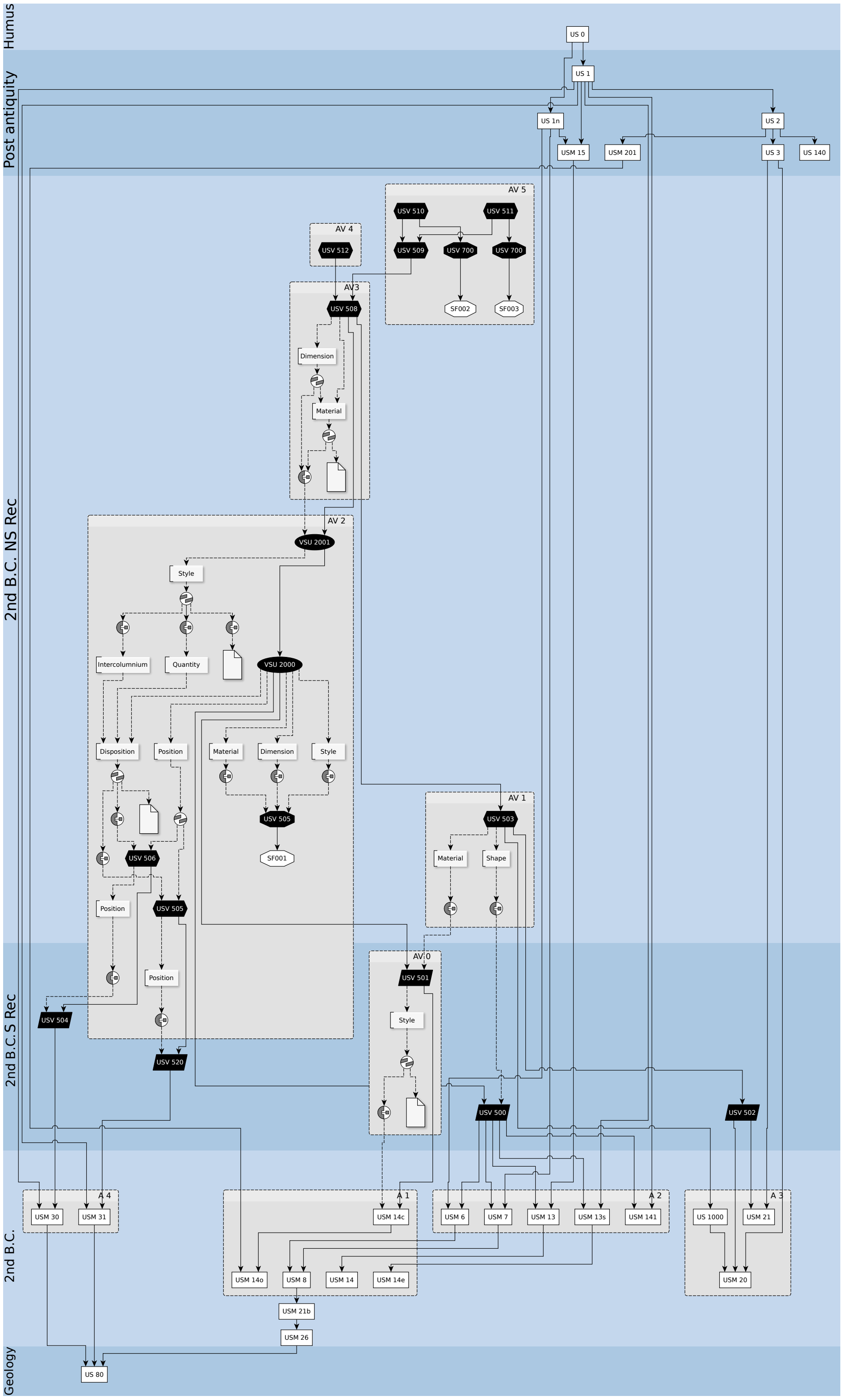



Figure 20: Example of an Extended Matrix applied to a temple.

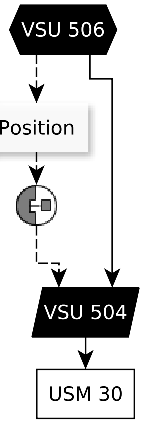



Figure 18: Extract from the EM of the Temple (Figure20) representing the USM30 wall with its USV/S 504 reconstruction hypothesis and a USV/N 506 column above.

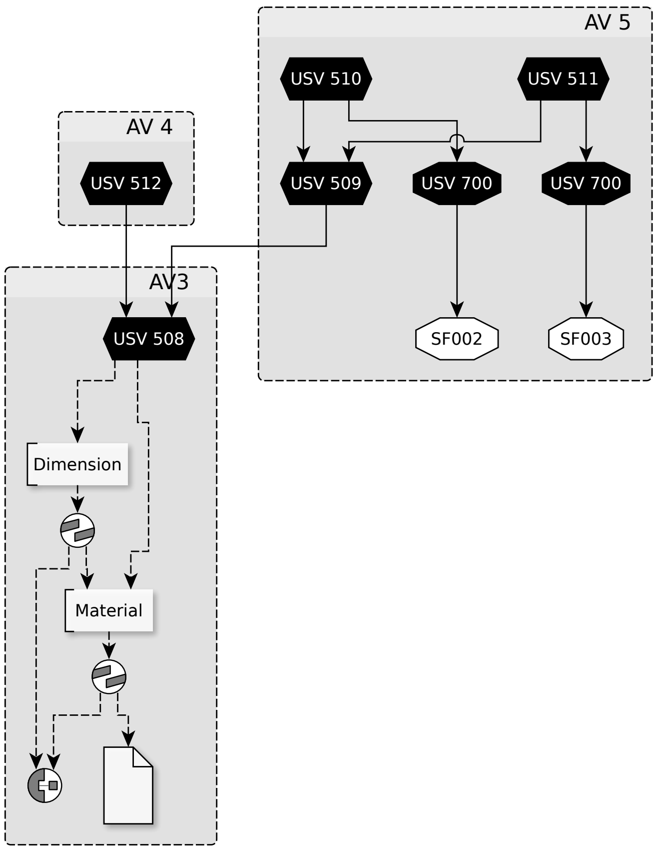



Figure 19: Extract from the EM of the Temple (Figure20) representing the Virtual Activities 3 (lintel), 4 (decoration), and 5 (roof).

## 5. Applicability and definition of uses

Is it possible to use the Extended Matrix and the USV in instances in which the archaeological excavation has not been investigated with a stratigraphic approach? Documents show that there have been many surveys and excavations of archaeological contexts in which no information about the stratigraphy has been collected. Regardless, in these cases a "posthumous" stratigraphic reading may be performed, thus obtaining a Matrix of Harris of the masonry sequence. Setting aside concerns regarding the integrity of this archaeological record, a stratigraphic reading can generally be achieved (preservation and accessibility of the archaeological context permitting). A well-known example of this type of situation is the archaeological remains in Pompei, which were excavated without documenting the SU and these days are surveyed and studied according to a stratigraphic approach (Apollonio et al. 2012).

The significance of this topic is immediately clear if one thinks of the enormous amount of data collected before the introduction of the stratigraphic reading, and an even higher number of datasets were created before the recent introduction of "digital born" data and 3D survey techniques, also known as "legacy data" (for use of the terms "legacy data" and "digital born data", *see* De Felice et al. 2008b, pp. 277-278 and De Felice et al. 2008b, pp. 278-283, respectively). It is very common for virtual reconstruction specialists to have to deal with these kind of "lacunous" datasets. Furthermore, archaeological reconstruction theory is based on a comparative analytical approach and, for that reason, the contexts must be related to one another. As a result, a common approach must be used to handle all of these cases, an approach which relies on a stratigraphic reading and which is independent from the survey techniques or digging methods.

## 6. Conclusions

The current version (1.0) of the *Extended Matrix* is able to synchronously and synoptically represent:

- the stratigraphy of the remains, such as earth, walls, etc. (positive stratigraphic units);
- the structural gaps in the elements (negative stratigraphic units);
- the reconstruction hypothesis based on:

    stratigraphy (SU, USM);

    structural gaps (-SU);

    related sources involved (source nodes)[14];

    hypothesis about the structural gaps (USV/S);

    hypothesis about the non-structural gaps (USV/N).

[14] For details about source management *see* 4.3.1.

### 6.1. Future works

The stratigraphic approach presented in this paper has been tested in several archaeological contexts, but additional case studies need to be conducted in order to refine the framework, especially in the solutions to represent the virtual stratigraphy directly on the 3D model. At the same time, an integration of methodologies with which to store the source quality in the EM (according to the scenarios specified in sec. 5) could be included in a future version (2.0). At present, the Extended Matrix is drawn with the free desktop edition of yED[15] and linked to models in Blender 3D[16], while the data exchange is based on xml format intended for graph data storage (graphml). For the next version of the EM, a software solution could be provided to link USVs and 3D models with the goal to make easy the annotation of the 3D reconstruction processes.

[15] *See* www.yworks.com.
[16] *See* www.blender.org.

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