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A white-box framework to oversee archaeological virtual reconstructions in space and time: Methods and tools

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ABSTRACT

The goal of this paper is to present original methods and visual tools able to formally document the scientific processes behind an archaeological virtual reconstruction, namely a new version of the Extended Matrix (EM 1.1) and the Extended Matrix Framework (EMF 1.1). The proposed approach aims to improve the EM as well as methods and tools for 3D query, visualization, and inspection of extended matrices in order to solve current bottlenecks and issues with the integration of 3D virtual environments and rich semantic descriptions (EMF). A real case scenario is provided to present the steps involved in a reconstruction project using EM/EMF: the Great Temple of the ancient Roman town Colonia Dacica Sarmizegetusa.

1. Introduction

The goal of this paper is to present original methods and visual tools which can formally document the *scientific processes behind an archaeological virtual reconstruction*, namely the Extended Matrix version 1.1 (EM 1.1). The "scientific process behind an archaeological reconstruction" includes not only the specialists' hypotheses regarding a specific context in order to reconstruct its "original aspect" in a given historical time period, but also the collection and the use of the "sources". The sources comprise all the physical evidence (such as discoveries made during excavation or pieces from a museum's collection), historical assumptions (i.e. in Roman times outside the city wall and along the main road there was a necropolis), and documents (drawings or writings) from the past that testify to the lost aspects of the archaeological site as well as its 3D survey and stratigraphic reading.

EM, as defined in its 1.0 version (Demetrescu, 2015), is a formal language specifically designed for the reconstruction of *lost contexts*[1] and operates with the same tools already in use in the archaeological domain in order to manage time sequences (matrix of Harris) and data granularity (stratigraphy). The version 1.1 of the Extended Matrix adds a complete support for 3D representation of extended matrices and scientific publication of the whole dataset behind a virtual reconstruction hypothesis. The EM 1.1 is focused on solving bottlenecks and issues that are currently present in the integration of 3D virtual environments and rich semantic descriptions (*see infra* sez. 3). Examples from a real case scenario are provided to present the steps involved in a reconstruction project using EM: the Great Temple of the ancient Roman town Colonia Dacica Sarmizegetusa.

2. Theoretical domain of the research

Arguments like data provenance, uncertainty management, and data modelling are core topics when it comes to *source based models*[2] (reconstruction of *lost contexts*). The intricacy of the sources and reasoning behind a reconstruction hypothesis may blur the scientific communication of the archaeological process. This situation needs an efficient "white-box" system that permits easy data management, rich data ingestion, and expert data retrieval through visual tools.

The integration of the EM with digital tools for 3D representation of virtual reconstructions and visual inspection of extended matrices is identified with the expression *Extended Matrix Framework* (EMF). The EM is the theoretical and methodological background, usable even outside a digital environment (an EM can be sketched out on a sheet of paper with a pencil as well as with cutting-edge software) while the EMF includes digital solutions and software platforms (which can substantially change in the future if relevant technological innovations occur). EM is about scientific-driven content creation, EMF is about technological-driven solutions. Every version of the EM drives its own EMF digital framework identified by the same number (at present EM 1.1 has its EMF 1.1).

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[1] By *lost context* we mean a context that is no longer existent and/or has been completely or partially "lost" over time due to various causes (war, neglect, environmental factors, etc.).

[2] A 3D reconstruction can be thought of as a complex "source driven 3D model" because it is based on several "sources" (archaeological records, images, comparatives, etc.) combined together according to an analytic and comparative methodology (Demetrescu, 2015, p.43).

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The proposed EM-EMF 1.1 includes the following aspects:

1. A coherent language that makes it possible for various professionals to work together, following a smooth validation work-flow and a collaborative pipeline. EM allows archaeologists, IT scientists, and computer graphic experts to *share a common language which ensures that the scientific reasoning behind the reconstruction hypothesis remains consistent and transparent* (*see infra* sez. 4);
2. Methods and tools to populate a graph database (built on the Extended Matrix 1.1) with rich semantics intended to visually describe the elements involved in the reconstruction (sources, concepts, comparisons, *see infra* sez. 4 and sez. 4.3);
3. Foundations for the crafting of 3D visual inspection tools in order to query and validate Extended Matrices at runtime, addressing (a) temporal dimension, (b) automatic graph extraction from EM definition, and (c) visual presentation of meta-data elements (*see infra* sez. 5).

EMF is a multidisciplinary framework that operates both within the "historical" and "mathematical" domains (*see* the classification of Nicholaus Steno, Ascani et al., 2002). Through the historical language we can turn the *reconstructive record*[3] into an EM data model (the EM describes the elements and their relationships). On the other hand, through the mathematical language it is possible to consistently inspect data and represent it dynamically in a virtual world, enabling the exploration and experimentation of the reconstruction hypothesis within a 1:1 scale virtual space "shared" with other researchers.

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 infra* sez. 4.2.1) are used as a modular grammar to compose the final description of the reconstruction process (data-driven reconstruction). 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 reconstructive 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 (*see infra* paradata nodes at Fig. 5 (g), (h), (i), and (j)).

In the following sections, after a review of the *state of the art* regarding the topics mentioned above (*see infra* sez. 3), the theoretical and methodological background of the EM 1.1 as well as of the EMF 1.1 which include tools for 3D visualization and inspection will be presented (*see* sez. 4 and 5). In order to clarify them, examples from a real case scenario (the Roman Great Temple at Colonia Dacica Sarmizegetusa) will be provided in order to describe the steps involved in a virtual reconstruction project: from data collection (sez. 4.1) to EM creation (sez. 4.2), 3D modelling(sez. 4.3), and 4D data exploration and visualization (sez. 5).

3. Related work

3.1. Managing data provenance in archaeological virtual reconstruction

In the last few years an increasing number of experts have been paying attention to data provenance in (3D) virtual reconstruction (*see* recent introduction of classification proposals: Münster et al., 2016a, Münster et al., 2016b, Apollonio, 2016, Pfarr-Harfst, 2016). A common approach used to represent the thought processes behind the creation of a (3D) reconstruction is to annotate them using meta-data descriptions. For a critical review about data provenance strategies and data granularity in archaeological virtual reconstruction *see* Demetrescu, 2015, pp. 43–44.

At present, there are several semantic tools that describe existent objects of cultural heritage, each specialized in specific domains (monuments, objects, discoveries made during excavation, bibliography, etc.) and organized according to conceptual reference models (CIDOC-CRM, CHARM).

CIDOC-CRM has introduced a high degree of stability to meta-data enrichment of tangible objects (mainly collections) thanks to the use of a common standard. However, for the purpose of standardization, this ontology was first developed with specific objectives and with specific restrictions: "objects in museums, libraries, and archives"(Doerr, 2003, p. 84).

The process of metadata ingestion in the field of the reconstruction of lost contexts has a different workflow from the 3D survey and digitalization of real objects (*see* Fig. 1). It follows a circular process and results in an "open" output: the virtual reconstruction never becomes a "definitive" output because it can be modified at any time in the future if new sources become available.

At the same time the qualification of the provenance of the data follows a completely different path. When it comes to the digitalization of real elements, the "accuracy" can be expressed in *quantitative* units of measure (i.e. 2 mm) while in the case of virtual reconstruction the accuracy is a *qualitative* blending of different sources (it cannot be expressed in discrete units of measure). The focus of the semantics that describe virtual reconstruction processes is the network of the relationships between the sources involved (*see infra* sez. 4).

Despite the fact that CIDOC-CRM is specialized in handling the properties of *tangible* objects, in recent years some additions have been proposed which would extend its core-elements to include more abstract concepts and relationships.

CRM-sci is intended to support scientific observation and description of physical phenomena (Doerr et al., 2014). CRM-BA is intended to describe the elements and relationships involved in building archaeology (Ronzino et al., 2015). CRM-dig is a generic digital provenance model for scientific observation and can be used to create data paths to information provenance of digital elements from real world objects (Doerr and Theodoridou, 2011) and it has been used also to annotate reasonings behind a reconstruction (Bruseker et al., 2015).

In recent years, other tools and standards have been proposed with the specific purpose to annotate virtual reconstruction processes using different paradigms (stratigraphic approach combined with visual tools like the Extended Matrix: Demetrescu, 2015, Demetrescu et al., 2016), conceptual models (CHARM: Gonzalez-Perez et al., 2012, Apollonio and Giovannini, 2015) or customized formal languages (CHML: Hauck and Kuroczyński, 2014, Kuroczyński et al., 2016). In these cases, CIDOC-CRM has not been used as a semantic reference.

In 2012 CHARM was introduced, a conceptual reference model based on a visual representation: the ConML language. This feature sets CHARM apart from CIDOC-CRM.

> *"[…] CHARM aims to cover […] cultural heritage […] at a high level of abstraction. In contrast to CIDOC CRM, CHARM is much wider, since it does not focus only on the curated knowledge of museums but on cultural heritage in general. At the same time, it is much shallower, because of its high level of abstraction; CHARM has been designed under the assumption that extension mechanisms need to be applied before it can be used at all […], whereas CIDOC-CRM attempts to be an off-the-shelf solution."* (Gonzalez-Perez et al., 2012, p.191).

In CHARM, concepts like the Stratigraphic Unit (SU) and its relationships are already provided for. CHARM offers a higher level of abstraction and is modular, which means that each element can be easily modified for other purposes. On the other hand, the Cultural Heritage Markup Language has a reconstructive point of view that provides a visual language with which to describe a virtual reconstruction (Kuroczyński et al., 2016 and Kuroczyński et al., 2014)

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[3] *See* definition of *reconstructive record* at the end of sez. 4.

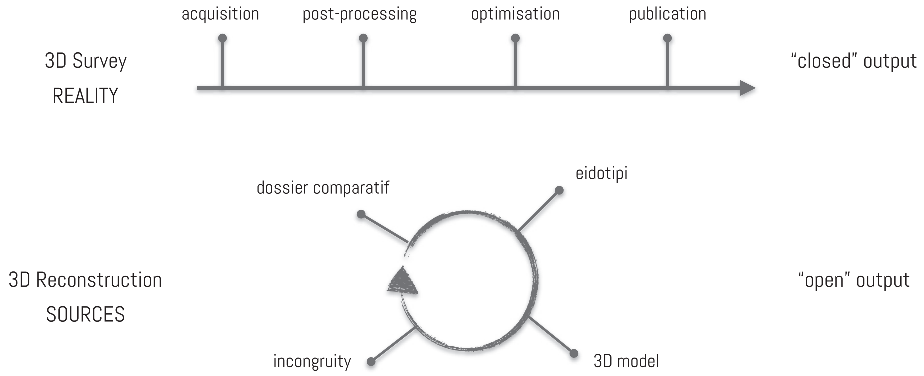

Fig. 1. Metadata from a workflow point of view: reality based and source based scenarios of metadata creation.

inspired by the Unified Modeling Language (UML) that is object-oriented and focused on the generic description of processes and their evolution in time (Rumbaugh et al., 2004).

Some research considers the organization of the sources of the reconstruction and the annotation of the steps in the creation of the reconstructive 3D asset (Baldwin and Flaten, 2011, Münster, 2013, Pfarr-Harfst and Grellert, 2016) to be a necessary starting point for data transparency. To this end, a wiki system which collects data about virtual reconstruction has recently been proposed (Münster and Niebling, 2016).

3.2. *Linking 3D models and data*

The 3D annotation has become, over the last decade, a major topic when it comes to accurately documenting an entity of cultural heritage. Common approaches within the interactive graphics domain applied to cultural heritage include different processes that define query-able descriptors in the form of basic 3D shapes (Serna et al., 2012), semantic structures produced by 3D segmentation of digitized models (Apollonio et al., 2012), and tools offering multiple annotation modes (i.e. point, surface, and frustum, *see* Shi, 2016). In terms of interactive on-line fruition by means of modern WebGL capabilities, previous research on interactive queries has focused on 3D query-able geometrical shapes integrated in web-based viewers (Auer et al., 2014, Potenziani et al., 2015).

3.3. *Scientific publication of virtual reconstructions*

Despite the fact that a thorough publication of the data related to virtual reconstruction is considered a primary issue in the field, as of yet there is no common standard to accomplish this task. An important aspect is the difficulty in making not only the sources used available, but also the reasoning behind a reconstruction hypothesis (Bruseker et al., 2015). Web-based tools oriented to track the processes behind a virtual reconstruction (Bruschke and Wacker, 2016) stress the importance of connecting the source with the hypothesis (Pfarr-Harfst and Grellert, 2016), while others are committed to showing reconstructions on-line (Pompei: Dell'Unto et al., 2013, Çatalhöyük: Forte et al., 2012, MayaArch3D: von Schwerin et al., 2016) through a 3D GUI focused on a hierarchical organization of the digital collections. In some cases the researchers combine the release of the project's stratigraphic database with the synthetic publication of the excavation and include the reconstruction as part of the archaeological investigation using the Extended Matrix (The Swedish Pompei Project: Landeschi et al., 2016, Demetrescu et al., 2016). In some cases the GUI is also focused on the study of user perception (The Gabii Project: Opitz and Johnson, 2016). For a broader *state of the art* about the projects focused on GUIs for the exploration of 3D models of archaeological excavations and related data *see* Opitz and Johnson, 2016, p.7.

4. Definition of norms, tools and practical aspect of EM 1.1 workflow

In this section we will present the guidelines (norms, terms, methods) for the EM 1.1 work-flow. At the end of the section, the Great Temple of Colonia Dacica Sarmizegetusa (Romania) will be presented in order to provide an example of the practical actions and tools used in "standard scenario".

The guidelines include the steps in the documentation of a virtual reconstruction (*see* upcoming numbered statements in Fig. 2):

1. **Data collection**: *3D survey* of the remains and of the special findings (i.e. *non in situ* blocks of stone from the architectural *apparatus*), *stratigraphic reading* (4D analysis of the palimpsest), creation of a *Dossier Comparatif* (comparative study);
2. **EM model creation** to organize data within the Extended Matrix: writing down of the *Extended Matrix* and the *Report of Virtual Activities*;
3. **Creation of 3D models**: The survey creates a *3D snapshot* (*see infra* 6) of a monument at a specific moment in time (i.e. 2017) that represents a palimpsest of different phases of life (i.e. prior to construction, construction, destruction, modern restoration). It has to be segmented in order to provide different geometrical bases for the subsequent *3D source based modeling*. The EM must be divided into chronological horizons and for each one, a reconstructive model is proposed, filling the gaps highlighted in the 3D snapshots (negative stratigraphic units).

We do not have to think of these steps as separate phases of a reconstruction project: during data collection we can start populating the EM with interpretative elements as well as sketch out some visual representations of a given epoch. This synchronous work-flow enables a cross-fertilization of the relationships between the archaeological elements, the external sources, and the hypotheses. We can call the information stored during the above-mentioned steps an *archaeological reconstructive record*. The documentation of a *reconstructive record* that is coherent and as complete as possible is the primary scope of the EM work-flow.

4.1. *Data collection*

Data collection can include diversified methodologies and technical solutions. Different contexts require different approaches. Some scenarios cannot involve a 3D survey due to disparate limitations (physical, legal, etc.) but can make use of legacy data (drawings or blueprints). Furthermore, when the reconstruction project regards a completely lost context, all the data collection is focused on the sources organized within the *Dossier Comparatif* (DosCo) (*see infra* 4.1.3).

4.1.1. *3D Survey of the context*

An archaeological site is a palimpsest of different epochs in which

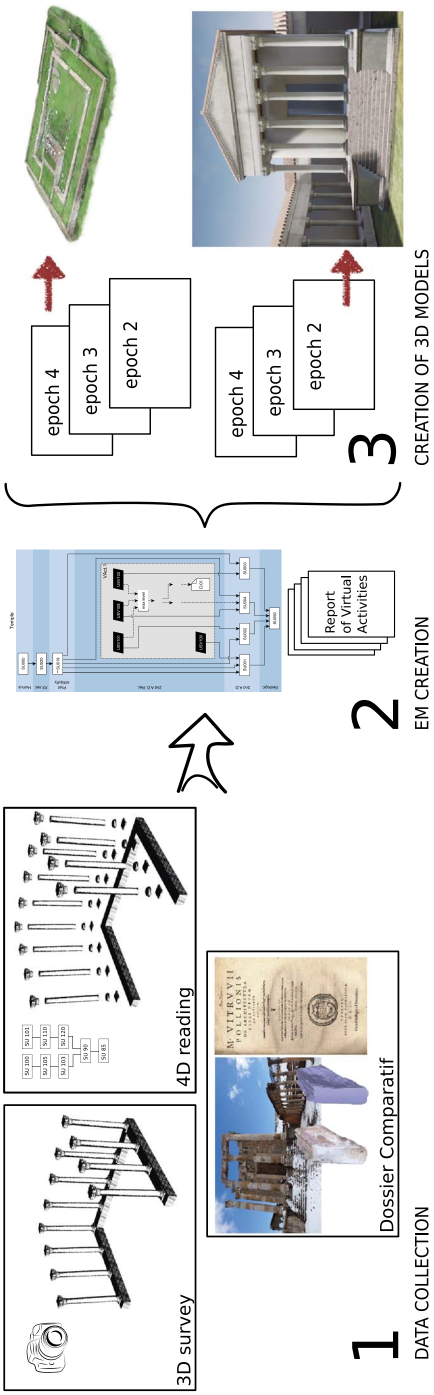

Fig. 2. Production work-flow, from data collection to 3D visualization.

each of these epochs must be purged of non-coeval elements in order to highlight the preserved ones and the overall shape of each chronological phase. Furthermore, a clear distinction between the different stratigraphies (grouped by epoch of belonging) is crucial to proposing a reconstruction hypothesis. In Fig. 3 there is an example of digital 3D geometry acquisition of the Great Temple in Sarmizegetusa.

Alongside the *in situ* elements, the 3D acquisition could include the survey of all the *non in situ* objects. The 3D measurements result in metrically accurate 3D models or *digital replicas* with colour information. In the example of the Great Temple in Fig. 4, every architectonic fragment has been formalized in a high resolution blueprint. In this case, each element is represented through different orthometric views (front, back, right, left, top, bottom), its measurements are provided (depth, width, height), cross sections are cut, and, finally, joint-areas are highlighted in order to check its topological compatibility with the remains of other stone blocks.

4.1.2. 4D reading: the stratigraphic sequence and the Matrix of Harris

During (or after) the 3D survey, a stratigraphic reading must be performed in order to highlight the temporal sequence (4th dimension) of the actions. In the example of the Great Temple in Fig. 13, the Matrix of Harris (green areas) visually summarizes the stratigraphic elements involved and the epochs which they belong to. In this case the stratigraphic reading has been performed on the field and includes the building stratigraphy.

4.1.3. Dossier Comparatif

All the sources and the comparisons with other contexts are stored in the *Dossier Comparativ* (comparative study Gros, 1995, p.322). The *Dossier Comparatif* (DosCo) is a collection of documents which follows a specific nomenclature: a composite known as “D.”(Document), plus an increasing number (i.e. D.01). The number is set according to the cronological sequence of data ingestion. All the documents are linked inside the EM and used to validate the reconstruction hypothesis. These are represented inside the EM through the *source node* (Demetrescu, 2015, pp. 48–50).

4.2. Creation of the Extended Matrix and the Report of Virtual Activities

In archaeological practice, a virtual reconstruction is usually created at the end of an excavation project or 3D survey and is not part of the research itself. The 3D model, in this sense, is intended as a posthumous work which synthesizes different hypotheses made during the investigations (Medri, 2003). Generally these are not formally annotated. In some cases, experts write down intermediate reports to fix certain general ideas, but the collection of the archaeological record lacks a precise way to store the rich connections that are recognized between pieces of evidence during the fieldwork. The EM is committed to fixing this issue.

Virtual reconstruction should be part of the archaeological investigation right from the earliest stages of research. Even if the final results are not to be shared until the end of a survey/excavation, the reconstruction hypothesis must be formally “documented” along with the archaeological record which it is derived from. “Early collection” simplifies the management of the reconstructive record and “drives” the subsequent source-based modelling. This approach makes it possible to publish a thorough account of the scientific process, highlighting the connection between the archaeological and the reconstructive records and enabling other researchers to actively check, modify, and consciously reuse the virtual reconstruction. The Extended Matrix was used during the survey of the Great Temple in order to manage the sources, acting as a “mind map” of the researcher's intuition and of the connections discovered in case a new document is added to the research. Besides the Extended Matrix, a more discursive document, the *Report of Virtual Activities*, provides a textual version of the EM for quick sharing of the reconstruction hypothesis (*see infra* sez. 4.2.2).

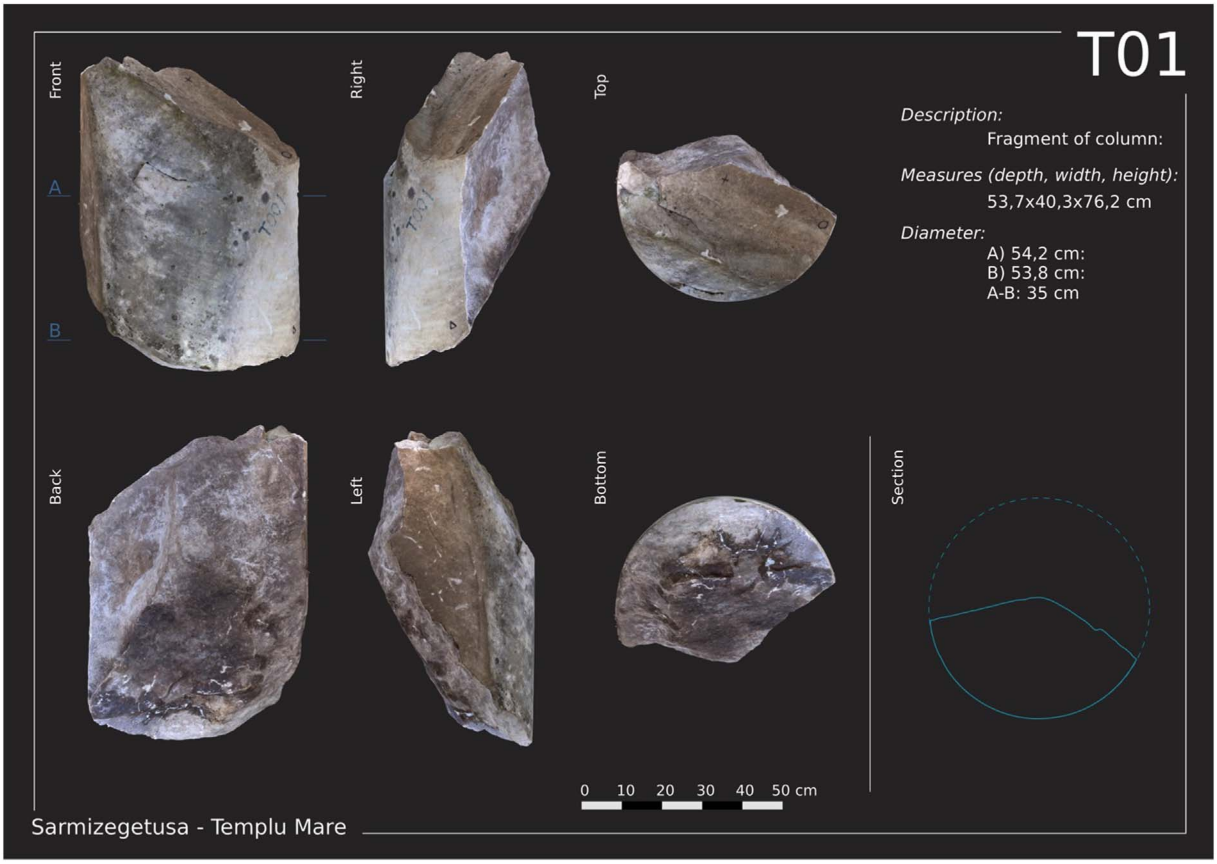

Fig. 3. 3D model of the Great Temple (photogrammetric survey).

Fig. 4. Example of a blueprint with a fragment of a column (Special Finding T01).

4.2.1. *The grammar of the Extended Matrix*

EM uses two sets of standardized nodes[4]: USV and validation nodes (see Fig. 5). The USV nodes represent virtual stratigraphic units (according to a specific typology) while the validation nodes express the reconstruction process behind the USV. These nodes are connected to each other by arcs in the same way as with the archaeological Matrix of Harris.

Validation nodes (or paradata nodes, *see* Fig. 5 (g), (h), (i), and (j)) have unique names (as well as the USVs) in order to be correctly referenced. They adhere a name convention model (see Fig. 2): extractor nodes are composed of a "#" plus a sequence of numbers (i.e. the first extractor of an EM will be #01). Combiner and document nodes use the "$" and "D.".

The EM shows the epochs of the site. Each epoch is divided into two rows (fig. 13): one row for the physical remains (SUs) and another row for the reconstruction hypothesis (USVs). An EM including only the physical remains is equivalent to a standard Matrix of Harris.

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[4] For full details about EM nodes and their use, *see* Demetrescu, 2015, pp. 47–50.

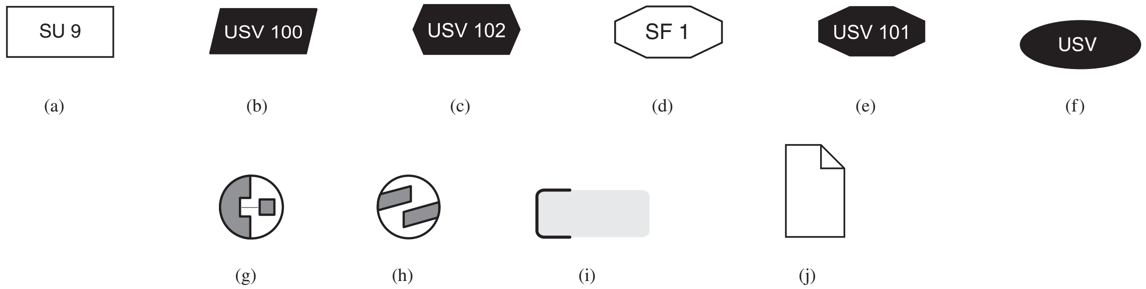

Fig. 5. Examples of symbols used in the Extended Matrix: (a) Stratigraphic Unit or "SU"; (b) Virtual Stratigraphic Unit or "USV/S", related to a structural gap; (c) USV/N related to a non structural gap; (d) SF (Special Find) not *in situ*; (e) USV serving as a representation of an SF not *in situ*; (f) Seriation node; (g) Extractor node, capable of extracting specific information from the sources and transforming them into properties of the USV; (h) Combination node, useful in combining two or more extractor nodes; (i) Property node, validates the USV it is connected to; and (j) source useful for the reconstruction (text, image, etc.).

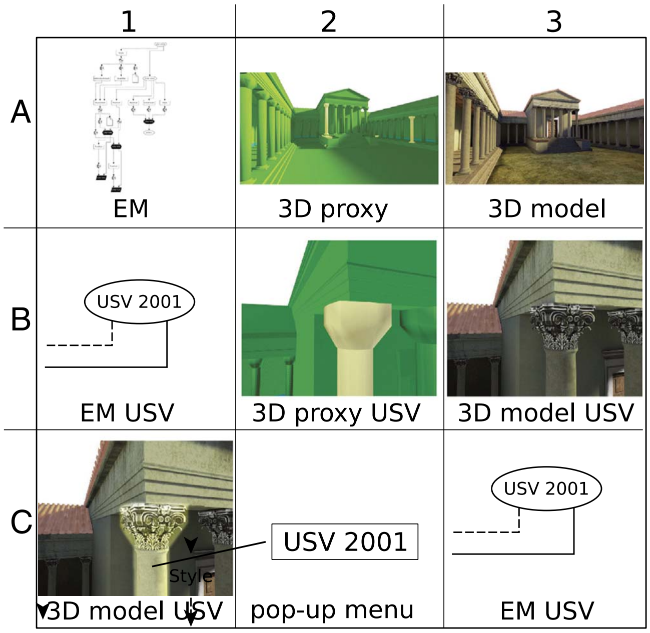

Fig. 6. Relation scheme between *representation models*, *proxy models*, and Extended Matrix (A1-A3, B1-B3); and an example of query on the 3D model selecting the corresponding USV in the EM (C1-C3).

4.2.2. Report of Virtual Activities

As happens with real stratigraphic units, Virtual Reconstruction Units (USV) are combined in Virtual Activities (VAct. *see* Fig. 11) using rectangular shapes in the EM canvas. VActs are described in the Report of Virtual Activities (*see* Demetrescu, 2015, p. 51), a textual report that acts as an intermediate output and is useful for quickly sharing a reconstruction hypothesis. A Report of Activities is written down for each reconstructed epoch (*see* Fig. 2). In the following text box there is an extract of the VAct. 3 from the Report of Activities of the Great Temple.

> **Box 1 Virtual Activity 3: lintel over the columns.** In this reconstruction it is presumed that over the colonnade USV104 there was a wooden lintel with stuccoes USV106. According to *Vitruvius* (Vitr. III,2), the diastil module manner is fragile when we come to the lintel and mentions collapses which happened in the past. For that reason, for this kind of module, he suggests a wooden lintel (with stuccoes for the decoration). In other words, in this kind of module we can expect both a wooden and a stone lintel. The lack of stone blocks during the recent excavations of the lintel suggests however that it may be wooden. The overall width of the lintel is normally 1/4 or 1/5 of the whole length of the column.

4.3. Creation of 3D models (source-based modelling)

In this section the 3D modelling steps, starting from the sources organized in the EM (source-based modelling), are described. These have different levels of representation, from small details to a broad perspective:

- *Digital restoration* of *digital replicas* (*see* Fig. 8);
- *Digital anastylosis* of the elements in order to restore their original position and spatial relationships (*see* Fig. 9);
- *Virtual Reconstruction* of a given epoch starting from all the sources available and the anastyloses performed (*see* Fig. 10). It is important to take into account that from a reality-based model it is possible to

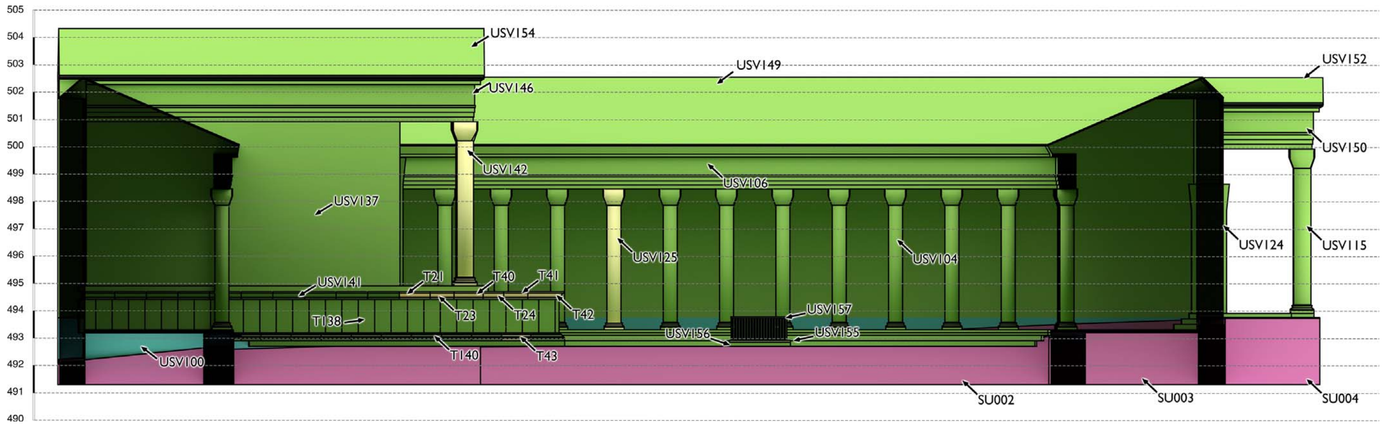

Fig. 7. Section N-S of the Great Temple's proxy - II A.D. epoch (*see* its EM at Fig. 13).

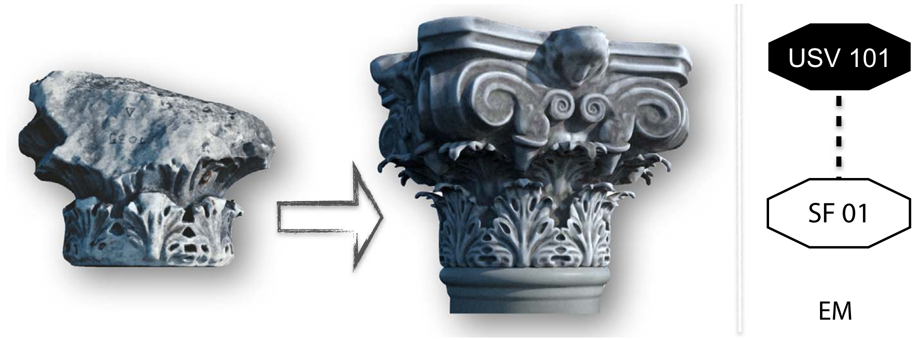

Fig. 8. Digital restoration (USV 101) of a digital replica (SF 01). On the right the EM representation.

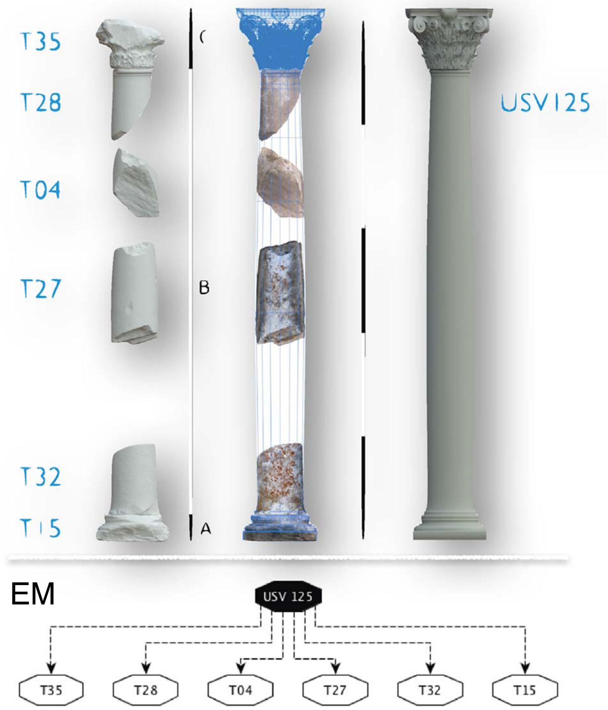

Fig. 9. Digital anastylosis (USV 125) of the special findings (T35, T28, T04, T27, T32, T15) in order to restore their original position and the spatial relationships. In the lower part of the figure it is its EM representation.

make several reconstruction hypotheses: ideally at least one for each period formalized in the Matrix of Harris (*see* Fig. 12);

Despite the fact that it does not contain geometry information, for the sake of clarity, we summarize here the next level of data representation of this series:

- *Extended Matrix* is the highest level of synthesis and simultaneously represents the site in all its epochs and hypotheses, highlighting the elements involved in the reconstruction and their relationships: it is a semantic of the virtual reconstruction (*see* Fig. 11) and is based on the relative sequence of actions (stratigraphy) or deduced from the sources.

4.3.1. *The proxy-representation model approach*

The creation of 3D content follows two levels of abstraction: *proxy models* (*see* Fig. 7) which are simplified representations of the reconstruction through basic geometrical shapes (cylinders, boxes, spheres, etc.) and *representation models* (*see* Fig. 10) which are focused on fine geometries, colour, and material simulations resulting in the final, aesthetic depiction of the reconstruction hypothesis. The Proxy level makes it possible to highlight portions of the *representation model* and to interact with it (*see* Fig. 6 and sez. 5). Furthermore, it also represents the first draft model of the reconstruction and is useful, along with the *Report of Virtual Activities* and the EM, for the sharing of intermediate results with colleagues and other experts and for providing feedback.

The Extended Matrix contains the elements of all the 3D models (a model for every reconstructed epoch). Each USV node of the EM is linked, on a one-to-one basis, to a specific proxy geometry in the 3D model. A common issue in 3D data granularity is the segmentation of the meshes. A model created using a computer graphics approach (like the representation model) may indeed be quite different from a reality-based model, resulting in an even more challenging segmentation process. A very popular solution in source-based modelling is “polygonal modelling with control point” in which the resolution is usually parametric and controlled by “modifiers”(mirror, subsurf, bevel, etc.). In general, the computer graphic approach requires an accurate topology in order to guarantee render time (in the case of a computer animation) or FPS (in the case of a real-time application) remaining in a “green zone” of performance. In this type of situation a geometric segmentation of the model may compromise its overall “usability”. For this reason, the EM approach adheres to the solutions proposed by the 3D-COFORM project (Serna et al., 2012) for reality-based models. In this case a *proxy* 3D model is used to semantically enrich the representation mesh. In Fig. 6, for instance, the extended matrix (A1) of a temple has a proxy geometry (A2) which highlights and semantically enriches the 3D representation model (A3). Each USV in the EM (B1) may be individually selected, with the corresponding 3D proxy model (B2) highlighting the details in the representation model (B3) with a different colour and providing a conceptual visualization. At the same time, while exploring the 3D model (C1), the EM (C3) can be retrieved through a pop-up menu (C2).

4.3.2. *Graphical documentation for the reconstruction hypothesis*

As said before, the reconstruction hypothesis of a context has two depictions: a *proxy model* and a *representation model*. These enhance communication of research results and make it possible to explore and experience it in a virtual space (this will be discussed in detail in Section 5). The EM approach however is not focused only on digital media but it pertains, first of all, to the archaeological documentation for a site's interpretation and scientific publication. Each stratigraphic unit - virtual or real - has a proxy representation. Making sections and plans out of proxy models is possible in order to provide technical documentation along with the description of virtual activities: in Fig. 7 the numbers of the SU/USV are labels of the proxy elements while colours follow a standardized chart (*see* Demetrescu et al., 2016, p. 55) based on the typology of SU/USV (remains, USV/n, USV/s, anastylosis, etc.). Extended Matrix, Report of Virtual Activities, and graphical documentation published together allow for a coherent formal representation of the reconstruction hypothesis.

Fig. 10. Virtual Reconstruction of the II A.D. epoch of the Great Temple starting from all the sources available and performed anastyloses (*see* Fig. 9).

4.4. *The 3D-as-a-container metaphor and its limits: the multidimensional approach of the EM*

A very common approach when using 3D technology for scientific applications is to "link data to 3D elements" In this case the role of the 3D space is to "contain" and manage all information. It represents the *fulcrum* around which all the sources are structured. This approach derives from the well known metaphor of space as a container like in the case of BIM (Building Information System) or GIS (Geographical Information System). The idea behind the Extended Matrix is to reverse the 3D-as-a-container perspective switching the *fulcrum* from space to time making a multidimensional (3D + 4thD + different self-excluding hypotheses) approach possible, in which the container of all the reconstructive processes is not 3D space but a semantic network (the Extended Matrix). In this way *the focus is no longer on the 3D model itself but on all the possible models derived through data and reasoning*. Another result is that the creation of a 3D digital model is no longer the first attempt at virtual reconstruction since the majority of the work can be done (or at least organized) in the mind of the specialist in charge of the reconstruction with the help of the EM. During the study, the

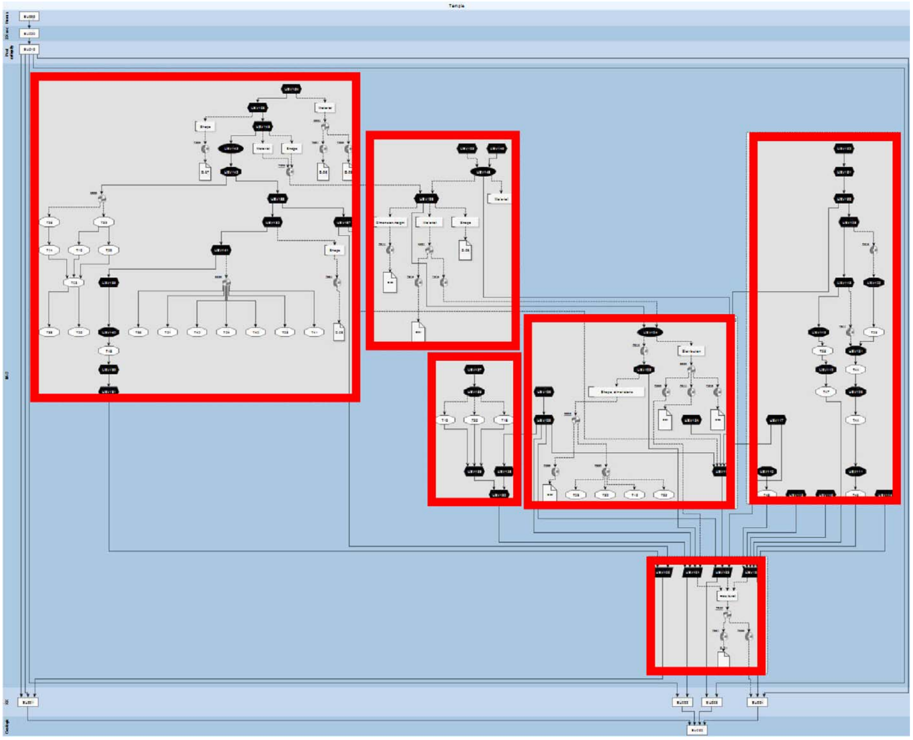

Fig. 11. Extended Matrix represents the Great Temple in all its epochs and hypotheses, making explicit all the elements involved in the reconstruction and their relationships. In red, the Virtual Activities. For a detail (with the VAct. 1), *see* Fig. 13.

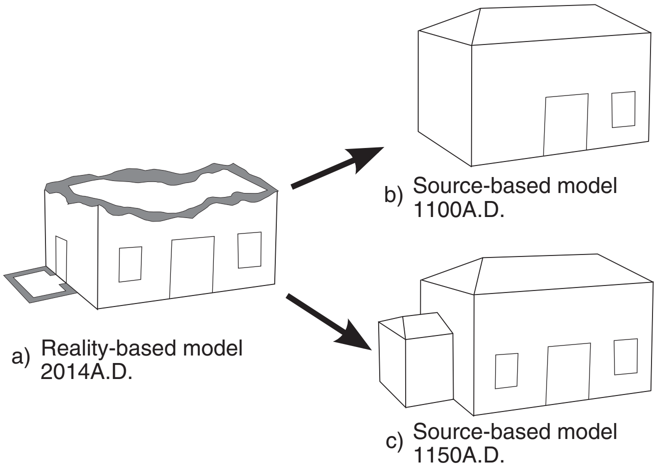

Fig. 12. From a reality-based model it is possible to make several reconstruction hypotheses: ideally at least one for each period formalized in the Matrix of Harris.

researcher's eye reads and interprets the sources, finds similarities, and performs a task it is very good at: making connections between pieces of data. The "mind map" of the researcher is "sketched out" through the EM language: it is the *fulcrum* of the reconstruction and makes it possible to organize all the sources in the 4th dimension (*y* axis of the oriented graph). The EM can lead to several reconstruction hypotheses: one model for each chronological horizon to be represented or, in the case of persisting doubts and equivalent hypotheses, a chronological horizon can spread out in different models, one for each, self-excluding, hypothesis. If the EM contains all the reconstruction information, the resulting 3D model follows a "data-driven" work-flow: changing sources and reasonings in the EM will result in new *proxy* and *representation models*.

5. Interactive visualization and interrogation foundations of EM

This section will present foundations for visualization and interrogation of Extended Matrices at runtime. One of the main goals within visual data mining is to present the whole ontological richness of the EM (relationships between SUs, chronological horizons of reconstruction hypothesis, sources behind scientific reasoning, etc.). First we will introduce a minimal set of requisites to efficiently represent and visualize an Extended Matrix, data granularity aspects and common bottlenecks typically encountered during the engineering of specific interrogation tools. We will stress the advantages of 3D visual inspection of Extended Matrices applied to interactive and collaborative workflow. We will then provide a set of best practices, developed for the design and implementation of consistent algorithms for real-time extraction and visualization within virtual environments. Such guidelines abstract from the actual 3D framework or software library adopted, except for the assumption that basic scene-graph functionalities have to be provided by the chosen framework.

5.1. Introduction and requisites

One of the main requirements for functional inspection and interrogation within the Extended Matrix Framework is a clear separation between the visible scene-graph and query-able graph (or Proxy-Graph), as proposed in previous work and researches (Tobler, 2011, Serna et al., 2012). Such approach offers great advantages and flexibility when dealing with different data granularity between the two graphs: specifically it separates the 3D graphics requirements for visible scene-graphs (multi-resolution, hierarchical culling, cascading transformations, etc.) from semantic segmentation requirements. This avoids conceptual pollution between two really different representations and domains. For instance, even if a 3D floor element can be modelled by a simple geometry (i.e: a single node) within the visible scene-graph, it may present a richer and finer Proxy-Graph for semantic interrogation (a 3D floor can have different phases and restorations). On the other hand, a complex scene-graph employed to represent a 3D element - for instance, a very detailed, multi-resolution column through hierarchical level-of-details - may map to a single proxy-node. Such requirement is even enforced if we deal with procedural scene-graphs, for instance, a columnade generated by instancing rules where just one column is query-able. Complexity is even increased when we deal with the mapping of multi-temporal virtual environments: an Extended Matrix spans across multiple time periods, thus leading to multiple scene-graphs, each per period. Consequently, another requirement is indeed to provide mechanics for visualizing and switching multiple scene-graphs representing the same context at different temporal slices. Once again, the hierarchy used for a 3D acquisition of a specific

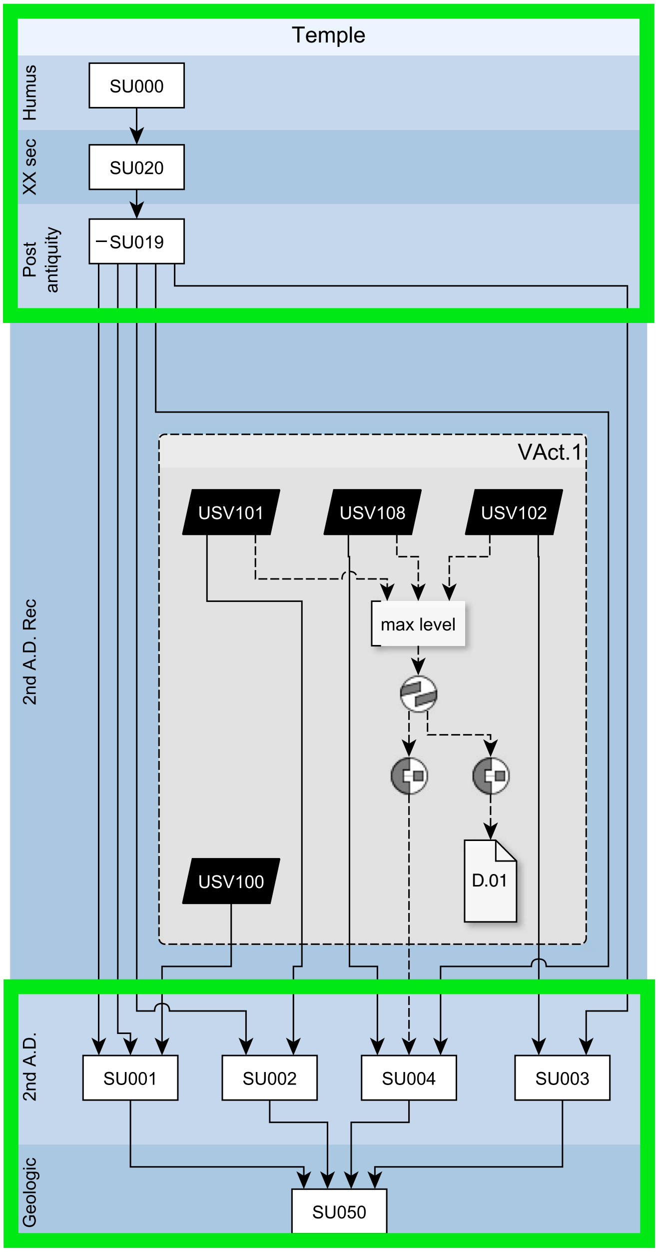

Fig. 13. Time management in the EM (1.1). Multiple phases are eventually integrated with 3D models snapshots as in the case of the 2nd A.D. horizon. The image represents an extract from the EM of the Great Temple (*see* Fig. 11). At present a reconstruction has been proposed only for the 2nd A.D. epoch.

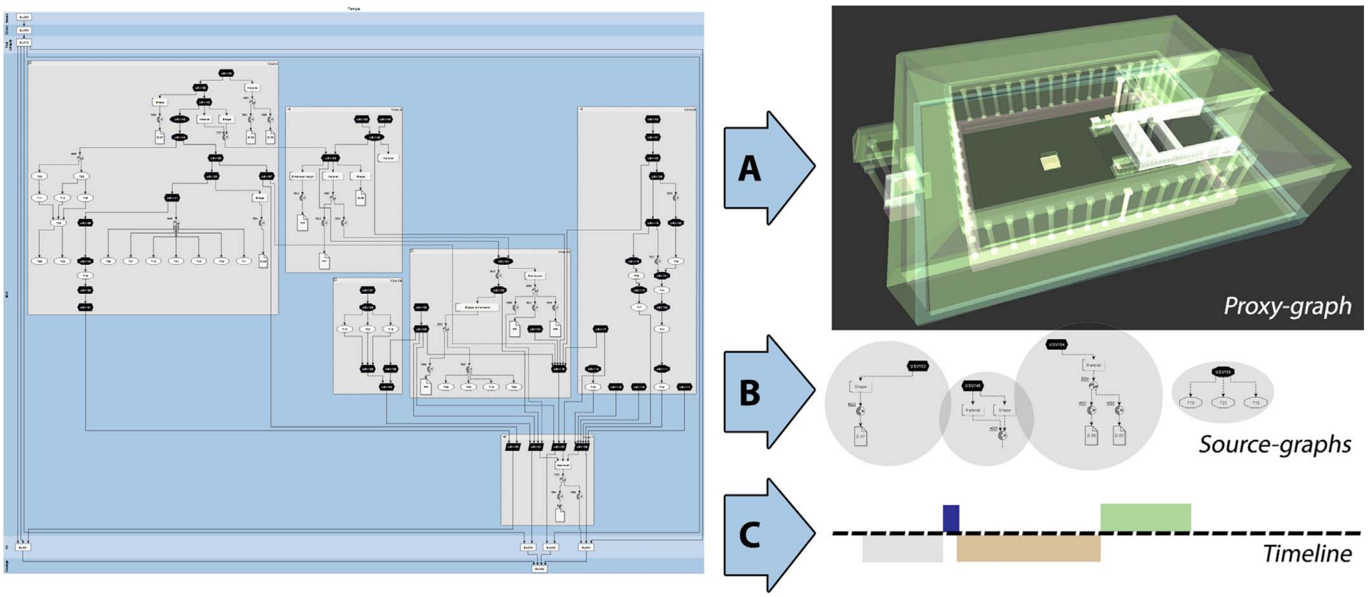

Fig. 14. An Extended Matrix (left) from which the following are automatically extracted (right, from top to bottom): Proxy-graph (A) including realized seriation-nodes for procedural column proxies, Source-graphs (B) and Timeline (C).

archaeological site may dramatically differ from the one used for the 3D reconstruction of the same site. To obtain a smooth and efficient pipeline, combined with interactive and collaborative aspects dealing with inspection, visualization and query of a single Extended Matrix, the following are generally required:

- An Extended Matrix (EM), described through means of GraphML format
- Resource folders containing 3D proxy elements, expressed by common 3D formats
- Multiple visible 3D scene-graphs, for each time-period expressed in EM
- A cloud storage (optional) for all the above data, providing a distributed workflow

The following sections will describe the blueprint and necessary concepts in order to craft correct and interactive 3D inspection tools dealing with Extended Matrices.

5.2. The EMviq tool

In order to validate described foundations in this section and provide a complete visualization and interrogation context within the framework, a 3D inspection tool "*Emviq*" was developed. The implementation focuses on extraction correctness (described in the next section), ease-of-use and performance, in order to establish a fast and robust pipeline within the EM. The interactive tool allows users to define a collection of Extended Matrices (by providing paths or URLs to GraphML files, geolocation and other attributes) and a collection of scene-graphs covering different time periods described by the main EM-timeline (see Section 5.5). Since the collaborative and iterative nature of EM pipeline, a *cloud-based* approach is employed to allow smooth EM design and consequent visual interrogation sessions, in order to validate or debug current Extended Matrix. Furthermore, the cloud enables different professionals to design and operate remotely on multiple Extended Matrices and Scene-graphs for each time-period, including reconstruction hypotheses.

5.3. Extraction and 3D translation

A single Extended Matrix (EM) can be described by a GraphML file, readily editable through existing visual tools offering flexible and iterative workflow between design and visualization phases. To inspect and query such data within a 3D interactive context, we need to perform a translation of the EM into appropriate, queryable structures, suitable for 3D interactive interrogation. First of all, the following need to be extracted or computed - more precisely - every time an Extended Matrix is modified or updated:

1. *Source-Graphs*: an internal runtime representation of EM sources relationships (paradata)
2. The *Proxy-Graph*: a graph for real-time queries and interrogation, handling 3D proxies objects well defined in 3D space
3. A *Timeline* (or EM-Timeline): a finite number of time-periods, identified by beginning and end values

Source-graph, *Proxy*-graph and *Timeline* can be extracted using any GraphML or XML parser, by taking into account the basic graph-topology (nodes and edges) defined for the GraphML format (Brandes et al., 2010). Such extraction step needs to be performed only when the involved EM is modified, more precisely, it has to be performed only on the modified EM sub-graphs. Source-graphs are the induced sub-graphs of the Extended Matrix obtained by filtering dotted edges (paradata). The Proxy-Graph instead, is generated from the EM and a given set of 3D shapes (*3D Proxies*) as proposed in Demetrescu (2015) and Serna et al. (2012), with each proxy-node identified by a unique ID. The EM-nodes that will be realized as *proxies* are: *Special Find* nodes, *SU* nodes, *structured* and *non-structured virtual SU* nodes and *Seriation* nodes. The Seriation node in particular, generates a sub-graph by procedurally instancing the referenced 3D proxy element into multiple locations, depending on transformation rules: these are provided as list of transformation matrices (translation, rotation and scale) for that specific 3D proxy element. A typical application for a Seriation node are for instance columnades, generated from a single proxy column (see Proxy-graph in Fig. 14).

For a given Extended Matrix and a starting EM-Node, Algorithm 1 recursively build a Proxy-graph **G**. A *RealizeProxyGeometry*() procedure will first realize the proxy geometry for current input EM-node **e**: this will also take care of the special Seriation-node, by procedurally instancing the proxy-geometry if a correspondent transformation-list is found. Finally it will recursively proceed with its children and return the finalized Proxy-graph.

Algorithm 1. Realize and return Proxy-Graph, starting from an Extended Matrix node e

```
procedure RealizeProxyGraph($e$)
    $G \leftarrow \emptyset$                              ▷ Initialize local graph

    $p \leftarrow RealizeProxyGeometry$(e)
    if $p$ then
        $addChild(G, p)$                          ▷ Add p to G
    end if
                              ▷ Realize recursively for all children
    for all $c \in getChildren(e)$ do
        $addChild(G,$ RealizeProxyGraph(c))
    end for

return $G$                          ▷ Return the Proxy-Graph G
end procedure
```

The realized Proxy-graph is actually the query-able 3D skeleton of an Extended Matrix, spatially plunged in a virtual environment. When coupled with a visible Scene-graph, the Proxy-graph is typically hidden and only perceivable by 3D queries, except for specific highlighting requirements. Each node in the Proxy-graph has the following attributes:

- A unique identifier, mapping a specific EM-node (e.g.: "SU010")
- The node type: Special Find, SU, structured and non-structured virtual SU or Seriation
- URL, Description and Label
- A temporal value: in the Extended Matrix this corresponds to vertical axis (y) - see Fig. 14. Through the extracted EM-Timeline, this value also maps to a specific time-span or *Time period* (e.g.: "2ndAD")
- The EM ID the proxy-node belongs to

On the other hand, each node in each Source-Graphs (paradata) has the following attributes:

- A unique identifier, mapping a specific EM-node (e.g.: "SU010")
- A set of direct Source-graph children

After the realization of Proxy-Graph and Source-Graphs, the interactive tool can access a proxy-node in the 3D virtual space through a 3D query: through the unique ID we have direct access to its Source-graph, its type, its time period, labelling information and of course which Extended Matrix we are interrogating.

5.4. *Interactive 3D interrogation*

An interactive interrogation is spatially performed on a Proxy-Graph or even several Proxy-Graphs, when we deal with multiple Extended Matrices. This task is carried out by the interactive tool by fast intersection routines (the 3D querier) - typically offered by all modern 3D frameworks and libraries - to retrieve all needed information previously described. Since the simplified nature of proxy-geometries in fact, such routines are performed quickly against basic 3D shapes. More importantly, they totally abstract from the complexity of the visible Scene-graph, potentially presenting very complex geometries. The 3D query is performed from a specific position in virtual space (typically the user camera, but not limited to) with a given direction (typically camera target or a custom one).

An issue that may occur when rich or complex Proxy-graphs are defined, is query occlusion. This basically causes some proxy geometry to occlude each other (for instance, when multiple SU-proxies are stacked) thus making some queries partially or fully inaccessible at runtime. This can be solved by providing *query peeling*: this mechanism makes it possible to temporarily *"peel off"* or *carve* proxies with a given policy, to reach otherwise inaccessible ones. The policy is typically based on camera position and an interactive radius (spherical peeling - see Fig. 15), although other approaches can be employed, depending on specific user or application needs (e.g.: camera-independent peeling).

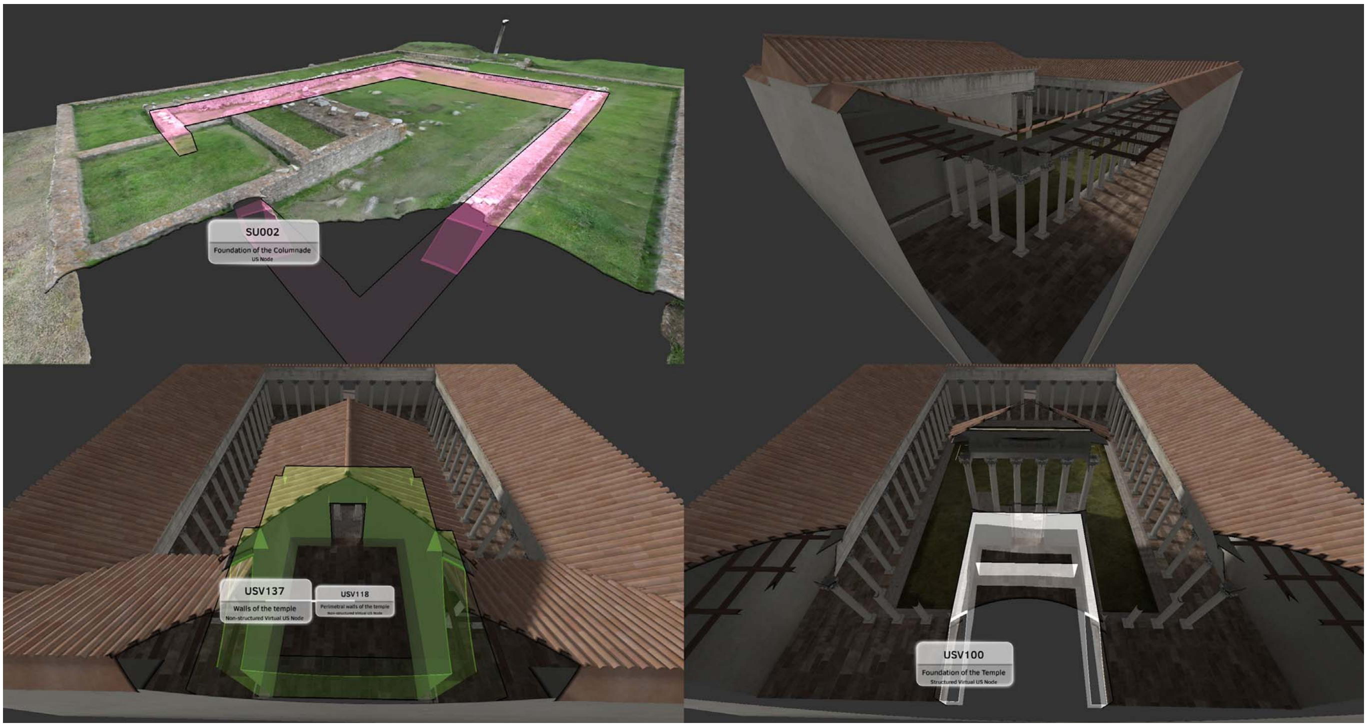

Fig. 15. An example of interactive spherical 3D peeling that makes it possible to perform 3D queries on occluded or partially occluded proxies. User-controlled radius provides visual interrogation on nested proxies.

The query peeling is often coupled with a corresponding 3D cut applied to the visible Scene-graph, to offer a clear visual feedback.

5.5. Handling temporal dimension

We already introduced the *Timeline*, extracted from an EM (see Section 5.3) and requirements to handle multi-dimensional virtual environments: the latter is realized by means of multiple Scene-graphs, each covering a time-period (e.g.: “2ndAD” will map a specific visible Scene-graph) all representing the same context. This section will define management of temporal warping and visualization of multiple time-periods. For a given Extended Matrix and its Timeline, we define a direct mapping from a generic EM-node **e** to a time-period $\boldsymbol{\tau}$:

$$T(e) \rightarrow \tau$$

where $\boldsymbol{\tau}$ is a unique identifier (e.g.: “XX century”) that allows us to identify a Scene-graph for a given EM-node. A selector S can be deployed at runtime to activate on-demand temporal-warp (switch) of the visible Scene-graph **s** depending on input period $\boldsymbol{\tau}$:

$$S(\tau) \rightarrow s$$

Within an interactive inspection, such selector can be easily attached to a proxy-node and triggered by specific event (e.g.: some user input), thus elevating such nodes to *temporal hyperlinks* in a 3D virtual environment (see Fig. 16). Generally, the number of Scene-graphs matches the number of time-periods, although different time-periods ($\boldsymbol{\tau}$, τ', τ'', ...) may refer to the same Scene-graph or a part of it. Especially in the latter case, the hierarchical approach offers huge flexibility in terms of scene design. It is quite common in fact, that a single Scene-graph **s** may contain a sub-graph that is shared with another time-period (thus a scene portion re-used by another graph **s′**). This kind of cross-temporal organization, allows elegant and compact scene design (see Fig. 17).

It is important to highlight the abstraction from number or complexity of visible scene-graphs (**s**,*s′*,...) and duration of time periods: a given $\boldsymbol{\tau}$ can in fact represent an entire era, a single year, one day or even a few minutes. Such level of abstraction well suits Extended Matrix requirements and multi-temporal visualization needs. During interactive fruition in fact, proxy-graph itself is exploited as temporal *medium* and *interface* to explore current context at different periods.

5.6. Presentation of Source-Graphs

During interactive interrogation of a Proxy-graph, it is often required to visually present data relationship associated with a specific proxy-node. As previously introduced, such information can be retrieved from Source-graphs, although different solutions can be employed to *present* and *explore* such semantic data through clear layouts in a 3D space. Previous research has already dealt with appealing representation and visualization of hierarchies and linked data, especially in 2D contexts (Book and Keshary, 2001 Pavlo et al., 2006 Mazumdar et al., 2015). Within interactive visualization and query of extended matrices, parent-centered layouts are typically the most appropriate solution, although the third dimension play an important role into the layout algorithm, especially when the interactive query is performed through immersive visualization systems (Head-mounted Displays, CAVE systems, etc.).

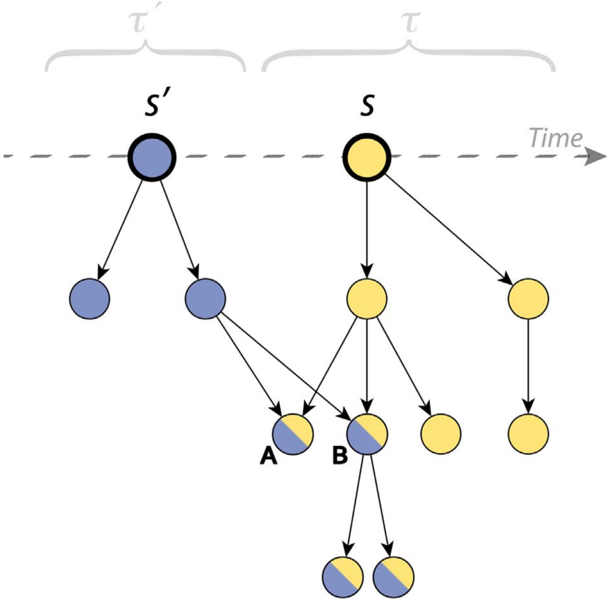

Fig. 17. A sample visible scene-graph s (right) shares sub-graphs A and B with another scene-graph s' (left): A and B consequently span across two different time periods τ and τ' (respectively $S(\tau) \rightarrow s$ and $S(\tau') \rightarrow s'$) through cross-temporal instancing.

Within extended matrices, the main guideline for visual presentation of Source-graphs is to create a set of 3D *radial-graphs* - for each proxy-node - encapsulating *proxy-centered* source-graphs and connected information, shown upon user interrogation. The main goal is to produce a consistent but non-intrusive 3D layout (see Fig. 18), exploiting and taking advantage of third dimension within standard or immersive VR sessions, thus aiding and enhancing interrogation of complex datasets.

6. Change-log for the EM 1.1 - EMF 1.1

The version 1.1 of the Extended Matrix adds a few tools and

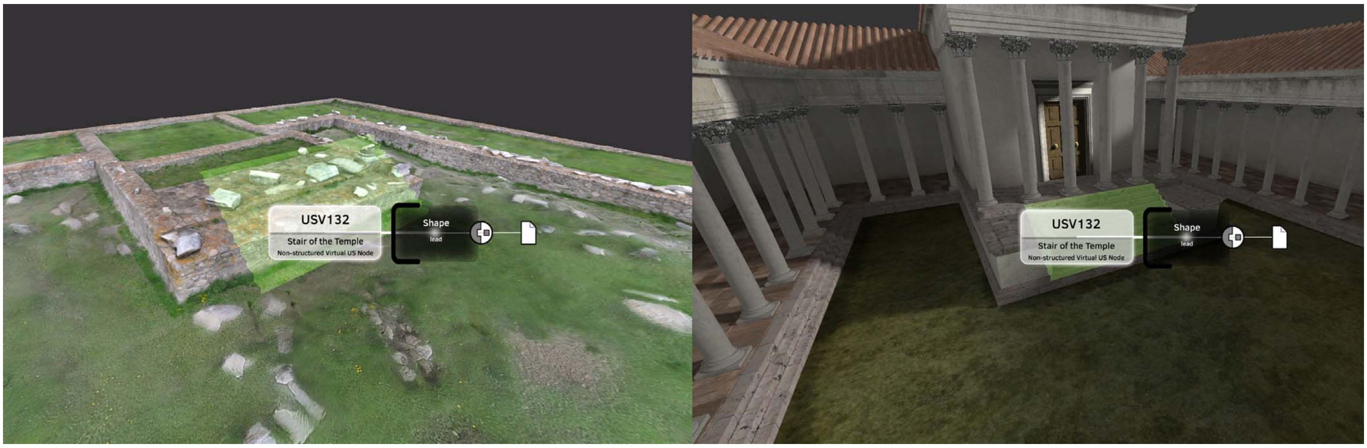

Fig. 16. A proxy-node (USV132) exploited as temporal hyperlink from current period (today) back to its connected time period (2nd A.D.) and its reconstruction hypothesis.

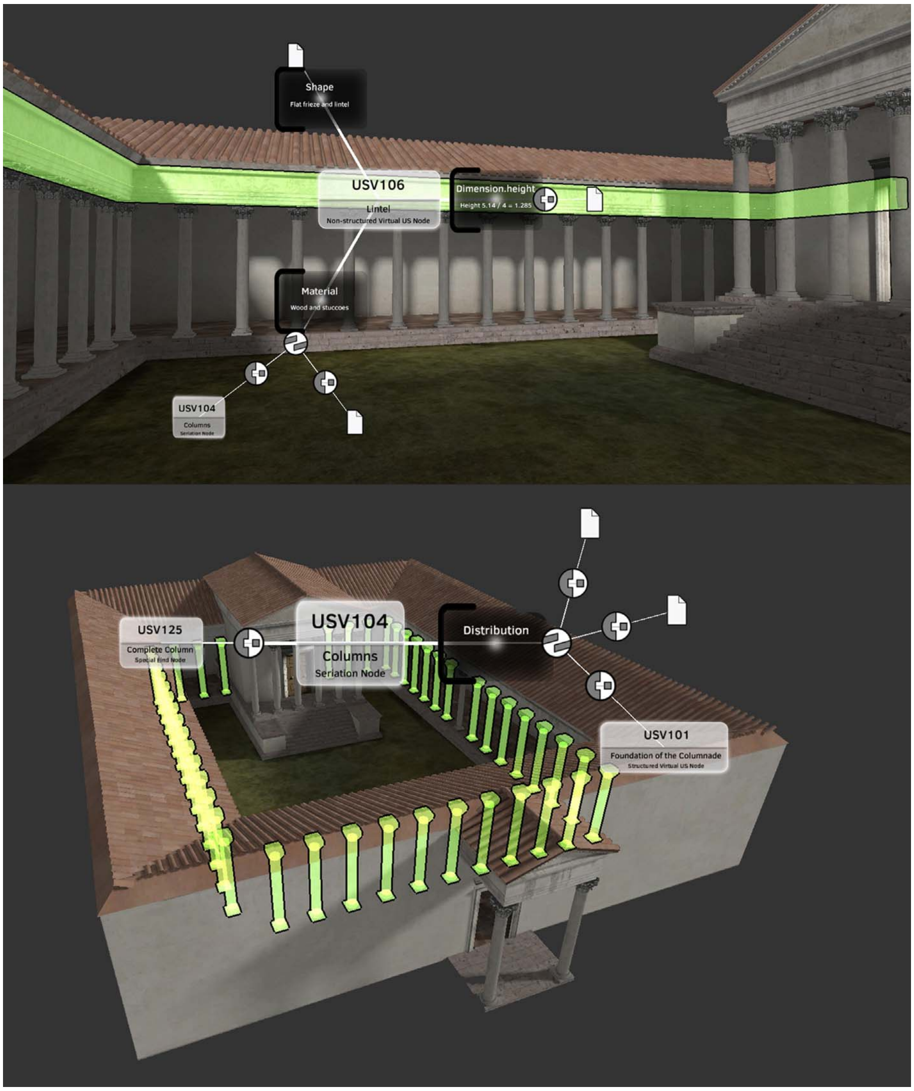

Fig. 18. An example of parent-centered 3D layout to present Source-graphs upon interactive interrogation. Each node 3D position is computed depending on graph hierarchy, user position, distance, node content and spatial extents.

conventions for the integration with a 3D representation.

EM 1.1 version:

- *Proxies* and *representation models*: they allow coherent visualizations of a reconstruction hypothesis in the 3D space (for details *see* examples in Section 4.3).
- *Snapshots*: a snapshot is a survey of a model collected in a precise moment in time (i.e. the photogrammetric survey of the Great Temple in 2014). The snapshots are palimpsest of a context. In order to isolate the elements pertaining to a given epoch they have to be geometrically segmented and cleaned by posthumous portions.
- *Graphical and textual documentation for scientific publication* of a reconstruction hypothesis (EM): EM with subdivision in virtual activities, Report of Virtual Activities, Dossier comparatif, lists of EM nodes grouped according to the virtual activities, sections and plans of the proxy model (per-epoch).
- *New conventions in node connection* (archs) to simplify and made clearer the visual representation of the EM have specific documentation (whitepapers, on-line wiki, etc.).

EMF 1.1 version:

- *Emviq*: it connects the 3D models (reconstructive and snapshots) with the reconstruction hypothesis (EM). It can be used as a convenient test for the formal correctness of the EM (*see* Section 5).

7. Conclusions

This contribution adds full support to 3D representation (*see* Sections 4 and 4.3) of the Extended Matrix (ver. 1.1). A real case scenario (the Great Temple of the ancient Roman town Colonia Dacica Sarmizegetusa) is used in order to make clear the introduced notions and validate the adopted formal solutions.

Within the Extended Matrix Framework (EMF), an interactive tool (*"Emviq"*) was designed and developed to *validate* visual foundations described in Section 5. Resulting blueprints include: algorithms and formalisms for *automatic generation* of 3D Proxy-graphs starting from EM descriptions, design of cross-temporal scene-graph, techniques for expert inspection, interactive 3D query and scalable visualization of graph data in multi-temporal virtual contexts. Important outcomes of the research include:

- An *iterative workflow* within the EM that involves data collection, visual validation and debug of EM description, simplification of data sharing between researchers with different background;
- *Blueprints for robust 3D interactive inspection and query* of Extended Matrices, applied to the development of visual tools that focus on 3D presentation (including immersive fruition) of complex information and adoption of cloud-based approaches for automatic data aggregation and runtime 3D validation;
- A *data driven approach* from reconstructive record (EM) to 3D

depiction that encourages quick information exchange and interactive workflow on dynamic 3D scenes;

While EM stimulated the development of different tools and technical solutions, on the other hand, it does not focus on the technologies employed. It offers specialized semantics for description of multidimensional elements within a visual approach: (A) a set of nodes and relationships to describe the reconstruction process using a schema-less approach and (B) blueprints for interactive 3D query and exploration of multidimensional graph databases including spatial inspection, complete data retrieval and coherent navigation of temporal dimension. EM does not focus on the description of the digital asset but aims to a detailed documentation of a “potential context” perceived as if it were still existing in front of the specialist in charge of the reconstruction. In this way the digital instance is just one of the properties of the reconstructed context along with the other properties declared in the EM database.

7.1. Future works

The development of the EM and its related EMF will result in new versions (1.2, 1.3, etc.) with the addition of both methodological and technical improvements. The next steps will be:

- **EM.** Support for different, self excluding reconstruction hypotheses (as a 5th dimension for the EM). In some cases there are more than one possible reconstructive solution that have to be stored and organized accordingly in the EM.
- **EM.** A classification of standard scenarios where EM can be employed is work in progress. It could clarify the limits of applicability in certain typologies of context.
- **EMF.** Use of server side graph database solutions (like, as an example, Neo4j): they are a fast-growing trend that enables smart data aggregation and mining on complex and large scale scenarios.
- **EMF.** Another future step, already in progress, involve porting of *Emviq* to WebGL, on top of multiple scene-graph based javascript libraries. Such process will enable on-line 3D fruition of Extended Matrices on all major browsers without installing any additional plug-in or software.

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