EM-BIM: VPL interoperable processes for paradata management in archaeological virtual reconstructions using Extended Matrix (EM) and bSDD as knowledge representation

EM-BIM: VPL interoperable processes for paradata management in archaeological virtual reconstructions using Extended Matrix (EM) and bSDD as knowledge representation systems

Anna Sanseverino [1], Elisabetta Caterina Giovannini [2]

[1] Dept. of Architecture, University of Naples Federico II, Naples, Italy – anna.sanseverino@unina.it
[2] Dept. of Architecture and Design, Politecnico di Torino, Valentino Castle, Turin, Italy – elisabettacaterina.giovannini@polito

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Abstract

The paper presents a two-phase methodological protocol for creating an Extended Matrix (EM) based BIM model (EM-BIM). The EM, developed by the ISPC-CNR institute, was designed to manage data, metadata, and paradata related to virtual reconstructions in archaeology. This research introduces a methodology for geometric and informational modelling, based on an HBIM approach, of existing architectural heritage using EM tools within Historical Building Information Modelling (HBIM) approach. Knowledge-based structure of EM is similar to object-based system of BIM: both methodologies are grounded in a relational approach to 3D data structuring. Furthermore, EM explicitly incorporates paradata using a visual knowledge graph system. Tested on the Doric Stoa of Priene, the first phase of the study focused on decoding the graphic language of EM to automatically generate and populate ad hoc descriptors within the HBIM environment using a visual programming language (VPL). A second phase involved the setting up of a BuildingSMART Data Dictionary (bsDD) to map the EM classification against the IFC classes, to standardise the generation of dedicated ‘property sets’.

1. Introduction

In recent years, virtual reconstruction has become a central practice in archaeological and architectural heritage research, supported by the increasing adoption of Historic Building Information Modelling (HBIM). HBIM extends BIM principles to existing and stratified contexts, enabling the parametric modelling of complex geometries while associating geometric elements with historical, material, and chronological information. Within the archaeological domain, ArchaeoBIM approaches have further adapted HBIM to excavation-based contexts, focusing on stratigraphic units, phases, and interpretative modelling, although often prioritising architectural plausibility and data organisation over explicit representation of interpretative processes. In parallel, the Extended Matrix (EM) methodology has been developed as a graph-based knowledge representation system aimed at modelling data provenance, interpretative reasoning, and paradata in archaeological reconstruction. While EM and HBIM-based approaches share the goal of producing information-rich virtual models, they differ in epistemological focus, data structures, and operational workflows.

Current research presents a methodological protocol for creating an Extended Matrix (EM) based BIM model (EM-BIM) to bridge geometric modelling, archaeological reasoning, and transparency of interpretation.

1.1 EM as a knowledge graph system for archaeology

The Extended Matrix (EM) is a methodological and conceptual framework developed to manage the complexity of data, metadata, and paradata generated in the process of digitally documenting and reconstructing cultural heritage assets related to archaeological field (Prodomo & Lanzara, 2024). Created within the ISPC-CNR Institute, the EM builds upon traditional archaeological recording systems, such as the Harris Matrix, expanding their capacity to encompass a far richer semantic domain. Instead of focusing solely on the stratigraphic relationships between archaeological units, EM structures a wide range of heterogeneous information sources, including textual descriptions, archival images, measured surveys, excavation notes, and interpretative hypotheses, into a coherent, interconnected knowledge graph (Demetrescu, 2015). This graph-based structure supports not only the storage of explicit documentation but also the representation of interpretative processes and reasoning chains, enabling the preservation and visualisation of the provenance of each decision in a virtual reconstruction. The emphasis on paradata, data about the process of interpretation, marks a fundamental difference from many other 3D modelling approaches in cultural heritage, where the reasoning behind reconstructed features often remains implicit or is lost after the modelling stage (Mancuso, 2023).

By capturing these interpretative steps, EM ensures that reconstructions remain transparent, traceable, and open to future scholarly revision. Furthermore, EM’s architecture supports interoperability with multiple platforms, enabling information exchange between modelling software, archival databases, and semantic web technologies. This makes it a cornerstone for integrating digital archaeology into broader cultural heritage information ecosystems, where the same asset may be referenced in museum catalogues, excavation archives, and international Linked Open Data (LOD) repositories. This facilitates interoperability not only within the archaeological domain but across cultural heritage sectors, from conservation science to architectural history.

Unfortunately, EM framework works within a specific set of tools (EM tools) that are compliant with open environments (eg. Blender) but with a vertical interoperability with BIM.

In this research we develop a tool with the aim to address horizontal interoperability between EM and BIM tools using standards such as Industry Foundation Classes (IFC) and CIDOC-CRM to manage archaeological reconstructions data towards and integrated and interdisciplinary approach.

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	EM-BIM Sanseverino & Giovannini, 2026	**EM–ArchaeoBIM** Mancuso, 2023	**Extended BIM** Galeano et al., 2023	**EM–HBIM** **Prodomo & Lanzara, 2024**
Purpose of the approach	Integrate EM reasoning and HBIM information modelling within a single, coherent workflow.	Analyse similarities and differences between EM and ArchaeoBIM.	Enable interoperability between EM and HBIM through data exchange.	Support multilevel virtual reconstruction using EM, HBIM, VPL, and GIS.
Extended Matrix usage	Used as the central structure for data provenance, interpretation, and reconstruction logic.	Used to describe logical–deductive and source-based reasoning.	Used as an external semantic structure linked to HBIM outputs.	Used to organise stratigraphic and interpretative relationships across scales.
HBIM role	Primary modelling environment, semantically aligned with EM concepts and paradata.	Evaluated as a parametric system for architectural validation.	Main environment for geometric and parametric modelling.	One of several modelling environments in a broader framework.
VPL role	Core integration mechanism enabling bidirectional management of geometry and information.	Not explicitly addressed; focus is methodological.	Used to automate import/export operations between software.	Used for parametric modelling and coordination across platforms.
Interoperability level	Explicit semantic, methodological, and technical interoperability.	Conceptual and methodological comparison only.	Mainly technical interoperability.	Mainly methodological interoperability.
Paradata management	Explicit, structured, and traceable within and across platforms.	Discussed as a key analytical criterion.	Linked to models but often external to HBIM.	Managed at different levels with variable formalisation.
Workflow structure	Integrated and bidirectional, designed for reuse and scalability.	Analytical and comparative workflow.	Sequential workflow based on intermediate formats.	Exploratory workflow adapted to complex archaeological contexts.
Scope of application	Designed as a transferable framework applicable to different case studies.	Focused on theoretical and methodological assessment.	Applied to specific case studies.	Applied to complex, multiscale archaeological contexts.
Main limitation	Higher complexity due to full semantic and technical integration.	No operative integration workflow.	Possible data loss due to intermediate formats.	Limited standardisation and reproducibility.

Table 1. Comparison between the hereby proposed and the literature EM-BIM approaches (E.C. Giovannini)

1.2 An interoperable and interdisciplinary approach

The methodological direction proposed by this paper aligns with a broader research trend that seeks to bridge EM with Historic Building Information Modelling (HBIM).

All previous developed activities (Diara, 2022; Giovannini & Sanseverino, 2024; Prodomo & Lanzara, 2024) share the goal of transforming virtual models into information-rich containers of data, metadata, and paradata, yet differ in their approach.

EM prioritises logical-deductive traceability and explicit source referencing, while HBIM focuses on parametric definition and standardised component families to validate architectural plausibility and ensure interoperability via formats such as IFC.

While Galeano et al. (2023) have demonstrated the potential of using Visual Programming Languages (VPL), such as Dynamo, to connect HBIM environments (e.g., Autodesk Revit) with EM workflows in Blender (a free and open-source 3D software). This approach preserves the semantic structure of EM while leveraging the parametric capabilities of HBIM. Unfortunately, this approach is mediated by the import/export of a .xls file format combined with .obj 3D model that are then visualised inside blender.

The EM-BIM approach proposes a direct connection between the graphically mapped archaeological data and the HBIM environment, avoiding multiple pieces of software, which has been further formalised by developing a dedicated BuildingSMART Data Dictionary (bSDD). A bsDD is an online service that provides a standardised library of construction terms, concepts, and properties to improve communication and interoperability in the building industry and architectural heritage, such as MIDAS (Argasiński & Tomczak, 2025). The EM Data Dictionary (EM bSDD) is used to manage EM classification inside HBIM model, while the VPL-based set of algorithms decodes the EM knowledge graph system (developed by using EM palette in yED) and integrates them into HBIM, enabling an interoperable model that enhances transparency, reproducibility, and information traceability in archaeological virtual reconstruction projects. This approach enables the definition of a three-level interoperability framework:

1. Semantic: EM via bSDD ↔ IFC
2. Methodological: EM ↔ HBIM knowledge structure
3. Technical: EM ↔ HBIM via VPL and bSDD.

Table 1 presents a comparison of recent approaches that integrate EM, HBIM, and VPL, highlighting how the proposed workflow (EM-BIM) represents a methodological advancement by formalising semantic, methodological, and technical interoperability within a single, coherent framework.

2. The HBIM model of the Doric Stoa of Priene

The chosen subject of study comprises a portion of the ancient city of Priene. The city is situated on four terraces on the slopes of Mount Mycale in Anatolia and was rebuilt in the mid-4th century according to the urban planning principles of Hippodamus of Miletus. The city was abandoned in the 12th century BC, even though it was an important centre of a bishopric. The city is cut by orthogonal streets, all paved in breccia, with water pipes. Numerous excavations conducted in recent centuries also uncovered traces of the acropolis and agora, several shrines, a theatre, a stadium, and several private houses.

The city's plan consisted of rectangular blocks of strictly identical dimensions. A Doric Stoa was constructed in Priene during the second half of the 2nd century, near the Athena Polias sanctuary. The colonnade of the Doric Stoa turned its back on the Athena Polias temple rather than facing it as expected. The stoa faced south on a narrow, empty terrace, apparently serving as a promenade and a giant balcony that offered a panoramic view of the city and the Maeander River plain (Figs. 1-2).

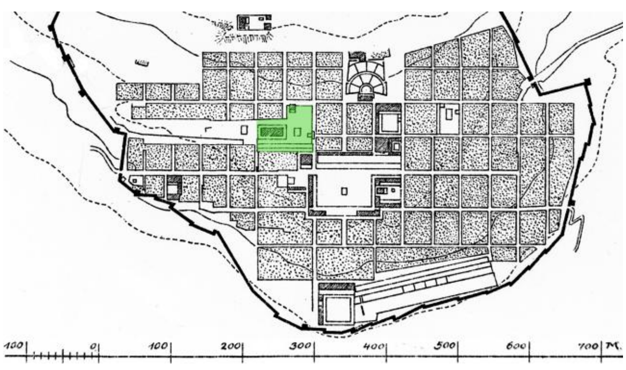

Figure 1. Annotated Plan of Priene in Griechische Stadeanlagen.

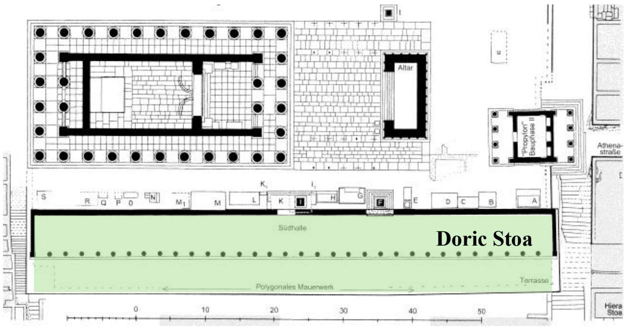

Figure 2. Plan of the Temple and Stoa of Priene from Hennemeyer (2013, Tafel 158).

The HBIM modelling phase comprises, for both geometric and informative modelling, the use of a visual programming language (VPL) approach. Starting from the digital acquisition of the archaeological area, after a cleaning phase, the point cloud was converted into a mesh model thanks to reverse modelling algorithms. The VPL modelling approach differs from numerical modelling and implies a simplified approach within the HBIM software environment.
To manage the obtained mesh, a VPL script was developed with Grasshopper (GH) within the McNeel Rhinoceros environment. The output was then imported via VPL algorithms into the BIM authoring software using Dynamo for Revit (Figs. 3-6).

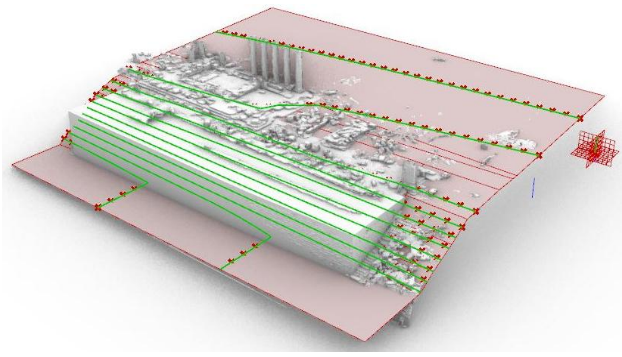

Figure 3. VPL approach for HBIM modelling of the terrain (E.C. Giovannini).

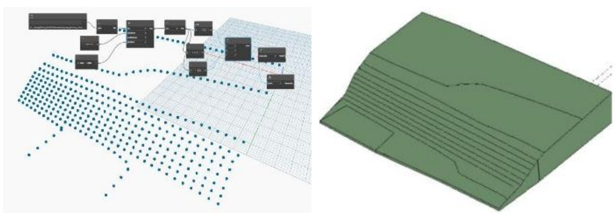

Figure 4. HBIM imported terrain using VPL (E.C. Giovannini).

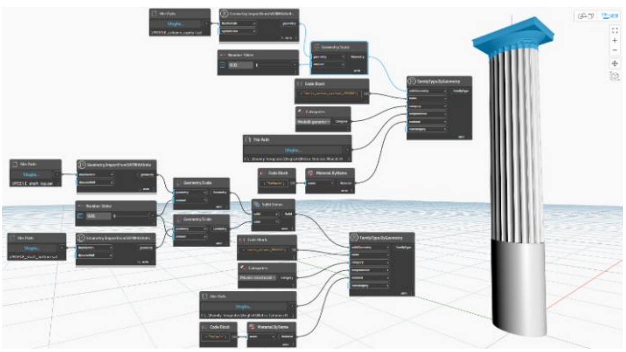

Figure 5. Algorithmic modelling (AIM) within the Dynamo for Revit environment (E.C. Giovannini)

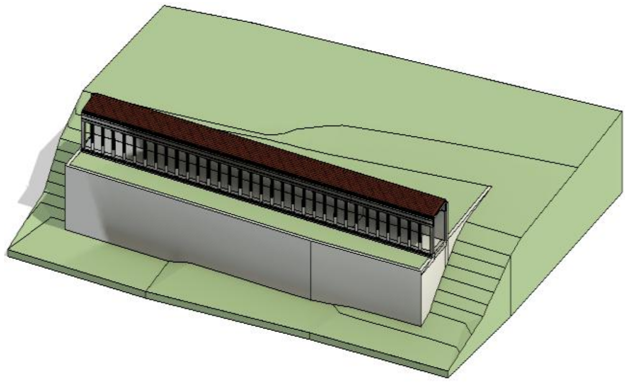

Figure 6. HBIM model of the Doric Stoa (E.C. Giovannini).

3. An integrated EM-BIM virtual reconstruction approach using Visual Programming Language (VPL) and GraphML

The Extended Matrix (EM) methodology has already been applied to the Doric Stoa of Priene in previous research (Giovannini et al., 2024), producing a detailed knowledge graph that integrates geometric, semantic, and interpretative data related to its virtual reconstruction. In that implementation, EM was employed to structure the paradata associated with archaeological hypotheses, the reconstruction of missing architectural elements, and the correlation of digital models with primary documentation sources.
The resulting graph was reused by this research as a starting point to link the 3D model created in the HBIM environment to excavation records, architectural surveys, and interpretative annotations. The original EM graph schema for the Doric Stoa remained largely unidirectional, with the geometric model and the knowledge graph only loosely coupled. This due to the use of yEd software (Fig. 7) that allows to create a knowledge graph system interoperable within EM framework (2024).

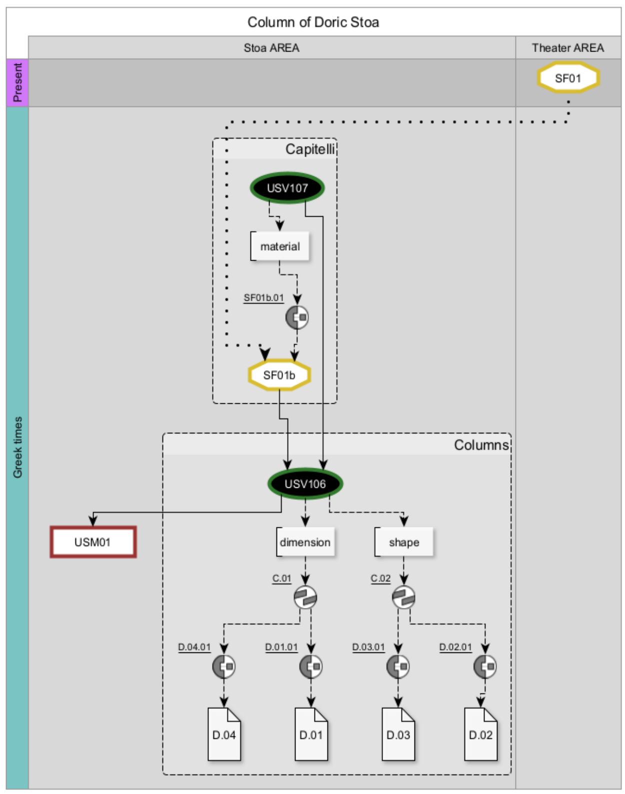

Figure 7. EM knowledge graph (E.C. Giovannini).

The integration of paradata into HBIM authoring tools was limited, and the bidirectional flow of information between modelling platforms was not fully automated. The EM-BIM extension proposed in this work directly addresses these limitations. First, by embedding the EM knowledge graph into the HBIM environment via a VPL Script (Figs. 8 and 9), available via the Zenodo database (Sanseverino & Giovannini, 2025), that allows to simulate, customise, and initiate the nodes of the EM graph within the BIM authoring tool.
Namely, the nodes used in the EM graph, with the only exception of the "EPOCH", whose values have been mapped via the native "PHASES", are automatically generated as "shared parameters" to subsequently be populated using the retrieved datasets, as shown in the properties tab of the Doric Column (Fig.10).
Moreover, it was necessary to design a few additional Python Nodes within the Dynamo environment, six of which employs the xml.etree.ElementTree python library to parse and retrieve EM information directly from the .graphml file.
The code can identify the data associated with each EM nodes drawn using the EM palette in yED.
The developed parameters follow this encoding:

- EM_NODE_NAME,
- EM_PLACE,
- EM_DESCRIPTION,
- EM_GROUP,
- EM_NODE_CONNECTED_Sources,
- EM_NODE_CONNECTED_Targets,
- EM_PROPERTY_Shape,
- EM_PROPERTY_Dimension,
- EM_PROPERTY_Material.

The "EM_NODE_NAME" is the only one generated prior to the algorithmic implementation for data import. Specifically, it is compiled manually, using the ID of SU, USV, SF, and so on, as assigned within the Archaeological Matrix, to serve as a reference key for the subsequent automatic population of HBIM descriptors corresponding to EM data.
In addition to the "EPOCH", the location (e.g., Stoa and Theatre Area) is stored in the "EM_PLACE" parameter.
The specific "descriptions" (e.g., USV Series) and "groups" (e.g., Columns and Capitals) associated with the SU, USV, SF, and so on, are recorded in the "EM_DESCRIPTION" and "EM_GROUP" parameters, respectively.
Then the "Extractor" and "Combiner" nodes, together with the other input/output related EM nodes, are listed within "EM_NODE_CONNECTED_Source/Targets".
Finally, eventual "dimensional/material/shape properties" became "EM_PROPERTY_Dimension/Material/Shape".
Leveraging attributes mapped via native or shared parameters, it is then possible to configure "schedules" consisting of descriptors populated with values from selected dictionary classes, thereby consistently enriching the HBIM model also upon IFC export (Sanseverino, 2024, pp. 204-211).

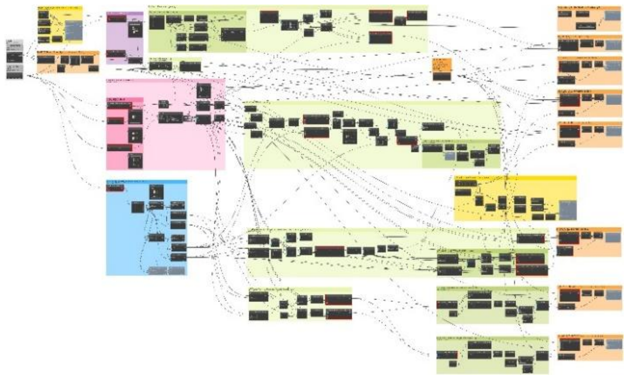

Figure 8. VPL Script developed to map EM data directly within the BIM environment (A. Sanseverino)

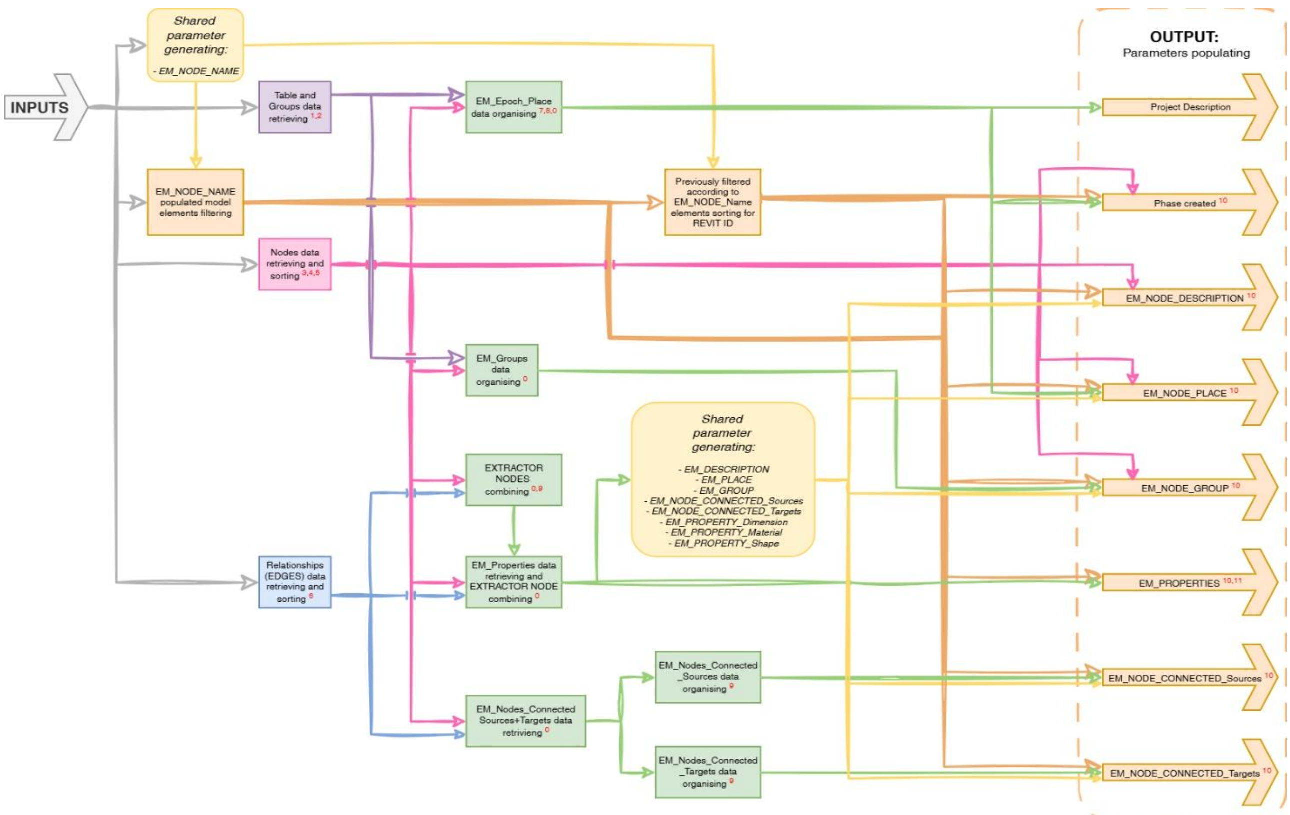

Figure 9. Diagram breaking down the VPL Script developed to map EM data directly within the BIM environment (A. Sanseverino)

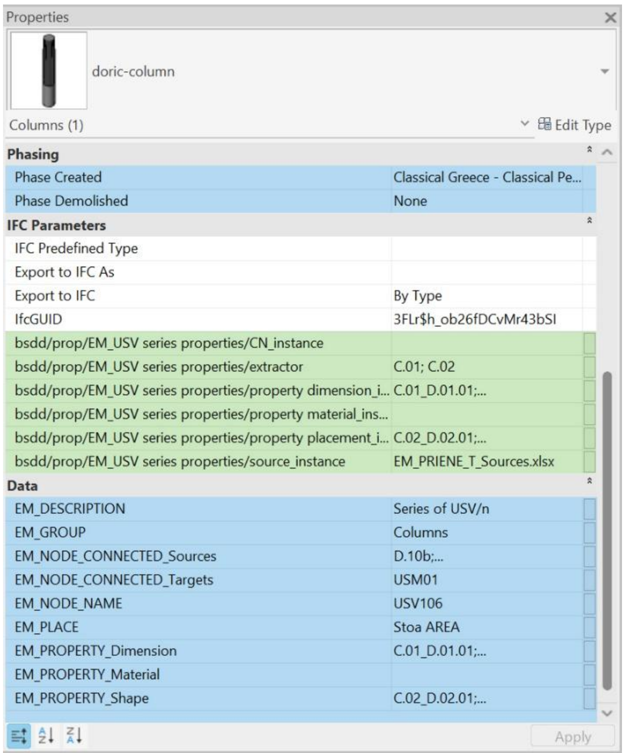

Figure 10. EM-BIM VPL-generated (blue) and EM bsDD-implemented (green) "instance parameters" of the Doric column of the Stoa in Priene (A. Sanseverino)

The Doric Stoa of Priene thus becomes a benchmark testbed for validating EM-BIM as a method capable of enhancing data interoperability, improving traceability of interpretative decisions, and increasing the transparency of archaeological virtual reconstructions

4. The EM bSDD as a semantic overlay for the Extended Matrix within HBIM framework

In the cultural heritage and HBIM domains, the use of bSDD has so far been primarily focused on classifying historical building components, materials, and construction techniques. Existing heritage-oriented dictionaries concentrate on the typological and material aspects of built assets, supporting interoperability with IFC-based workflows and facilitating data exchange across platforms and institutions.
In recent years, bSDD has been developed and used to document the preservation state of architectural heritage in open-HBIM systems (Scandurra & Di Luggo, 2023). Other approaches are focused on preservation and conservation planning (Parente et al., 2025; Argasiński & Tomczak, 2024; Scandurra et al., 2024) and exploring new strategies for data exchange, integration and asset management (Kuroczyński & Argasiński, 2025).
However, these implementations typically address tangible objects and physical attributes, while neglecting the representation of interpretative processes, hypotheses, and paradata central to archaeological virtual reconstructions.
The workflow presented so far is primarily graph-driven, relying on the Extended Matrix (EM) as a visual and logical knowledge representation system for managing data, metadata, and paradata related to archaeological virtual reconstructions. In this framework, the EM knowledge graph served as the starting point, from which semantic information is extracted and transferred to the HBIM environment via VPL scripts, as shown in the previous paragraph.
Although this approach has proven effective in preserving interpretative traceability and semantic richness, it remains heavily dependent on procedural logic and custom scripting, limiting its reproducibility and long-term standardisation.
To address these limitations, this research proposes a novel approach, introducing a bSDD-based methodology as a complementary, higher-level semantic layer for the EM-BIM integration.
The bSDD is conceived not merely as a classification system for architectural elements but as a formalised semantic infrastructure that governs the definition, organisation, and reuse of EM-related parameters within HBIM environments.
The adoption of a bSDD represents a paradigm shift from a graph-centric to a dictionary-centric workflow. In this configuration, the EM graph is no longer the sole semantic authority but is aligned with a structured dictionary that explicitly defines classes, properties, and relationships.
The bSDD thus serves as a stable semantic reference that mediates between EM, HBIM, and IFC, ensuring that parameters instantiated within the BIM environment are not only syntactically consistent but also semantically standardised and machine-readable.
As a result, a semantic gap persists between heritage-oriented knowledge graph systems, such as the Extended Matrix or CIDOC-CRM ontology, and bSDD-based BIM workflows.
To date, no consolidated approach has been proposed for using the bSDD as a bridge between graph-based archaeological knowledge representation and parametric HBIM environments, particularly regarding the management of paradata and interpretative transparency.

4.1 From a graph-centric to a dictionary-centric workflow

Within this framework, EM nodes are mapped to bSDD classes, and EM properties are translated into property sets associated with those classes. Relationships between nodes, already formalised in the EM graph and aligned with CIDOC CRM, are preserved and expressed as semantic associations within the dictionary structure. The .xlsx template designed to effectively implement the EM bsDD has been made available via the Zenodo repository (Sanseverino & Giovannini, 2026), while the working .json version, suitable for testing and validation, can be downloaded from the BuildingSMART Data Dictionary online repository (Fig. 11).
This dual representation allows the EM graph to retain its role as a reasoning and provenance-tracking tool, while the bSDD provides a standardised, reusable semantic definition of its components.
From an operational perspective, the bSDD-based approach shifts the role of VPL scripts from parsing and interpreting graph structures to instantiating dictionary-defined classes and properties. Then either existing plug-in or Dynamo scripts can access the JSON-based EM bSDD to automatically generate "shared parameters" and "property sets" that are semantically anchored to predefined dictionary entries, rather than being procedurally defined on a case-by-case basis.
This ensures that parameters associated with EM nodes, such as identification, description, spatial attribution, material hypotheses, dimensional uncertainty, and source relationships, are consistently implemented across different projects and software environments. Moreover, by relying on a dictionary-based structure, the workflow becomes less dependent on specific graph configurations, facilitating scalability and reuse in other archaeological and architectural heritage contexts.

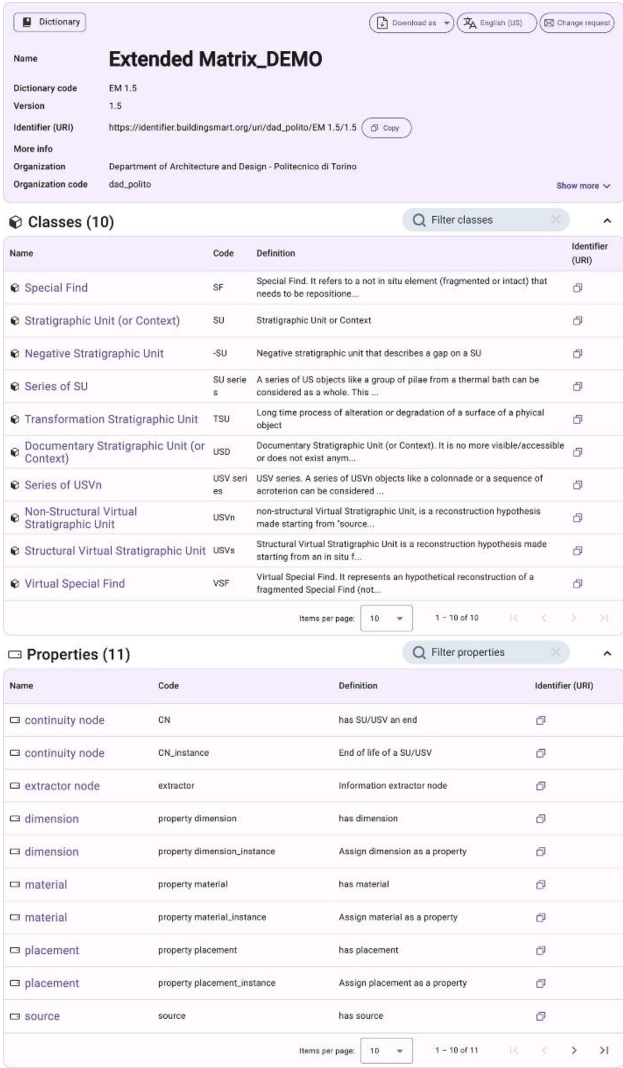

Figure 11. Extended Matrix bSDD Dictionary: classes and properties. (E.C. Giovannini & A. Sanseverino)

This ensures that parameters associated with EM nodes, such as identification, description, spatial attribution, material hypotheses, dimensional uncertainty, and source relationships, are consistently implemented across different projects and software environments. Moreover, by relying on a dictionary-based structure, the workflow becomes less dependent on specific graph configurations, facilitating scalability and reuse in other archaeological and architectural heritage contexts.

The embedding of the EM bsDD within the BIM authoring tool consists of associating the EM classification with the modelled objects, while it also enables remapping of the IFC classes with respect to those originally defined for a specific "category", if necessary.

To date the buildingSMART community has developed a plug-in for Autodesk Revit (versions 2023 and 2024) that allows to manage and use available bSDD already published in the online platform. Furthermore, the EM properties related to the classes (e.g., dimension, material, placement, source, extractor/continuity nodes) can either be added as "type properties", which are also directly writable upon first implementation, or "instance properties" (Figs. 12 and 13).

Namely, this phase generates standardised paradata ready to be exported as specific "property sets" for the IFC model, while the VPL workflow can only work with native "parameter groups" (e.g., "Data" in Fig. 10).

This means that combining these two steps allows for more in-depth and formalised customisation: first implementing the EM bsDD classification to set the descriptors according to a shared standardisation and then running the VPL scripts to automatically retrieve the data to populate them, without creating additional "shared parameters" (Fig. 14).

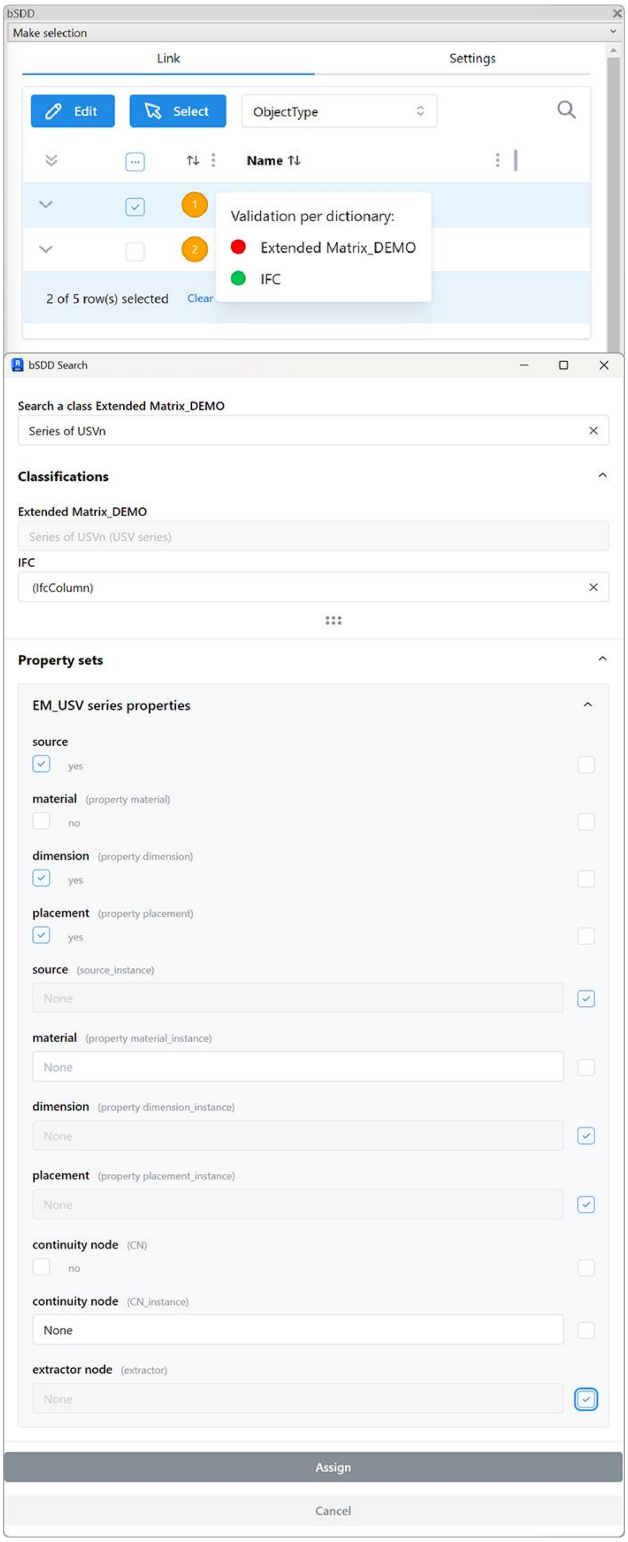

Figure 12. Interface of the plug-in employed to map the EM classification and the IFC 4.3 classes against the BIM modelled objects within the Autodesk Revit environment (A. Sanseverino)

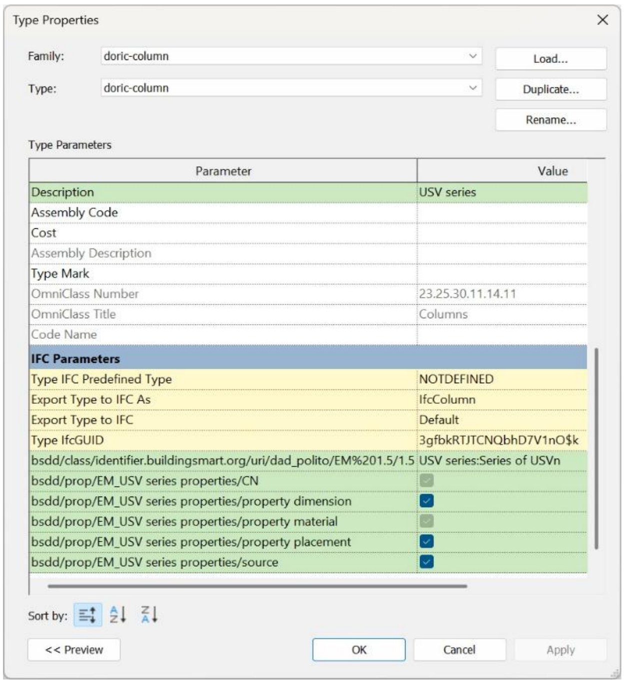

Figure 13. EM-BIM IFC-export configuration (yellow) and EM bsDD-implemented (green) "type parameters" of the Doric column of the Stoa in Priene (A. Sanseverino)

5. Ongoing work for an integrated and standardised EM-BIM workflow with CIDOC-CRM

A critical advancement in EM's development has been its formal mapping to the CIDOC Conceptual Reference Model (CIDOC CRM), the ISO standard ontology for cultural heritage documentation. Ontology mapping (or ontology alignment) is the process of creating semantic correspondences between entities (concepts, properties, classes, relations) from two different ontologies or knowledge representation systems. Mapping is the process of relating the concepts of two distinct semantic models so they can understand each other and exchange data consistently.

The future development of this research is to use bSDD for mapping diverse standards The aim is to make HBIM models interoperable with digital collections and archives that store sources and information used in the virtual reconstruction process. A mapping activity between EM and CIDOC-CRM was already developed by the research group of the Social Sciences & Humanities Open Cloud (SSHOC) project (Schmidle et al., 2022).

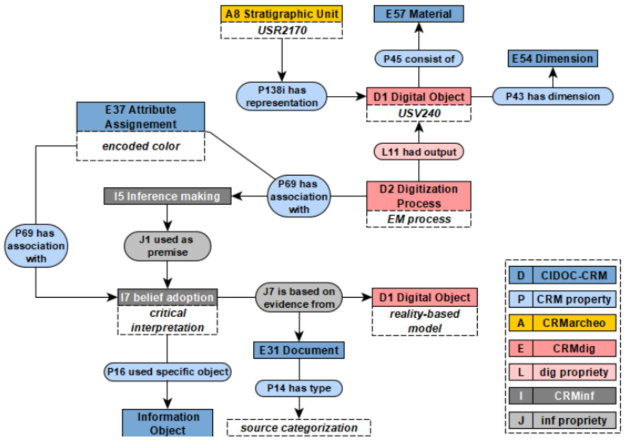

Figure 15. EM and CIDOC-CRM mapping (SSHOC report).

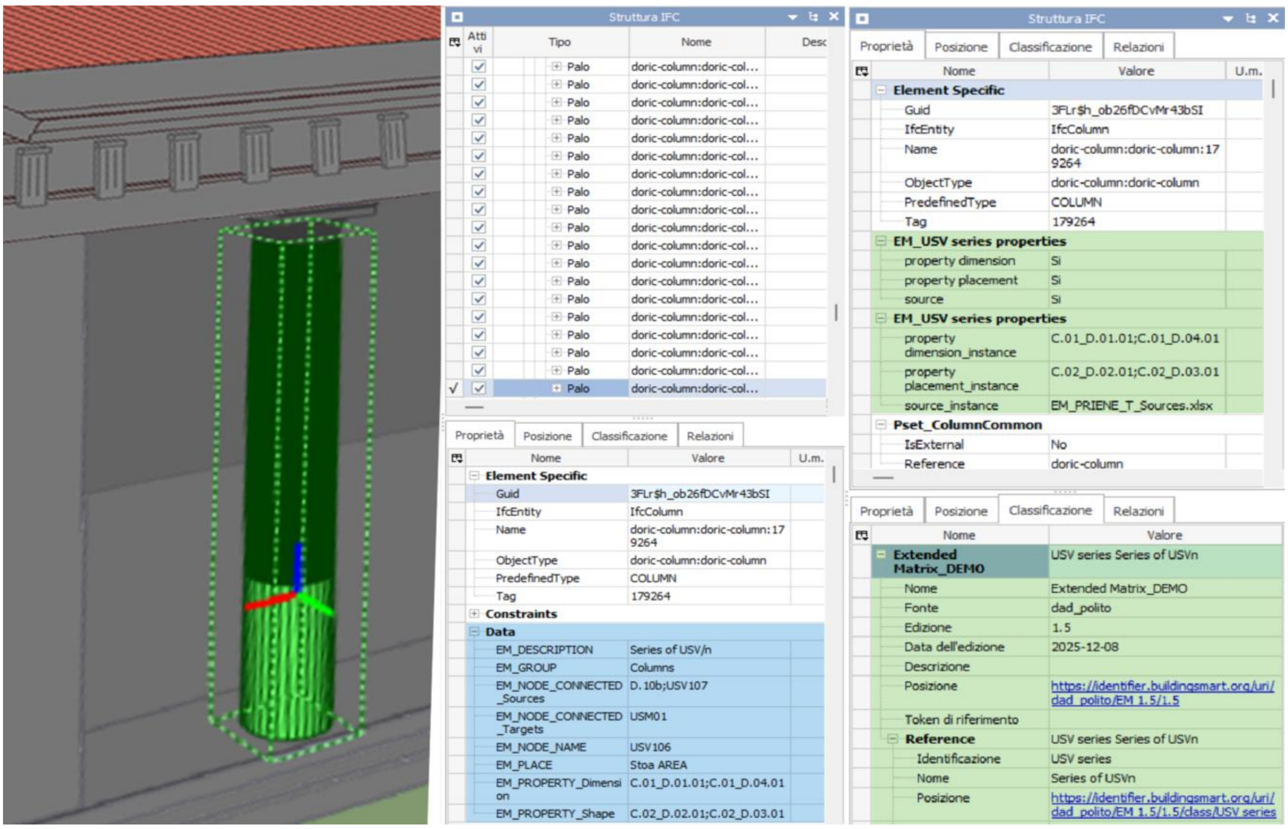

Figure 14. EM-BIM VPL-generated (blue) and EM bsDD-implemented (green) properties and classification within the exported to IFC model of the Doric column of the Stoa in Priene (A. Sanseverino).

Through the mapping, each EM entity was mapped to an equivalent CIDOC CRM class, including CIDOC-CRM extensions such as CRMarcheo for archaeology, CRMdig for digitisation processes, and CRMinf for supporting critical inferences and beliefs.
Namely, an EM reconstruction can thus be integrated with other LOD datasets, such as Europeana, Arches, or national archaeological registers, allowing researchers to trace connections between virtual reconstructions, historical documents, and physical artefacts held in museum collections. This aligns with emerging trends in cultural heritage informatics, where interoperability and openness are increasingly seen as prerequisites for sustainable, reusable digital scholarship.

6. Conclusions

This study has presented an EM-BIM methodology that integrates the Extended Matrix (EM) framework with Historic Building Information Modelling (HBIM) environments using a complementary approach of VPL and bSDD.
Building on the semantic mapping of EM to IFC and its application in the virtual reconstruction of the Doric Stoa of Priene, the proposed workflow, using the EM bSDD, addresses a critical limitation of previous approaches.
The implementation of VPL-based geometrical modelling enables the faithful transfer of spatial and morphological data across platforms, while parallel, informative modelling via EM bSDD and VPL scripts ensures that metadata and paradata are preserved, structured, and interoperable.
The Doric Stoa of Priene has served as a benchmark case study, demonstrating the potential of EM-BIM to manage complex datasets, support interdisciplinary collaboration, and integrate heterogeneous information sources within a coherent and standards-compliant framework. By bridging semantic, methodological, and technical interoperability, the proposed workflow sets the groundwork for scalable applications in other archaeological and architectural heritage contexts

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