DIGITAL HERITAGE (2025)
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The collaborative Basilica Iulia Project: A Digital Knowledge Ecosystem for Integrated Archaeological Research

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Abstract
The Basilica Iulia Project addresses the challenge of integrating heterogeneous archaeological data through a collaborative digital ecosystem based on the Extended Matrix (EM) framework and s3Dgraphy ontology. By transforming traditional disconnected workflows into an integrated environment designed for alignment with CIDOC-CRM standards, the project enables seamless collaboration across architectural, archaeological, and conservation domains. The implementation demonstrates how open-source tools developed through a project-driven approach can create sustainable "Living Lab" environments for complex archaeological sites. Key innovations include the development of formal languages for process documentation and intuitive interfaces for multidisciplinary teams. The resulting framework, currently under validation through the Basilica Iulia case study, provides a scalable model for digital archaeology that maintains scientific rigor while fostering cross-domain collaboration.

CCS Concepts
• Information systems $\rightarrow$ ***Geographic information systems; • Computing methodologies*** $\rightarrow$ ***Mesh geometry models; Uncertainty quantification;***

1. Introduction

Archaeological sites with extensive excavation histories present unique challenges for digital documentation and interpretation. The Basilica Iulia in the Roman Forum, with its complex stratigraphy spanning multiple construction phases and modern interventions since 1788, exemplifies these challenges. Traditional archaeological workflows, characterized by disconnected data silos and limited cross-domain collaboration, prove inadequate for such sites.

This paper presents the Basilica Iulia Project's innovative approach to these challenges through a collaborative digital ecosystem. At its core, this ecosystem employs the Extended Matrix (EM) framework and Scientific 3D Graphs (s3Dgraphy) ontology to create an integrated knowledge graph that connects diverse data types—from stratigraphic records to 3D documentation—within a CIDOC-CRM compatible structure.

Our approach addresses three critical objectives: (1) developing tools that evolve through direct engagement with archaeological practice, (2) establishing protocols that ensure transparency in data transformation and interpretation, and (3) creating sustainable workflows that facilitate genuine cross-domain collaboration. This paper demonstrates how these objectives are realized through the systematic implementation and testing of our digital ecosystem in the ongoing Basilica Iulia research project.

2. Problem Definition and State of the Art

2.1. Initial State of Documentation

At the outset of the Basilica Iulia Project, the documentation presented a complex mosaic of heterogeneous datasets, each with distinct characteristics and challenges. The archaeological record consisted of diverse materials including textual documentation in various formats (excavation reports, restoration records, scientific publications), photographic archives spanning decades, and numerous survey datasets produced through different technologies and methodologies [GI22].

Photogrammetric and laser scanner surveys of the different sectors of the vast monument have been conducted in various campaigns since 2015, in accordance with the scientific goals of the Project, which initially focused on the Republican phases of the southern sector of the Roman Forum, and later shifted to the study of the Augustan basilica and its transformations. This has complicated the integration of the different results .

The scientific documentation reflected traditional data management approaches: stratigraphic unit records were maintained in MS Word documents, while artifact cataloging relied on MS Excel spreadsheets. The photographic archive, though rich in content, was organized primarily in thematic folders without standardized metadata.

DOI: 10.2312/dh.20253358

The documentation of architectural blocks presented additional challenges. These elements had undergone digitization through portable structured-light scanner, producing a collection of 3D models stored on cloud platforms as OBJ files with associated textures. The primary limitation of these models was their high geometric complexity, with polygon counts that complicated management and integration within comprehensive visualization systems.

2.2. Challenges in Archaeological Data Integration

The Basilica Iulia Project inherited documentation spanning two centuries of archaeological investigation, presenting multifaceted integration challenges that exemplify broader issues in digital archaeology.

Recent advances in digital archaeology—including GIS integration, HBIM modeling, and semantic databases—have addressed individual aspects of these challenges but often perpetuate fragmentation by creating new domain-specific tools. The Basilica Iulia's documentation exemplifies this fragmentation: laser scans processed in disparate software, stratigraphic records as text documents, architectural blocks as isolated 3D models, and historical photographs lacking spatial context.

The fundamental challenge lies not in the individual technologies but in the absence of a framework that maintains connections between primary evidence, analytical processes, and interpretative outcomes. In archaeological reconstruction this "Black Box" problem [Dem15] undermines scientific transparency and reproducibility. These challenges are further illustrated in Table 1.

3. Methodological Framework

3.1. Extended Matrix as a Formal Language for Archaeological Knowledge

The methodological approach developed for the Basilica Iulia Project centers on the Extended Matrix (EM, *see* extendedmatrix.org), a formal language and conceptual framework to document, analyse, interpret, and reconstruct spatio-temporal elements in archaeological contexts. First introduced as a structured language for archaeological virtual reconstruction [Dem15] and later expanded into a comprehensive white-box methodology [DF17], EM addresses a fundamental challenge in digital archaeology: conventional documentation systems typically fail to maintain clear distinctions between objective documentation and interpretative hypotheses, leading to potential ambiguity in scientific reasoning.

EM creates a formalized graph structure that documents the complete chain of reasoning from primary evidence to reconstruction hypotheses, while maintaining clear boundaries between these domains. This approach ensures transparency and repeatability throughout the research process [DF21], a critical requirement for the Basilica Iulia with its complex interplay of *in-situ* remains, displaced architectural elements, multiple phases of construction, and extensive archival documentation.

The framework's domain-specific vocabulary enables precise definition of space-time elements and their relationships, focusing on different levels of possible existence in time and space, justified by established stratigraphic principles:

- **Stratigraphic Units (SU)**: *in situ* stratigraphic evidence;
- **Documentary Stratigraphic Units (USD)**: textual, visual, and archival sources;
- **Virtual Stratigraphic Units (USVs)**: reconstruction based on *in situ* evidence;
- **Virtual Non Stratigraphic Units (USVn)**: reconstruction based on comparisons;
- **Transformation Stratigraphic Units (TSU)**: processes of change, degradation, and alteration [SDB24];
- **Special Finds (SF)**: Representing an object out of its original context that can be useful for reconstruction purposes.

The Extended Matrix Framework (EMF) implements this formal language using a graphical WYSIWYG approach, primarily through yED for graph creation and visualization, and the Extended Matrix Tool for Blender for spatial integration. These tools transform EM from a theoretical framework into a practical methodology accessible by researchers without specialized technical skills.

3.2. s3Dgraphy: An Ontology for Heritage Metaverse Science

While EM provides the conceptual framework, Scientific 3D Graphs (s3Dgraphy) transforms this language into a structured ontology that operationalizes archaeological knowledge within three-dimensional space. Developed as a Python library available through pip and GitHub[†], s3Dgraphy treats the 3D environment itself as an integral part of the knowledge graph, rather than a separate visualization layer.

Currently implemented as a property graph database system, s3Dgraphy enables efficient storage and querying of complex archaeological relationships through labeled nodes and edges. The ontology is being developed as a potential extension of CIDOC-CRM, with ongoing work to establish systematic mapping procedures that will enable transformation from property graph format to RDF triplestore representation, ensuring full semantic web compatibility.

The ontology enables several critical capabilities particularly relevant to the Basilica Iulia case:

- seamless integration between knowledge graphs and 3D environments;
- clear semantic distinction between documented evidence and reconstructive hypotheses;
- explicit documentation of data provenance and reasoning chains;
- representation of multiple existence states for stratigraphic units;
- management of multiple interconnected knowledge graphs and alternative interpretations.

For the Basilica Iulia, this integration proves essential when working with extensive missing architectural elements whose original positions must be hypothesized based on fragmentary evidence, and when positioning historical imagery in its original spatial context, building on methodologies developed in projects like CNRS's Imago [DLBS*11].

s3Dgraphy is currently implemented as a property graph

[†] https://github.com/zalmoxes-laran/s3Dgraphy

Table 1: *Comparison of Traditional vs. Integrated Approaches in Archaeological Documentation*

Traditional Approach	Required Integration	Current Limitations	Our Approach
Sequential workflows with limited feedback between phases	Concurrent collaboration across domains	Incompatible tools and data formats	Interoperable file formats and hybrid viewers for multiple data types (e.g. E57, OBJ+RDF, GLB, GLTF, Cesium)
Domain-specific silos (archaeology, architecture, conservation, art history)	Cross-domain dialogue and shared understanding	Divergent vocabularies and methodologies	Transdisciplinary ontologies aligned with CIDOC-CRM
Separate documentation systems for different data types	Unified knowledge graph connecting all data	No formal semantic connections	Federated data models using shared identifiers
Linear progression from documentation to interpretation	Iterative refinement with continuous validation	Loss of decision rationale	Multi-collaborative environments and interpretative logs embedded in knowledge graph
Static final deliverables	Dynamic, queryable knowledge system	Limited reusability of research outputs	FAIR-compliant publication on open repositories (e.g. Zenodo)

database system that enables efficient storage and querying of complex archaeological relationships through labeled nodes and edges. The ontology is being developed as a potential extension of CIDOC-CRM, with ongoing work to establish systematic mapping procedures between the property graph format and RDF triplestore representation. This development incorporates elements from existing CIDOC extensions (CRM-archaeo, CRM-inf, CRM-sci) while introducing new classes and properties specifically addressing three-dimensional representation of stratigraphic elements—aspects currently not covered in the CIDOC family of ontologies.

The mapping work between EM and CIDOC-CRM began within the SSHOC EU project [BCD*22] and continues within the European ECHOES project, aiming to ensure compatibility with international standards [BCA*23, NMT*23] and facilitating future integration with initiatives like the European Collaborative Cloud for Cultural Heritage (ECCCH).

The ontology is currently under active development within the H2IOSC Italian national project, coupled with Heriverse, a vertical web 3D application under development, oriented to inspect, query and explore Heritage Knowledge Graphs. s3Dgraphy is in a preliminary version operating as a property graph; the definitive release to the scientific community, along with comprehensive CIDOC-CRM mapping documentation and triplestore transformation capabilities, is planned to coincide with the publication of a dedicated paper that will fully outline its structure, semantic web integration, and application scenarios.

3.3. Knowledge Graph Implementation

The EM formal language and s3Dgraphy ontology converge in a knowledge graph which maps the archaeological research process. This implementation transforms textual, 2D and 3D archaeological documentation from a collection of disconnected data into a coherent web of interconnected knowledge that can be queried, analyzed, and extended through time.

Figure 3 demonstrates a practical application of this approach, showing how stratigraphic elements from the Basilica Iulia are represented within the EM framework. The graph illustrates stratigraphic nodes (152, 151, 150) corresponding to architectural elements documented both in the field and through 3D scanning, with associated property nodes documenting dimensions, positioning, materials, and chronological data. Document nodes (D.01-D.05) provide archival evidence supporting the interpretations, maintaining explicit traceability between physical evidence and documentary sources.

Within this graph structure nodes represent distinct entities—ranging from physical stratigraphic units to archival documents, from 3D scans to reconstructive hypotheses—while edges encode the semantic relationships between them. This approach offers several key advantages:

- **Flexibility**: the graph structure evolves organically as new information is discovered or new interpretations are proposed, without requiring fundamental restructuring of the knowledge base.
- **Expressivity**: complex relationships between entities are represented explicitly; including: temporal sequences, spatial associations, evidence-based support, and degrees of certainty.
- **Queryability**: when queried the knowledge graph provides information about the monument's history, construction techniques, or restoration processes.
- **Traceability**: every interpretative process can be traced back to its foundations, ensuring transparency and repeatability.

The current implementation utilizes yED, for knowledge graph creation and visualization, and the EM Tool for Blender, for the representation of EM data in a 3D environment. The modular design of s3Dgraphy allows for future expansion to additional platforms and visualization tools, ensuring long-term sustainability and accessibility of the knowledge ecosystem.

By combining in a knowledge graph the formal precision of EM and the semantic richness of s3Dgraphy, the Basilica Iulia Project demonstrates how structured data ingestion can transform archaeological practice while maintaining scientific rigor throughout the documentation, analysis, and reconstruction process.

Proceedings published by Eurographics - The European Association for Computer Graphics.

3.4. Data Transformation Chain

A key innovation within our methodological framework is the Data Transformation Chain (DTC), a formal language and visualization system for documenting the complete process of data acquisition, processing, and interpretation. Similar to the EM in its graph-based approach, the DTC focuses specifically on making transparent the technical and methodological decisions involved in transforming raw data into research outputs (*see* Fig. 1).

The DTC addresses a critical gap in archaeological documentation by formalizing the often-overlooked intermediate steps between data collection and interpretation. For each data-set in the Basilica Iulia Project, the DTC explicitly documents:

- hardware configurations and acquisition parameters;
- data cleaning and pre-processing steps;
- algorithms and software tools applied;
- parameter settings and methodological decisions;
- transformations between different data formats;
- quality assessments and validation procedures.

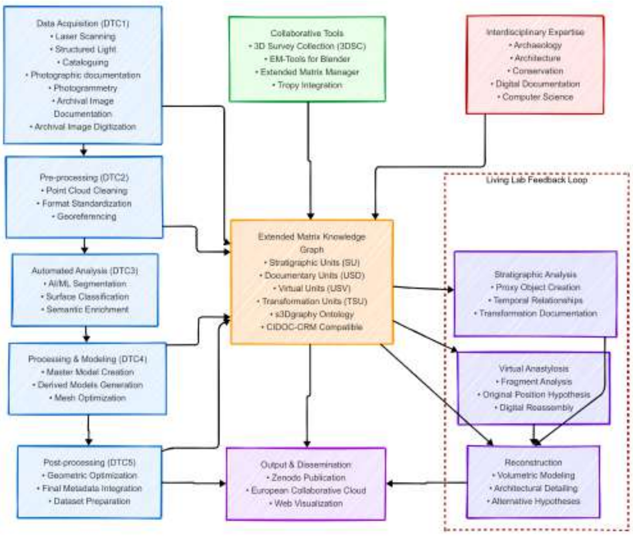

Figure 1: *Detailed workflow showing the Data Transformation Chain (DTC) phases from data acquisition through processing to reconstruction, illustrating the Living Lab feedback loop that enables continuous refinement of methods and tools.*

This comprehensive documentation ensures that all data processing steps are reproducible and editable, addressing a key requirement for scientific transparency in digital archaeology. By adopting ISO-standard XML and Graph-ML formats, the DTC ensures that data processing histories are transparent, reproducible, and machine-readable.

3.5. The Living Lab Approach

The methodological framework described above has been implemented through a "Living Lab" approach where digital tools and workflows continuously evolve in response to practical challenges and user feedback. Rather than imposing predefined digital solutions, we have adopted an iterative development cycle that closely integrates tool development with archaeological practice [DdFF20]. This approach recognizes that effective digital tools for archaeology must emerge from close collaboration between technology specialists and domain experts. It facilitates cross-domain knowledge transfer and distributes digital expertise across the team, rather than concentrating it among a few specialists.

This methodological framework—combining EM formalism, s3Dgraphy ontology, knowledge graph, DTC, and Living Lab approach—creates a comprehensive foundation for the Basilica Iulia Project's technical implementation, which will be detailed in the following section.

4. Technical Implementation

4.1. System Architecture Overview

The technical implementation of the Basilica Iulia Project follows an integrated spiral architecture that coordinates multiple specialized tools and formal languages within a unified workflow (Figure 2). This architecture represents a paradigm shift from linear, sequential workflows to a dynamic, interconnected system where each component can both consume and produce semantic data.

The system operates through three concentric processing rings, each with distinct but interconnected functions:

- **Ring I - Hard Data Processing**: This outer ring encompasses reality-based documentation workflows, including 3D Survey Collection (3DSC) for managing laser scanning and photogrammetric data. This ring transforms physical artifacts and spaces into digital representations while maintaining complete documentation of processing workflows.
- **Ring II - Soft Data Processing**: This intermediate ring handles semantic structuring through the Extended Matrix (EM) formal language and Extended Matrix Framework (EMF) tools. It includes yED GraphML for knowledge graph creation, Tropy for visual documentation management, and EMtools for Blender integration. This ring transforms digital representations into semantically enriched knowledge structures.
- **Ring III - Knowledge Graph Triplestore**: This core ring implements the central s3Dgraphy ontology integrated with the Heritage Digital Twin (HDT) framework. The triplestore refers to a database optimized for storing and querying RDF triples (subject-predicate-object statements), enabling complex semantic queries across the entire knowledge base.

At the center of this architecture lies the Knowledge Graph Triplestore (KGT), a semantic database that stores relationships between all project entities as RDF triples following CIDOC-CRM standards. The KGT integrates the s3Dgraphy ontology—our domain-specific extension for archaeological 3D knowledge—with the Heritage Digital Twin (HDT) framework through the formal relationship `HP28 contains_subgranular_elements`. This relationship enables the HDT to encompass detailed archaeological knowledge while maintaining compatibility with broader cultural heritage information systems.

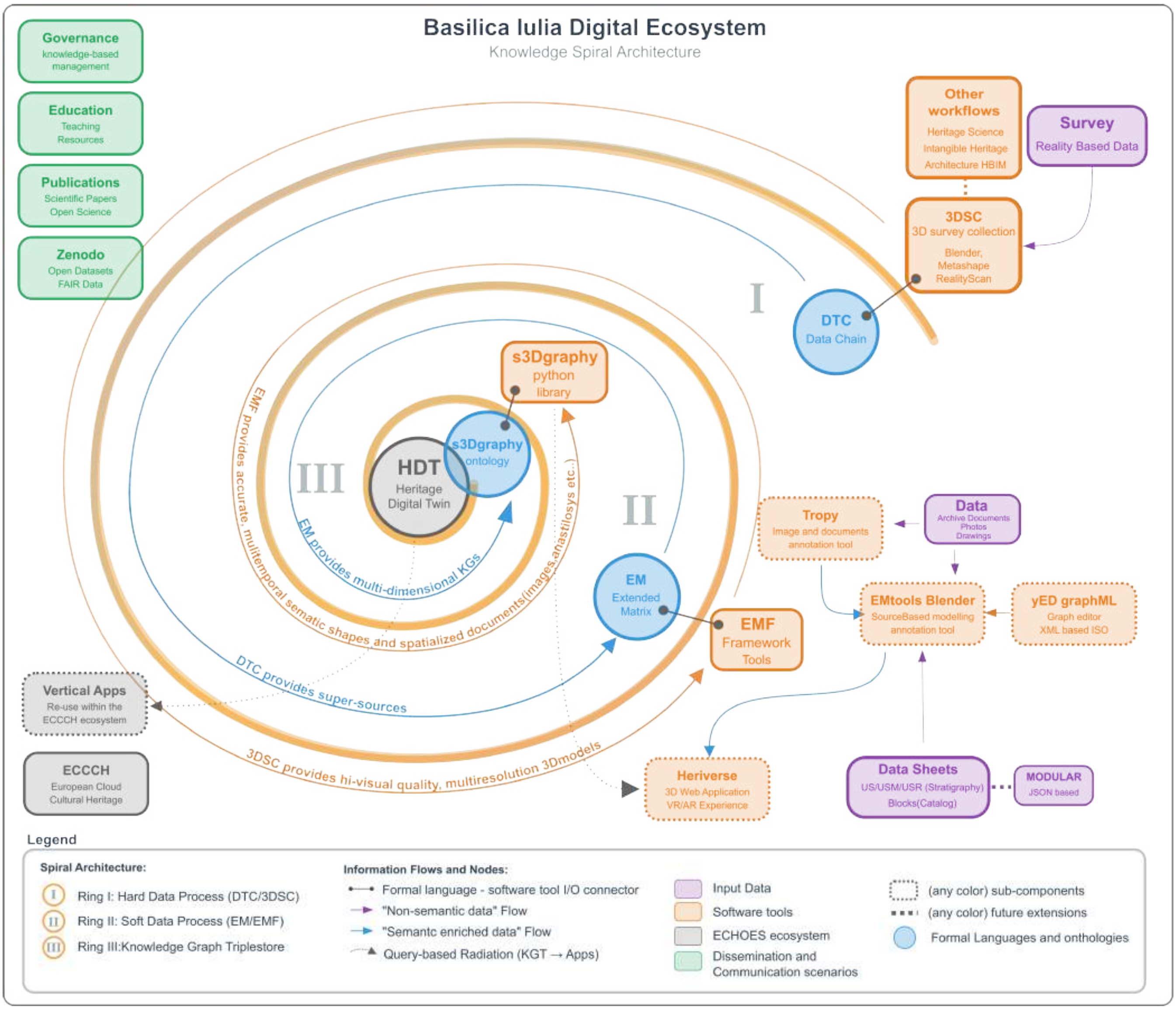

Figure 2: *High-level workflow diagram showing the integration of tools, formal languages, and data flows within the Basilica Iulia digital ecosystem. The Knowledge Graph Triplestore (KGT) coordinates all processes, from reality-based documentation through semantic structuring to collaborative dissemination.*

The Heritage Digital Twin (HDT) represents a comprehensive digital replica of the Basilica Iulia that extends beyond geometric representation to include semantic, temporal, and evidential dimensions. Unlike conventional 3D models, the HDT maintains explicit connections between digital representations and their real-world referents, supporting queries such as "show all architectural elements from the Augustan phase with uncertain reconstruction status" or "trace the documentary evidence supporting the positioning of column capital AF.142."

The *Digital Continuum Portal* represents the outermost ring of interaction, encompassing dissemination and communication scenarios through platforms like Heriverse (the 3D web application for collaborative exploration), Zenodo (for FAIR-compliant dataset publication), and integration pathways to the European Collaborative Cloud for Cultural Heritage (ECCCH).

The spiral architecture facilitates bidirectional data flows between processing layers. Unlike traditional pipelines where data flows unidirectionally from acquisition to interpretation, this architecture enables insights from semantic analysis to inform data processing decisions. For example, archaeological interpretations developed in Ring III can guide the optimization of 3D models in Ring I, while new documentary evidence processed in Ring II can trigger reanalysis of existing reconstructions in Ring III.

Currently, process documentation relies on established protocols within each tool and manual documentation procedures. The development of a formal Data Transformation Chain (DTC) framework—designed to automatically document all processing steps with complete parameter settings, decision rationale, and validation criteria—is planned as future work to enhance reproducibility and scientific transparency across the entire workflow.

The standardized inputs feeding into this system include:

- **Stratigraphic Unit sheets**: Traditional archaeological documentation transformed into structured data through modular JSON-based importers
- **Architectural fragment catalogs**: Detailed documentation of displaced architectural elements with 3D geometric data and typological classifications
- **Survey data**: Laser scanning and photogrammetric datasets processed through 3DSC workflows with comprehensive metadata
- **Historical documentation**: Archival materials processed through Tropy and integrated as spatially-referenced nodes within the knowledge graph
- **Analytical results**: Scientific analyses (archaeometric, conservation assessments) integrated as property nodes with explicit provenance documentation

This integrated architecture transforms the traditional archaeological workflow from a collection of disconnected specialized tools into a coherent knowledge ecosystem where semantic relationships are preserved and made queryable throughout the research process.

4.2. Evolution from Legacy to Integrated Workflow

The Basilica Iulia Project implements a phased transition from legacy documentation systems to an integrated digital ecosystem. This process required both the development of tools and the transformation of existing datasets into inter-operable formats aligned with the knowledge graph.

Initially, we conducted a comprehensive assessment of all available documentation, categorizing datasets according to different features (format, completeness, accuracy, and relationship to the EMF). This procedure revealed significant gaps and inconsistencies that needed to be addressed before the definition of the Integrated Workflow. For example, laser scan data from different campaigns required realignment and georeferencing to establish a consistent spatial framework, while archival materials needed digitization and standardized metadata.

Rather than attempting to migrate all legacy data simultaneously, we implemented a progressive transition strategy that identified critical datasets for immediate integration while establishing protocols for incorporating additional materials over time. This approach allowed research to continue uninterrupted while systematically improving the overall coherence of the digital ecosystem.

4.3. Tools and Protocols Development

The technical implementation required the development and adaptation of several specialized tools to support the collaborative workflow. These tools were designed with modular architecture and standardized data exchange formats to ensure interoperability throughout the ecosystem.

4.3.1. 3D Survey Collection (3DSC)

A key component of the technical implementation was the enhancement of the 3D Survey Collection (3DSC) system to facilitate the management of complex reality-based datasets. We developed a new integration component for Reality Capture (RC) which optimized the workflow for processing three-dimensional models, allowing the management of increasingly complex datasets.

Since 3DSC supports the DTC pipeline specific, it integrates modules for:

- Alignment and georeferencing of heterogeneous point clouds;
- Cleaning and noise reduction of survey data;
- Mesh generation and optimization for different levels of detail (LOD);
- Texture mapping and color correction;
- Metadata enrichment and provenance documentation;

These enhancements transformed 3DSC from a data processing tool into a comprehensive system for digital documentation that maintains explicit connections between raw survey data and processed outputs while preserving the complete processing history.

4.3.2. Extended Matrix Tools

The practical implementation of the EMF required specialized tools for creating, visualizing, and querying knowledge graphs. We developed an add-on for Blender (EM-Tools) as a central component of this ecosystem, allowing direct integration of semantic annotations with 3D models within a common work environment [BDC24].

EM-Tools was enhanced with several key capabilities specifically developed for the Basilica Iulia Project:

- Integration of a simplified GIS/3D GIS mode for direct manipulation of tabular data before transformation into knowledge graphs;
- Support for large-scale projects through parcelling of knowledge graphs, allowing the complex Basilica Iulia model to be divided into manageable sectors while maintaining logical connections;
- Direct visualization of documentary and photographic evidence within the Blender environment, with connections to records imported through the knowledge graph;
- Real-time collaboration features allowing multiple researchers to annotate and modify the knowledge graph simultaneously.

Additionally, we developed a standalone tool (EM Manager) which converts tabular archaeological data into EM graph, lowering the technical barrier for archaeologists without prior experience in knowledge graph creation [BDC24].

4.3.3. Integration with Tropy

A significant innovation in our technical implementation was the integration of Tropy (tropy.org), a research photo management tool, with the EM workflow. This integration established to systematically manage both historical photographs and documentation produced during the project, enabling coherent cataloging and meaningful relationships between different sources. Tropy provides structured metadata for visual sources and supports the spatial positioning of historical images within the 3D environment. The software consents to annotate images and documents using customizable ontologies, allowing researchers to apply domain-specific vocabularies that align with the EMF and archaeological documentation standards. By implementing a custom export module for JSON-LD format, we enabled seamless transfer of visual documentation to EM-Tools, where images can be spatialized within the Basilica's model through quad objects that identify the original viewpoint.

4.4. Reality-Based to Interpretative Reconstruction Pipeline

The technical implementation established a structured pipeline connecting reality-based documentation with interpretative reconstruction, maintaining explicit relationships between sources of evidence and hypothetical elements. For the Basilica Iulia Project this pipeline operates through several distinct phases:

4.4.1. Data acquisition and pre-processing

The acquisition phase incorporates a range of documentation techniques, from laser scanning and photogrammetry to traditional drawing and photography. All raw data undergoes standardized pre-processing phase, according to the DTC protocol, with complete documentation of processing parameters and transformations. This step involved realignment of the photogrammetric survey, precise georeferencing of point clouds in the RDN cartographic system, and detailed cleaning of the data to remove modern elements like trees and railings that interfere with archaeological interpretation.

4.4.2. Processing and Modeling

The processing phase transforms pre-processed data into master models—high-resolution, high-precision three-dimensional representations suitable for analytical, conservation, and documentation purposes. From these master models, we generate various derived models optimized for specific research or visualization needs. In this case, within RC, using only equirectangular images from laser scanners did not achieve the texture target resolution of 1-1.2 pixels per texel. This finding led to the implementation of additional terrestrial photographic campaigns to ensure optimal photographic coverage of all surfaces.

4.4.3. Semantic Enrichment

The semantic enrichment phase represents a bridge between geometric representations and archaeological interpretation, EMF tools allow to create a rich knowledge graph. This process transforms raw geometric data into semantically structured knowledge models that explicitly document stratigraphic relationships, temporal sequences, and interpretative hypotheses. The implementation employs a multi-tool approach, with yED serving to map stratigraphic temporal relationships at a conceptual level, while EM-Tools enables the practical connection between semantic information and spatial representation within Blender. This integration allows to:

- associate stratigraphic units with specific 3D proxy geometries;
- document transformation processes through the recently developed TSU;
- create explicit connections between physical evidence and interpretative reconstructions;
- trace the complete chain of reasoning from primary documentation to reconstructive hypotheses;
- generate multiple interpretation scenarios while maintaining the provenance of each decision.

The semantic structure created by this process serves as a foundation for subsequent analytical and reconstruction work, ensuring that all interpretations remain explicitly linked to their evidential basis, while facilitating cross-domain collaboration. For the Basilica Iulia, this approach is particularly valuable in addressing the complex stratigraphic relationships resulting from centuries of modifications, restorations, and archaeological interventions.

4.4.4. Virtual Anastylosis and Reconstruction

The final phase implements virtual anastylosis—the digital reassembly of fragmented architectural elements—and reconstruction of missing components based on archaeological evidence. This process is documented through the EM, with clear distinction between different levels of certainty and evidential support.

Three primary strategies for reconstruction are foreseen:

- **Direct Anastylosis**: Repositioning digitized blocks in their original locations based on dimensional, morphological and technical features.
- **Comparative Reconstruction**: creating missing elements based on surviving parallels within the same monument or contemporary structures.
- **Typological Reconstruction**: modeling elements according to established architectural traditions and proportional systems of Roman architecture.

Each reconstructive decision is explicitly documented within the EM, establishing transparent connections between evidence and interpretation.

4.5. Integration with Zenodo Extended Metadata Schema

A crucial aspect of the technical implementation is the preparation for long-term data preservation and sharing through alignment with the extended metadata schema for Zenodo developed specifically for cultural heritage datasets [BDF*23]. This integration ensures that all data produced through the Basilica Iulia Project will be accessible, discoverable, and reusable within the broader scientific community. The implementation includes automated extraction of metadata from the knowledge graph, standardized documentation of data processing methodologies according to the DTC, and explicit licensing information for all components of the dataset. This approach creates a FAIR-compliant repository that can be readily integrated with the ECCCH. By implementing these technical solutions within a coherent framework, we transform the fragmented documentation of the Basilica Iulia into an integrated knowledge ecosystem that supports collaborative research across domains while maintaining scientific rigor and transparency throughout the research process.

5. The Basilica Iulia Project - Current Implementation

5.1. Implementation Status of the Collaborative Ecosystem

The implementation began with the integration of existing documentation from previous research campaigns, particularly the excavations conducted by Laura Fabbrini between 1960 and 1964 [GI22], and continues through new documentation campaigns specifically designed to address gaps in the available data.

The practical implementation follows a phased approach that prioritizes the creation of a consistent spatial framework through reality-based modeling before proceeding to more interpretative tasks. This sequencing ensures that all subsequent analyses and reconstructions will be grounded in a metrically accurate representation of the monument's current state, facilitating collaboration across disciplinary boundaries.

A critical aspect of the implementation is the deliberate testing of the EMF under real-world multidisciplinary working conditions. To this end, we are forming interdisciplinary working groups that bring together archaeologists, architects, digital documentation specialists, and conservation scientists, specifically to evaluate how EM, EMtools, and Heriverse perform as collaborative instruments in complex research scenarios. These groups operate within the developing digital ecosystem, adopting the EM as a shared formal language for documenting observations, interpretations, and potential reconstruction hypotheses. The testing protocol includes regular collaborative sessions where different specialists share perspectives on specific research questions, with the knowledge graph functioning as both a central repository and a real-time collaboration space. This approach allows us to assess how effectively these tools facilitate cross-domain communication and knowledge integration. For instance, as archaeologists document stratigraphic relationships, they can immediately engage with architects about structural implications, while conservation scientists can link their material assessments to identified historical phases—all within the same digital workspace. This implementation serves as a comprehensive stress test for the digital ecosystem's capacity to bridge traditional disciplinary boundaries. Through practical application, we are evaluating how the combination of EM's formal language, EMtools' spatial integration capabilities, and Heriverse's web-based collaborative environment supports the kind of cross-pollination of expertise that leads to richer, more nuanced interpretations than conventional siloed approaches. The insights gained from this testing phase will directly inform the ongoing development of these tools, ensuring they meet the actual needs of multidisciplinary archaeological teams.

5.2. Reality-Based Documentation Current Status

The foundation of the collaborative workflow is a comprehensive reality-based model that integrates multiple documentation sources into a coherent spatial framework. The project has completed laser scanning of the entire Basilica, encompassing both the main structure of the Imperial monument and the underlying Republican remains located beneath the current ground level with the latter additionally documented through photogrammetry.

For the Basilica's imperial monument over 100 scans have been processed, and the resulting point cloud data has been aligned and georeferenced in the RDN cartographic system using geodetic reference points from the Palatine, and Roman Forum. The model is currently in the cleaning phase, with work ongoing to remove modern elements like trees and railings that interfere with archaeological interpretation. Terrestrial photogrammetry, for color information of the exterior surfaces, is planned as the next step in the documentation process, as current testing has shown that the equirectangular images from the laser scanner do not provide sufficient resolution for detailed texture mapping. The Republican structures beneath the current ground level presented particular challenges due to limited access and complex geometries. Here, a combination of terrestrial laser scanning and photogrammetry has been employed, with careful planning of acquisition positions to ensure complete coverage of all surfaces. The integration of these datasets required precise registration using common reference points, a process documented through the developing DTC protocol [Figure 3].

5.3. Knowledge Graph Development and Tool Integration

The EMF implementation is currently in a developmental phase, with significant progress made in establishing the conceptual structure while practical tools continue to evolve through project-driven refinement.

The team is beginning to model proxy objects for stratigraphic analysis of both the Republican and the Imperial structures. These simplified geometric representations will serve as containers for stratigraphic information, creating a bridge between the reality-based model and archaeological interpretation. This work is in its early stages, with the methodological approach established but implementation just beginning [Figure 4].

A significant current focus is the integration of Tropy for managing historical photographs and archival imagery within the collaborative ecosystem. This tool is being adapted to support the annotation of images for extracting structured information, which can then be mapped to nodes within the knowledge graph. The integration is actively being tested and refined, with workflows developing to streamline the process of connecting visual documentation to spatial locations within the 3D model.

The s3Dgraphy ontology alignment with CIDOC-CRM is in an advanced phase, with work progressing toward an extension of CIDOC specifically for three-dimensional representation of stratigraphic cultural heritage. This alignment will ensure that the knowledge produced through the Basilica Iulia Project is compatible with broader cultural heritage information systems.

5.4. Preliminary Reconstruction Work

Nearly all architectural blocks present in situ have been digitized using structured light scanning technology, specifically employing the Artec Eva scanner following the 3D-STONE workflow developed within the CHANGES project [Boz25]. This comprehensive digital collection of architectural elements forms an essential foundation for the future anastylosis work, which is just beginning. The structured light scanning approach provides unparalleled accuracy in capturing both geometry and texture of the marble blocks,

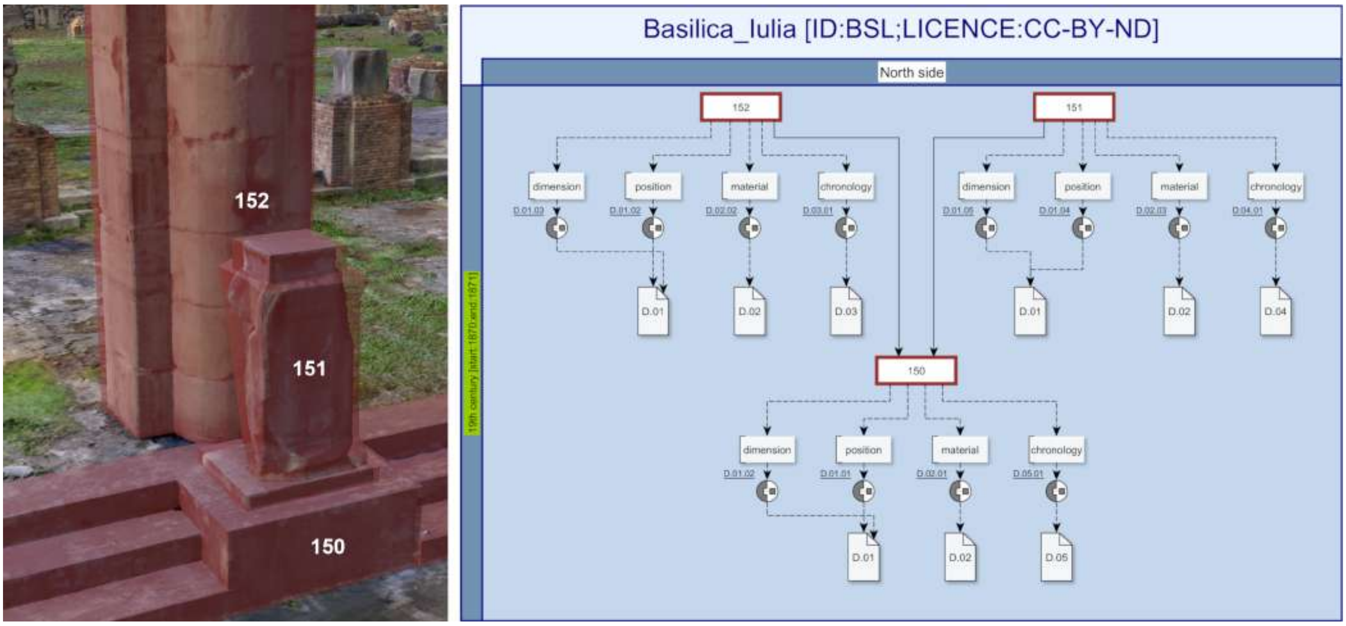

Figure 3: *Extended Matrix graph example from the Basilica Iulia Project showing stratigraphic nodes (152, 151, 150) with associated property nodes for dimensions, positioning, materials, and chronology. Document nodes (D.01-D.05) provide evidential support through archival sources. The 3D model shows the corresponding Stratigraphic Units in situ.*

Figure 4: *Mapping of the Special Finds architectural elements, in yellow, within the Basilica Iulia area.*

while significantly reducing field and processing times compared to photogrammetry-based approaches. This digital *lapidarium* forms an essential foundation for the future anastylosis work, which is just beginning. The reconstruction aspect of the project is currently in its initial phases, with work focusing on the direct anastylosis, thus repositioning digitalized blocks in their original locations.

Current efforts are focused on the marble façade, with the creation of volumetric models grounded in archaeological evidence. These representations of key architectural elements are employed to investigate critical questions—such as the various levels of the façades, the relationship between the outer marble half-columns and the pillars of the inner naves, and the configuration of the vaulted structures. These models serve as a foundation for future, more detailed reconstructions, which will progressively integrate information from architectural blocks. [Figure 5]. The current focus is on establishing the methodological framework and tools for this process, which will be implemented more fully as the project progresses.

5.5. Collaborative Tool Development

A distinctive feature of the Basilica Iulia Project is its project-driven approach to tool development, where software solutions evolve in direct response to research needs identified in the field.

For instance, 3DSC is being actively refined based on experience with the Basilica Iulia datasets. The integration with RC has proven successful for processing the large point cloud datasets, but continues to be optimized for specific requirements identified during the project. Similarly, a new 1.5.0 version of EM is undergoing testing and refinement as it is applied to real archaeological questions.

The project adopts an iterative development model, where research needs drive tool creation, tested through field application and refined via feedback. A key achievement—and ongoing challenge—is integrating specialized tools into a coherent ecosystem by standardizing data formats, workflows, and interoperability.

5.6. Knowledge Transfer Within the Team

Even in its current developmental state, the collaborative ecosystem is facilitating knowledge transfer across disciplinary boundaries. Team members from different specialties are learning from each

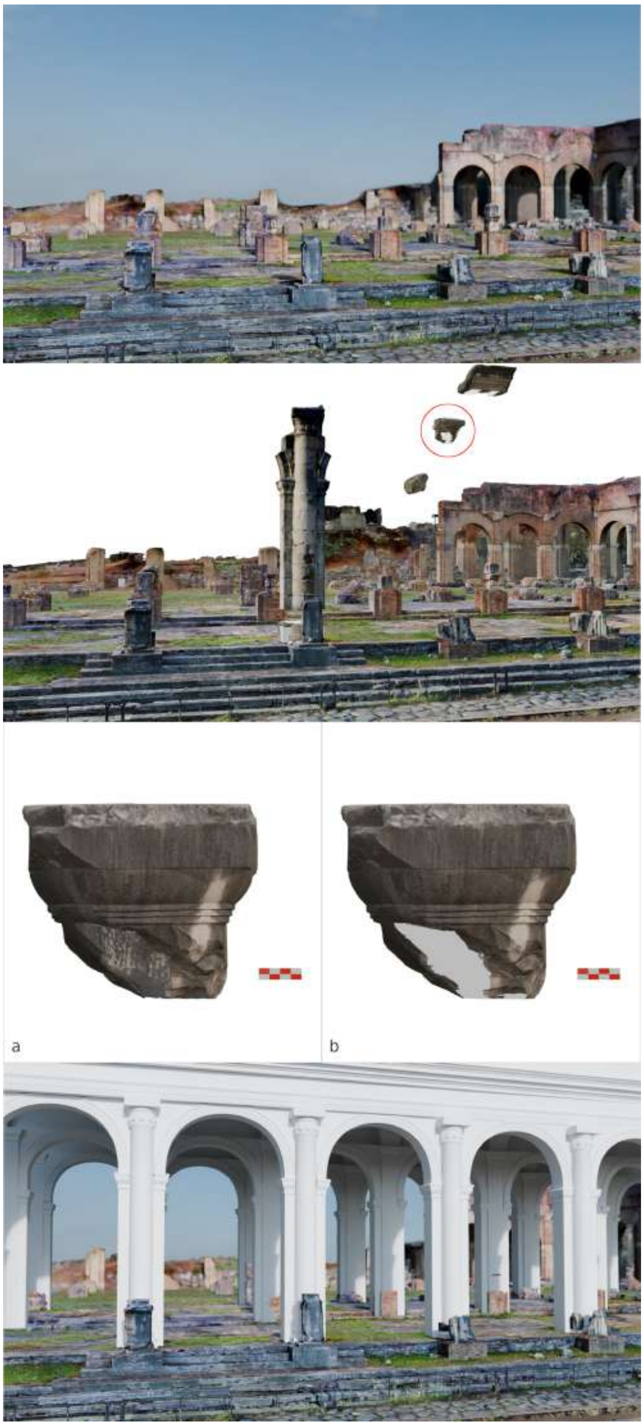

Figure 5: *The reconstruction process. Preliminary volumetric reconstruction of the pillars sequence, showing the current approach to architectural reconstruction based on available evidence.*

other through practical collaboration, with digital tools serving as mediators for cross-domain communication.

Archaeologists are gaining familiarity with digital documentation techniques, while digital specialists develop deeper understanding of the specific archaeological questions of the Basilica Iulia context. This mutual learning process is creating a more integrated research team capable of addressing the complex challenges presented by the Basilica Iulia. Within an hypothetical EM-Team 7 key roles are identified (1-Archaeologist; 2-Source-hunter; 3-DB manager; 4-Expert in survey techniques; 5-EM drawer; 6-Proxies Modeler; 7-Expert in 3D modeling), all these actors collaborates together to reach the final purpose of the project [BDC24].

The development of user-friendly interfaces, particularly for the EM tools, is helping to democratize access to digital tools among team members without specialized technical backgrounds. This accessibility is crucial for ensuring that all team members can contribute directly to the knowledge graph, recording observations and interpretations as they emerge rather than relying on technical intermediaries. As the project advances, this knowledge transfer aspect will become increasingly important, creating a sustainable research ecosystem that can continue to evolve beyond the current project timeline. The goal is not simply to document and reconstruct the Basilica Iulia, but to establish new methodological approaches that can be applied to other complex archaeological contexts in the future.

6. Future Work and Conclusion

6.1. Planned Development of the Digital Ecosystem

The Basilica Iulia Project represents an ongoing development of methodologies and tools for collaborative digital archaeology. As demonstrated in the previous section, significant progress has been made in establishing the foundation of this ecosystem, but substantial work remains to fully realize its potential. The planned development over the next twelve months encompasses several key areas:

6.1.1. Critical Technical Developments

Two fundamental technical developments are required to complete the digital ecosystem:

s3Dgraphy Semantic Web Integration: Currently implemented as a property graph database, s3Dgraphy requires systematic mapping to CIDOC-CRM equivalents and implementation of RDF triplestore transformation capabilities. This development will enable full semantic web compatibility and integration with international cultural heritage information systems.

Data Transformation Chain Implementation: The DTC framework, currently in early alpha stage, requires development of automated workflow documentation systems that will provide machine-readable process descriptions and complete provenance tracking for all data transformations, ensuring scientific transparency and reproducibility.

6.1.2. Completion of Reality-Based Documentation

The immediate priority is to complete the reality-based documentation phase through:

- finalizing the cleaning and optimization of the laser scan data;
- conducting the planned terrestrial photogrammetric campaign to acquire high-resolution color information for exterior surfaces;

- generating textured mesh models at appropriate levels of detail for different analytical purposes;
- completing the standardized processing of all architectural blocks.

This comprehensive documentation will provide the geometric foundation for all subsequent analyses and interpretations, ensuring that reconstructive hypotheses remain firmly grounded in accurate spatial data.

6.1.3. Full Implementation of Stratigraphic Analysis

Building on the methodological framework established thus far, the stratigraphic analysis will be extended to encompass:

- complete modeling of proxy objects for all stratigraphic units;
- systematic documentation of construction techniques and material characteristics;
- integration of archival information on previous excavations and interventions;
- implementation of TSU to document degradation processes.

This work will create a comprehensive stratigraphic understanding of the monument's evolution, from its original construction through subsequent modifications, degradation processes, and modern restorations.

6.1.4. Virtual Anastylosis and Reconstruction

Once the documentation foundation is complete, the virtual anastylosis process will advance to:

- systematic analysis of all digitized architectural blocks;
- development of robust hypotheses for original positions based on multiple lines of evidence;
- creation of detailed reconstruction models for key architectural elements;
- generation of alternative reconstruction hypotheses where evidence permits different interpretations.
- Creating virtual reconstructions that trace the transformation of the site across time, from the Augustan Basilica to the medieval church and the Renaissance landscape.

This process will move beyond the current volumetric representations to detailed architectural reconstructions that integrate information from the surviving blocks, comparative examples, and theoretical understanding of Roman architecture.

6.2. Open Science and Data Dissemination Strategy

A fundamental goal of the Basilica Iulia Project is to make its datasets, methodologies, and tools available to the broader scientific community through a comprehensive open science approach. The planned strategy encompasses:

6.2.1. Dataset Publication

In the next months, the project will publish portions of the dataset on Zenodo, structured according to the extended metadata schema for cultural heritage developed by CNR-ISPC [BDF*23]. This dataset will include:

- Raw acquisition data (laser scans, photogrammetric images);
- processed 3D models at multiple levels of detail;
- spatialized archival imagery and documentary sources;
- stratigraphic documentation and interpretations;
- virtual anastylosis and reconstruction hypotheses;
- processing workflows and validation documentation.

The dataset will be published with clear usage licenses and a defined embargo period, ensuring both accessibility and proper attribution of this substantial research effort.

6.2.2. Methodological Documentation

Alongside the dataset, comprehensive documentation of the methodologies and workflows developed through the project will be published, including:

- Detailed protocols for data acquisition, scanning, processing, and integration, such as the 3D-STONE workflow [Boz25] for scanning architectural elements;
- guidelines for implementing the EMF in archaeological practice;
- complete s3Dgraphy ontology specification with CIDOC-CRM mapping documentation;
- case examples demonstrating collaborative workflows across domains.

This documentation will enable other research teams to adapt and implement similar approaches in different archaeological contexts.

6.2.3. Tool Publication and Development

The tools developed and refined by the project are (already) available as open-source software and will be improved:

- public repositories, not only for 3DSC and EM-Tools, but also for Heriverse;
- comprehensive documentation and tutorials;
- support for community contributions and extensions;
- regular updates based on user feedback and identified needs.

This commitment to open-source development will ensure that the tools continue to evolve beyond the project timeline, benefiting from broader community involvement.

6.3. Alignment with European Collaborative Cloud for Cultural Heritage

A key strategic goal for the Basilica Iulia Project is to align its outputs with emerging European infrastructure for digital cultural heritage. The ongoing development of the ECCCH represents a significant opportunity to ensure long-term sustainability and broader impact for the project's outcomes.

The project team is actively monitoring the development of technical standards and protocols for the European Collaborative Cloud, with plans to:

- ensure semantic compatibility through completion of s3Dgraphy ontology alignment with CIDOC-CRM;
- adopt emerging standards for 3D cultural heritage data interchange;
- structure the project's dataset to facilitate future migration to the Collaborative Cloud infrastructure;

- contribute to the definition of best practices for collaborative digital archaeology.

This alignment will position the Basilica Iulia dataset as a valuable resource within the broader European infrastructure, while ensuring its long-term accessibility and reusability.

6.4. Methodological Contributions and Broader Impact

Beyond the specific case of the Basilica Iulia, this project makes several significant methodological contributions to digital archaeology and cultural heritage more broadly:

6.4.1. Data Transformation Chain Formalization

The formalization of the DTC represents an important step toward greater transparency and reproducibility in digital archaeology. By explicitly documenting the complete process from data acquisition through processing to interpretation, the DTC addresses a critical gap in current practice. As this approach matures through the Basilica Iulia Project, it has the potential to become a standard component of digital heritage documentation, ensuring that future researchers can fully understand, evaluate, and potentially reproduce analytical processes.

6.4.2. Extended Matrix Evolution

The continued development of the EMF through this project contributes to its evolution as a comprehensive methodology for archaeological documentation and interpretation. The integration of TSU [SDB24] and the alignment with CIDOC-CRM enhance the framework's expressivity and interoperability, making it an increasingly valuable tool for complex archaeological contexts.

6.4.3. Living Lab Model for Digital Heritage

The project's Living Lab approach to tool development and methodological innovation offers a valuable model for digital heritage research more broadly. By closely integrating tool development with archaeological practice in an iterative cycle, the project demonstrates how digital technologies can evolve in response to real research needs rather than being imposed as generic solutions. This approach has significant potential for other digital heritage projects, particularly those addressing complex, multidimensional research questions.

6.5. Conclusion

The Basilica Iulia Project demonstrates how a collaborative digital ecosystem can transform archaeological practice by integrating diverse datasets, methodologies, and disciplinary perspectives within a coherent knowledge framework. While the implementation remains a work in progress, the project has already established significant methodological foundations, software development, and practical approaches that address long-standing challenges in archaeological documentation and interpretation.

The transition from current property graph implementation to full semantic web compatibility, alongside the formalization of process documentation through the DTC, represents critical milestones that will enable broader interoperability and scientific reproducibility. The transition from disconnected legacy systems to an integrated digital workflow represents not merely a technological enhancement but a fundamental shift in how archaeological knowledge is produced, validated, and shared.

By explicitly documenting the connections between physical evidence, documentary sources, analytical processes, and interpretative hypotheses, the project creates unprecedented transparency in archaeological reasoning. The collaborative nature of this ecosystem enables more holistic understanding of complex archaeological contexts by facilitating dialogue across traditional disciplinary boundaries. Archaeologists, architects, conservation scientists, and digital specialists can now work within a shared conceptual and technical framework, combining their diverse expertise to address research questions that transcend individual domains.

As the project continues to evolve, its commitment to open science ensures that the methodologies, tools, and datasets developed will benefit the broader archaeological community. By aligning with international standards and emerging infrastructure like the ECCCH, the project contributes to the ongoing digital transformation of archaeological practice while establishing new benchmarks for scientific rigor, transparency, and collaboration.

6.6. Acknowledgments

The Basilica Iulia Project is carried out within the agreement between CNR-ISPC, Sapienza University of Rome, and the Parco Archeologico del Colosseo. The project is financially supported by Sapienza University of Rome (Grandi Progetti di Ateneo 2023) and by the National Research Council of Italy (CNR), within the framework of the CHANGES – Cultural Heritage Innovation for Next-Gen Sustainable Society initiative (Spoke 8: Sustainability and Resilience of Tangible Cultural Heritage) and the project "Cultural Heritage and Creativity in the Green and Digital Transitions for Inclusive Societies" (FOE 2021).

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