

SCAN-TO-MESHBIM FOR ROMAN HERITAGE: APPLICATION TO THE UNESCO-PROTECTED EMONA ROMAN WALL

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Abstract

This article presents a Scan-to-MeshBIM methodology for heritage documentation, applied to the EMONA Roman wall complex in Ljubljana, Slovenia. The workflow pairs mesh geometry, derived via Poisson surface reconstruction and quad-remeshing, with a high Level of Information through domain ontologies stored in a triple store, linked to IFC elements via GlobalID. Unlike conventional HBIM approaches that abstract point clouds into simplified parametric representations, this methodology preserves geometric authenticity at LOA20 accuracy ($2\sigma < 50\text{mm}$) while enabling rich semantic annotation for material characterization, damage assessment, and chronological conservation cataloguing. A web-based platform built on WebIFC delivers visualization and document management without proprietary software dependencies. We argue this represents the future of IFC collaboration: online, permissionless, and software-agnostic.

1. Introduction

Building Information Modelling's asset management capabilities have long been extending into heritage conservation through Historical/Heritage BIM (HBIM) [27]. Yet a fundamental mismatch persists: BIM tools are designed for new construction with parametrizable geometries, which inadequately serve historic structures where geometry results from construction variation, centuries of repair campaigns, and partial survival [1-4]. The parametric paradigm requires defining geometric rules that generate form, an approach problematic for archaeological remains where decay patterns and material heterogeneity constitute the archaeological record itself.

The EMONA Roman settlement in Ljubljana presents an exemplary case. The surviving wall fragments, characterized by 2.4m width of an *emplekton* cross section and the palimpsest of interventions from Walter Schmid's early twentieth-century reconstructions and Jože Plečnik's 1930s monumentalization [5,6], embody the geometric irregularity and layered history that parametric BIM cannot adequately represent.

This work proposes a different approach, in line with other authors exploring mesh-based and semantically-enriched HBIM workflows [7-11]: bringing real-world geometry into IFC via a Scan-to-MeshBIM pipeline. Mesh entities are segmented into IFC elements and semantically

enriched with linked data (material, diagnosis, previous tests) stored as off-file metadata exposed via ontologies. This approach anticipates IFC5 directions, where buildingSMART is exploring USD (Universal Scene Description) for efficient geometry handling with decoupled semantic layers. We also propose an openBIM methodology by deploying on a common environment: a server running WebIFC, but processing client-side, enabling limitless concurrent accesses.

2. Case Study: EMONA Roman Wall

The EMONA archaeological complex preserves substantial remains of the Roman colony established in the 1st century CE [12,13]. The wall's technical specifications follow Vitruvian recommendations [14]: 6-8m height, with 29 trapezoidal towers positioned a bowshot apart (30-50m) for overlapping defensive coverage. Materials include Lower Jurassic limestone from Podpeč quarries bound with hydraulic mortar containing volcanic pozzolana [13,15].

The *emplekton* technique uses river cobbles, smaller stones, gravel, and brick fragments forming the inner core. It is estimated that building the 1950m perimeter required excavating over 10,000m³ of gravel and incorporating more than 30,000m³ of stone [13].

Walter Schmid's early twentieth-century rehabilitation raised surviving sections to uniform height, reinforcing with internal earth embankments and marking original/reconstructed boundaries with pebble lines [5]. Plečnik's 1930s monumentalization re-used fallen and unstable pieces and rearranged them in elements foreign to Roman military architecture: the stepped pyramid (initially turf-covered, later exposed), passages through the wall, the vaulted Lapidarium housing spolia, and the peristyle with eight conglomerate columns [5,6].

The existing archive used for enrichment of the IFC file was organized into over 400 documents, including ground-penetrating radar surveys, petrographic microscopy studies, sonic testing campaigns, and material sampling analyses [16].

3. Methodology

3.1 Data Acquisition and Mesh Reconstruction

Documentation employed terrestrial laser scanning (Leica ScanStation P40) achieving density of approximately 0.5mm at 10m, producing 50-100 million points per scan position. Photogrammetry (Canon EOS R5, 100-250 ISO, f/8-f/11) with around 80% frame overlap provided texture and damage visibility that LiDAR could not capture [17,18]. These HD meshes are offered as complementary data to the IFC.

Stage 1 processes the hybrid dataset in RealityCapture, generating dense point clouds. Stage 2 applies Poisson surface reconstruction in CloudCompare, producing watertight meshes decimated to <1M faces [19]. Stage 3 performs mesh editing in Rhino and Geomagic Design X: boundary definition, hole filling, and semantic segmentation via Boolean splits (see Figure 1). Stage 4 employs Instant Meshes for quad-remeshing using 4-RoSy field-guided parametrization, achieving 20-55K quad faces while maintaining LOA20 accuracy ($2\sigma < 50\text{mm}$, see Figure 2) [20]. Stage 5 exports to IFC4 via VisualARQ (see Figure 3 for the complete workflow).

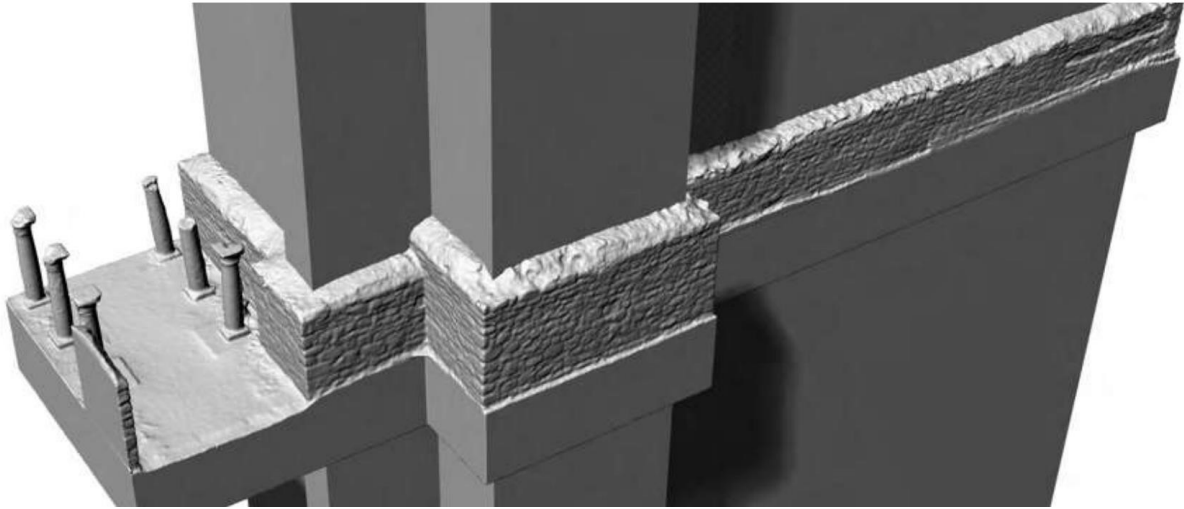


Figure 1: Boolean disjunction of the mesh model of the Section 7 of the Wall on Mirje (Peristyle passage) with auxiliary polygon volumes. In this case the separation of the emplekton (inner core) from the outer layer.

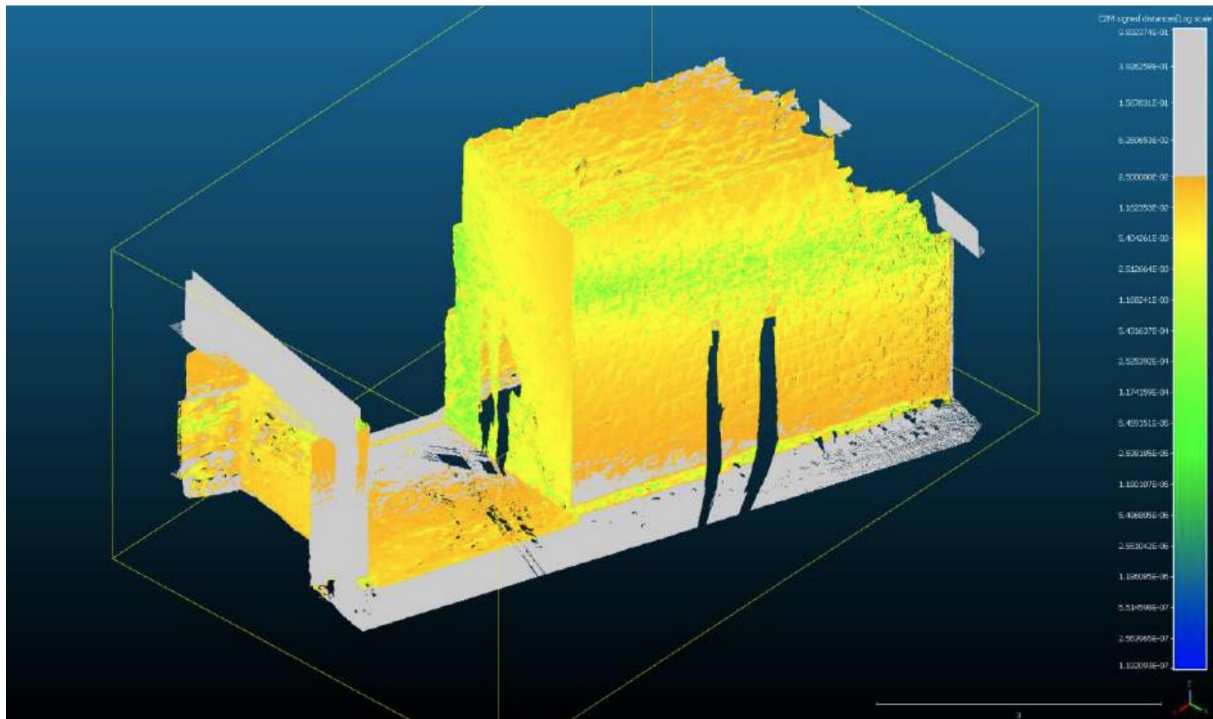


Figure 2: Distance of the point cloud data of the fragment of the Praetorian City gate, EW2, with the 25k faces quadmesh that will become the IFC, using the C2M algorithm of CloudCompare.

3.2 IFC Integration

Mesh geometry enters IFC through `IfcTriangulatedFaceSet` representation. Each segmented element becomes an `IfcBuildingElementProxy` instance (or `IfcWall` where structurally appropriate) with `GlobalID` serving as persistent identifier. Critically, the IFC file contains *only* geometry and spatial hierarchy. No property sets are embedded. All semantic information

resides in the triple store, enabling updates without IFC file modification and ensuring the IFC remains decoupleable.

3.3 Linked Data Architecture

Semantic data is stored as ontology individuals in TTL/RDF format, referencing IFC elements via GlobalID [21-24]. The main ontologies that provide classifications are: BuiltElementOntology for structural typologies, Damage Topology Ontology (DOT) for representing damage areas and their relations to affected construction elements [25,26], and MaterialPropertiesOntology linking petrographic analyses to spatial locations [27].

This separation offers advantages over embedded property sets: semantic updates require no IFC re-parsing. SPARQL queries enable complex cross-referencing ("show all elements where sampling occurred in 2022"); ontology reasoning derives implicit relationships [10,28,29].

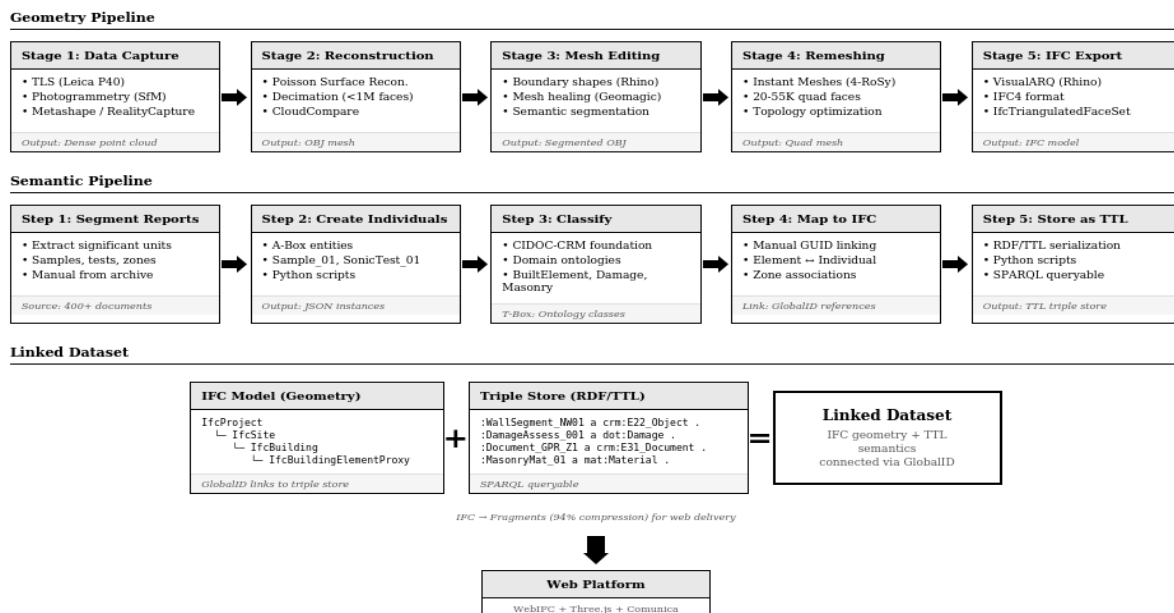


Figure 3: Scan-to-MeshBIM workflow pipeline: five stages from data capture to IFC export, with linked data architecture separating geometry (IFC) from semantics (TTL) via GlobalID.

3.4 Web Platform

The platform runs entirely in-browser using WebIFC [30] and Three.js [31]. The BIM viewer provides real-time rendering with element selection triggering linked data queries (see Figure 4), and customized SPARQL queries execute client-side via Comunica. Similar web-based approaches have demonstrated the value of accessible heritage platforms, though usability remains a challenge for non-specialist users [32].

Interoperability was validated in Solibri Model Viewer, BIMvision, and other IFC viewers: geometry displays correctly across applications. The semantic layer requires the web platform for full linked access, a trade-off preserving geometric interoperability while enabling richer capabilities than IFC property sets alone.

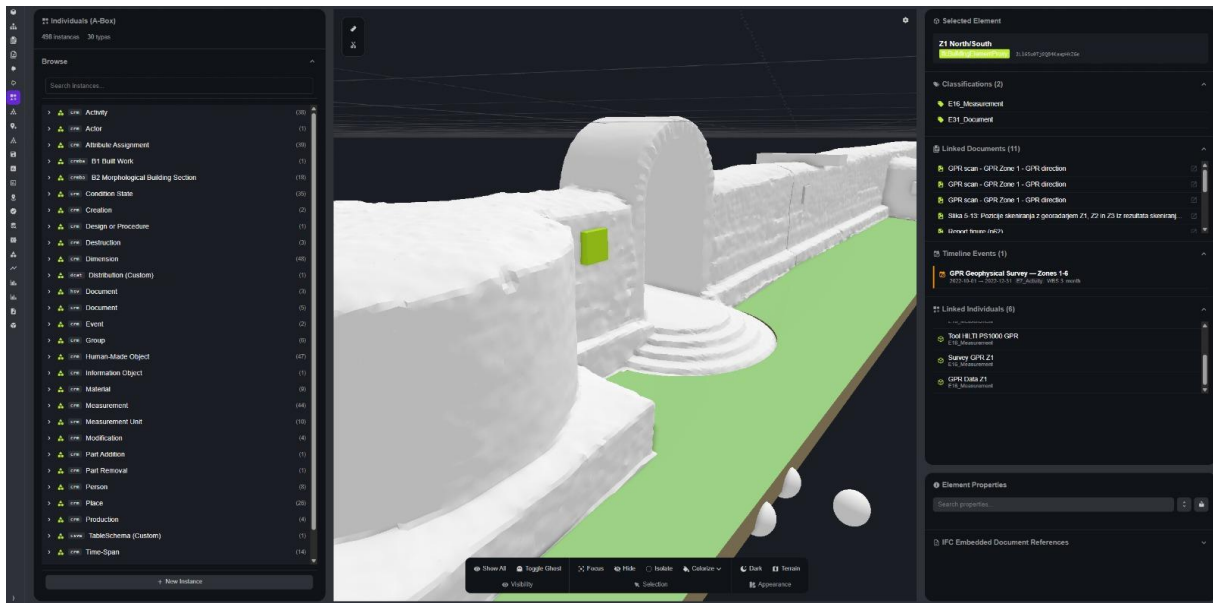


Figure 4: Web platform interface showing on the right the pool of A-Box individuals created to characterize the wall and on the left the documents and individuals and timeline events related to the selected element, which represents a GPR test location from 2022.

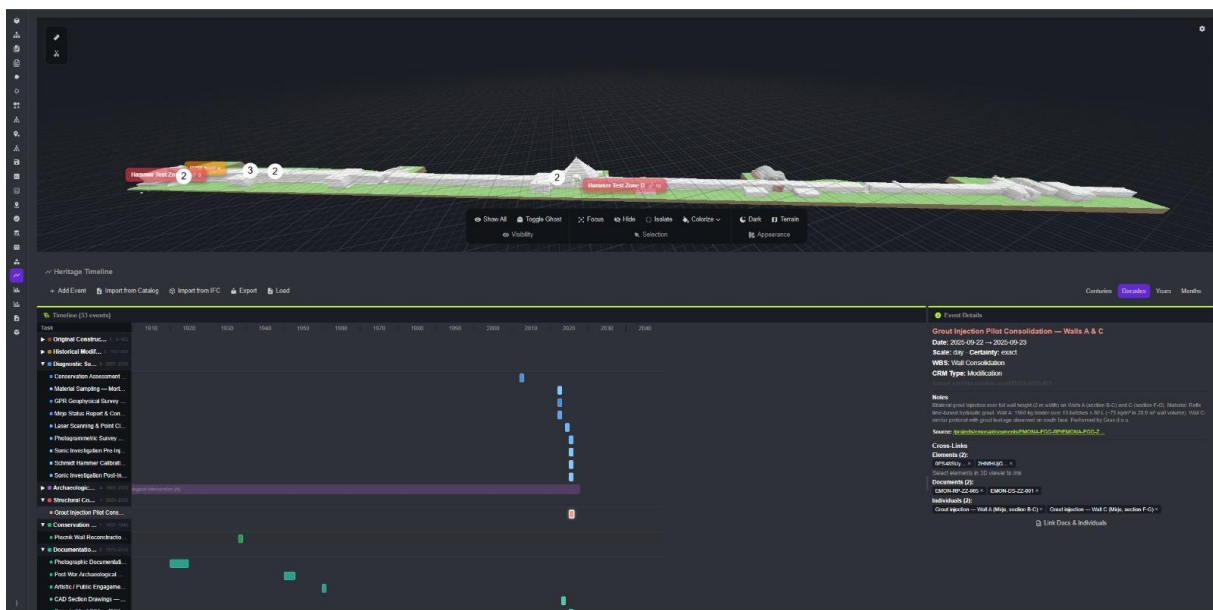


Figure 5: Web platform interface showing 3D visualization of the IFC model of the main section of the wall, with 3D annotations mapping to timeline events and documents.

4. Results and Discussion

The central advantage lies in preservation of surveyed geometry. Conventional HBIM interprets point clouds to create parametric models, necessarily involving geometric idealization [8,9]. Mesh-based representation directly encodes surveyed geometry: the triangulated surface

approximates the point cloud within controlled tolerances, retaining irregularities, damage patterns, and construction variations that constitute the archaeological record. This is particularly useful for new persons being introduced to the site, since they can instantly recognize the features of the forms.

Figure 6 presents comparative analysis across eight dimensions. The mesh methodology demonstrates advantages in geometric authenticity, software requirements (browser-only vs. commercial licenses), and alignment with IFC5 directions. Modeling effort reduces from days of manual reconstruction to hours of semi-automatic processing through the Poisson/quad-remesh pipeline.

Fig. 6. Conventional HBIM vs. Scan-to-MeshBIM: Comparative Analysis Applied to EMONA

Aspect	Conventional HBIM <i>Parametric reconstruction from surveys</i>	Scan-to-MeshBIM (This Work) <i>Direct mesh integration with linked semantics</i>
Geometric Fidelity	● Interpreted geometry Operator reconstructs idealized forms from point cloud; wall sections become regular rectangles EMONA: 2.4m embleton thickness averaged; actual 2.2-2.6m variation lost	● Survey-grade accuracy (LOA20) IfcTriangulatedFaceSet directly encodes Poisson mesh; $2\sigma < 50\text{mm}$ deviation from point cloud EMONA: Every bulge, crack, and repair scar in EW1-EW4 fragments preserved
Surface Evidence	● Lost in abstraction Tool marks, weathering patterns, repair campaigns simplified to flat surfaces EMONA: Schmid's pebble demarcation lines invisible; Plečnik insertions indistinguishable	● Full surface topology Mesh preserves sub-centimeter features; damage patterns available for analysis EMONA: GPR anomaly zones (Z1-Z6) correlate visually with mesh deformations
Semantic Depth	● IFC Property Sets Key-value pairs; limited to predefined schemas; no cross-referencing Material = "Limestone"; no link to which quarry, which analysis report, which date	● Ontology individuals (CIDOC-CRM) Full knowledge graph; SPARQL queryable; reasoning-capable "Show all elements with Podpeč limestone AND GPR anomalies AND sampling before 2020"
Document Linking	● IfcDocumentReference File path or URL; no classification; no temporal context Report attached to wall element; relationship to specific test location unclear	● Typed document individuals crm:E31 Document with production dates, authors, subjects, spatial scope 400+ docs: GPR surveys → zones; petrography → samples → elements → timeline
Software Access	● Commercial licenses required Revit/ArchiCAD for authoring; version dependencies; institutional barriers Slovenian heritage office needs same software version as Ljubljana faculty	● Browser-only (WebIFC + Three.js) No installation; works on any device; concurrent users unlimited MGML museum staff, UL researchers, ZVKDS inspectors access same platform
Update Workflow	● Re-export entire IFC Property change requires BIM software; file versioning challenges Adding 2024 sonic test results means re-exporting 571MB IFC file	● TTL update only Semantic layer edits independent of geometry; IFC untouched New petrographic analysis: add TTL triple, link via GUID, instant availability
IFC5 Readiness	● Migration required EXPRESS→USD transition; parametric definitions need rethinking Current Revit families incompatible with component-based IFC5 architecture	● Architecture already aligned Mesh geometry + modular semantics mirrors USD + JSON-LD direction GlobalID linking strategy transfers directly to IFC5 component model
Production Time	● Days to weeks per element Manual tracing; family creation; interpretation decisions Single tower reconstruction: 3-5 days skilled operator time	● Hours per element Poisson → decimate → segment → quad-remesh → IFC pipeline EW2 fragment (Praetorian gate): 4 hours from point cloud to IFC

● Clear advantage ● Partial / context-dependent ● Limitation

Comparison based on EMONA Roman Wall implementation. Conventional HBIM advantages (parametric flexibility, established workflows) apply better to buildings with regular geometry.

Figure 6: Comparative analysis: Conventional HBIM vs. Scan-to-MeshBIM across eight methodological dimensions including geometric representation, archaeological authenticity, software requirements, and future standards alignment.

The linked data architecture demonstrates particular advantages for heritage contexts [29,33]. The EMONA implementation manages over 400 sub-documents (report-derived entities and pictures) linked to mesh objects with full ontological classification.

Limitations include large IFC file sizes; complementary data visualization (point clouds and original HD meshes) constraining web rendering of very large datasets; mesh reconstruction requiring expert judgment for complex geometries [11,34]; and ontology integration presenting usability challenges for non-specialist users [32].

4.1 Future Developments

A user manual for efficient platform use is needed, since the majority of test users did not find it intuitive.

For true multimodal datasets, adding Gaussian Splatting visualization capabilities and tests with HD mesh rendering via GLB hierarchized in several LODs for seamless streaming are ongoing. Knowledge graph visualization must be improved to enable hierarchical understanding of the information.

An autonomous natural language processing workflow which automatically segments reports and other document types into A-Box instances is planned. At the moment the process is still hybrid.

Storing the IFCs as .frag format directly would reduce load times, requiring only an IFC GUID to fragment ID mapper.

5. Conclusion

This article has presented a Scan-to-MeshBIM methodology applied to the EMONA Roman wall and an experimental platform to visually interact with the data. By preserving mesh geometry derived directly from laser scanning rather than abstracting to parametric forms, the methodology maintains surveyed accuracy while enabling BIM functionality. Integration of ontologies via linked data provides semantic depth supporting advanced analysis. The web-based, open-standards platform extends capability across institutional boundaries.

Heritage documentation serves purposes extending beyond immediate conservation planning [33], and we argue these types of archives are a way forward in de-siloifying the normally very opaque fields of heritage records, which most of the time already exist but are tucked away in a drawer, locked server, or proprietary software. Open standards, web accessibility, and semantic richness reflect this long-term responsibility.

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