From Pocket to Knowledge Graph: Low-Cost 3D Capturing with Smartphones and Semantic FAIR Modelling in the SquirrelBase

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Abstract
Low-cost smartphone-based Structure-from-Motion (SfM) acquisition using tools such as the KIRI Engine enables rapid, accessible three-dimensional documentation of cultural heritage objects, ephemeral structures, and artistic installations. However, the resulting binary 3D artefacts — mesh files, textures, and associated data — typically exist outside the Linked Open Data (LOD) and RDF world, limiting their integration into semantic research infrastructures. This paper presents a workflow that bridges this gap by packaging 3D artefacts as FAIR Digital Objects (FDOs) using lightweight metadata files (MD.cff, CITATION.cff) and semantic crosswalks, generating RDF representations aligned with DCAT, CIDOC CRM, and GeoSPARQL. The resulting FDOs are ingested into the SquirrelBase, a Wikibase instance acting as a semantic meta-hub for 3D objects, assigning persistent Q-identifiers and enabling SKOS-based alignment with Wikidata and OpenStreetMap. Five case studies from the South Tyrolean Dolomites, Cologne, Kassel, and Graz demonstrate how objects ranging from ephemeral ice sculptures to urban art installations can be connected to the Federated Knowledge Graph Ecosystem and made findable, interoperable, and reusable in sustainable ways.

Keywords Low-Cost 3D · FAIR Digital Objects · SquirrelBase · Federated Knowledge Graph · Semantic Alignment

1 Introduction

The spontaneous 3D capturing of objects encountered in everyday life, from cairns balanced on frozen lakes to ephemeral ice sculptures and urban art installations, has become technically feasible for anyone carrying a modern smartphone. Structure-from-Motion (SfM) applications such as the KIRI Engine allow citizen scientists and researchers alike to capture high-resolution 3D models from a series of photographs within minutes, effectively turning a pocket device into a portable digitisation laboratory. Yet the resulting binary artefacts, including mesh files, texture maps, and associated documentation, typically remain isolated digital objects: stored on personal devices or uploaded to visualisation platforms, but disconnected from the semantic infrastructures that make research data FAIR: findable, accessible, interoperable, and reusable (Wilkinson et al., 2016). This disconnection represents a fundamental challenge for sustainable 3D documentation. Whilst Linked Open Data (LOD) and RDF-based knowledge graphs have become established tools for interlinking cultural heritage metadata (Berners-Lee, 2006; Schmidt et al., 2022), binary 3D data formats sit outside the RDF world by their very nature. Metadata describing the acquisition process, the documented object, its spatial context, and its temporal extent cannot simply be embedded in a mesh file in a machine-actionable way. Therefore, 3D models of ephemeral or at-risk objects, that is, structures that may no longer physically exist shortly after capture, risk becoming inaccessible and uncitable, despite their potential scientific and cultural value. FAIR Digital Objects (FDOs) have been proposed as a conceptual solution to this problem, encapsulating digital artefacts, their metadata, persistent identifiers, and contextual information into typed, machine-actionable units (Schwardmann, 2020). When combined with community-curated knowledge bases such as Wikibase instances and federated SPARQL endpoints, FDOs offer a pathway for binary research artefacts to participate as first-class entities in what may be described as a Federated Knowledge Graph Ecosystem, a distributed, interoperable network of RDF triplestores, controlled vocabularies, and shared ontologies.

This paper presents a concrete workflow that realises this pathway for low-cost smartphone-based 3D acquisition. Starting from a self-contained artefact package, the approach generates RDF-based FDO representations. It ingests them into *SquirrelBase*, a dedicated Wikibase instance that serves as a semantic meta-hub for 3D objects. The workflow is

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illustrated through five case studies drawn from the Research Squirrel Engineers Network, spanning ephemeral natural formations in the South Tyrolean Dolomites, urban art installations in Cologne, a landmark conceptual art project in Kassel, and a permanent sculpture in Graz. Together, these examples demonstrate that the journey from pocket to knowledge graph is not only technically feasible but reproducible, open, and scalable. The paper introduces the conceptual framework, describes the FDO workflow and SquirrelBase architecture, presents the case studies, and concludes with a discussion of findings and an outlook.

2 Conceptual Framework

The approach presented in this paper rests on three complementary conceptual pillars: the FAIR principles as a normative baseline for research data management, FAIR Digital Objects as a mechanism for making binary artefacts machine-actionable, and the Federated Knowledge Graph Ecosystem as the target infrastructure into which these objects are integrated. A fourth element, the SquirrelBase as a domain-specific Wikibase instance, serves as the semantic hub connecting all three. Together, they define the conceptual space in which low-cost 3D artefacts move from isolated binary files to interconnected, citable, and queryable entities (Fig. 1).

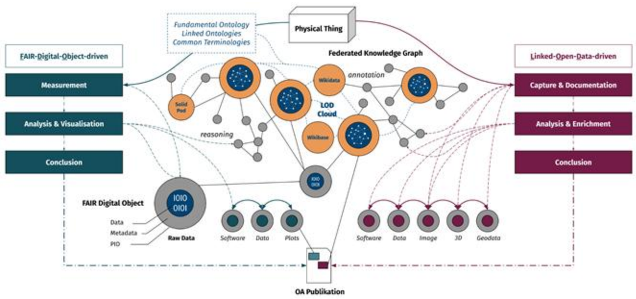

Figure 1. Scheme of the FDO- and LOD- driven Federated Knowledge Graph Ecosystem. Florian Thiery & Andreas Noback, CC BY 4.0.

FAIR Principles and Linked Open Data. The FAIR principles (Findable, Accessible, Interoperable, and Reusable) provide an established normative framework for sustainable research data management (Wilkinson et al., 2016). Whilst widely adopted, their operationalisation for binary data formats such as 3D models remains non-trivial. Linked Open Data (LOD), as defined by Sir Tim Berners-Lee, offers a complementary technical approach: by representing data as RDF triples with dereferenceable URIs, resources become interoperable across institutional and disciplinary boundaries. The combination of FAIR and LOD has been demonstrated to be particularly powerful in archaeological and heritage contexts, where heterogeneous data from diverse sources must be aligned and cross-queried (Schmidt et al., 2022). However, LOD infrastructures natively address metadata and semantic content, leaving a significant gap for binary 3D research outputs.

FAIR Digital Objects. FAIR Digital Objects (FDOs) conceptualise research outputs as typed, self-contained, and machine-actionable units that bundle digital content with persistent identifiers and rich metadata (De Smedt et al., 2020; Schwardmann, 2020). An FDO is not defined by a specific storage technology but by its role as a stable, semantically described, and persistently addressable entity. For 3D data, this means that a mesh file, together with its acquisition metadata, spatial context, temporal extent, and provenance information, can be encapsulated in a single, citable, and machine-readable object. A concrete operationalisation of these principles for packaged research artefacts, using lightweight metadata files (MD.cff for descriptive metadata, CITATION.cff for attribution) and semantic crosswalks to established vocabularies such as DCAT, CodeMeta, and PROV-O, is provided by the FDO*x* (FAIR Data Object, exchangeable) Squirrel reference implementation (Thiery, 2026a). The metadata schema for the heritage domain extends this base with domain-specific fields covering object type, material, acquisition technique, spatial coordinates, and conservation status (Fig. 2).

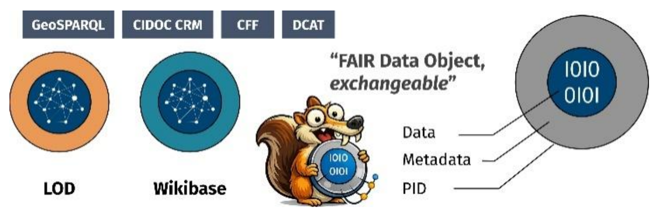

Figure 2. Scheme of the FDO- and LOD- driven Concepts. Florian Thiery, CC BY 4.0.

The Federated Knowledge Graph Ecosystem. The Federated Knowledge Graph Ecosystem combines RDF triplestores, community-curated knowledge bases such as Wikidata and specialised Wikibase instances, shared ontologies, and persistent identifier infrastructures into a distributed, interoperable network (Thiery, Rossenova, et al., 2025). Within this ecosystem, data and metadata can be queried, linked, and reused via open standards including SPARQL and GeoSPARQL across institutional and disciplinary boundaries. Metadata ontologies for the 3D acquisition domain, notably the schema proposed by Homburg et al. (2021), provide formal vocabularies for describing scanning workflows, equipment, and processing steps in RDF, enabling 3D acquisition metadata to participate directly in such federated environments.

SquirrelBase. The SquirrelBase is a Wikibase instance developed within the Research Squirrel Engineers Network, serving as a semantic meta-hub for 3D objects (https://squirrelbase.wikibase.cloud). Like Wikidata, it assigns persistent Q-identifiers to each registered object, enabling stable, citable references independent of any specific visualisation platform. Each SquirrelBase item stores identifiers linking to external resources, such as Wikidata Q-IDs, OpenStreetMap node or relation identifiers, and representative geographic coordinates, as well as structured metadata about the 3D acquisition, including method, hardware, software, creator, and licence. Crucially, the SquirrelBase implements a SKOS-based semantic alignment model that expresses the degree of connection between a registered 3D object and terms in external knowledge bases using mapping properties (skos:exactMatch, skos:closeMatch, skos:relatedMatch), and is extended with a graduated seven-star alignment score (Thiery, 2026b). This allows, for instance, a 3D scan of a cairn to be linked to the Wikidata concept of a cairn with an exactMatch at seven stars, whilst simultaneously being related to its specific geographic location in OpenStreetMap with a relatedMatch at three stars. The FDO URL for each object is stored as a dedicated property, directly connecting the SquirrelBase item to the machine-actionable RDF representation of the packaged artefact.

The interplay of these four pillars is illustrated in Figures 1 and 2, which show the full conceptual pathway from a physical object through measurement and binary capture, FDO packaging, and SquirrelBase ingestion, to participation in the Federated Knowledge Graph Ecosystem.

3 Methodology

The workflow presented in this paper transforms a smartphone-captured 3D model into a machine-actionable FAIR Digital Object and integrates it into the SquirrelBase and the wider Federated Knowledge Graph Ecosystem. The process comprises five sequential steps: acquisition, publication, FDO packaging, SquirrelBase ingestion, and federated querying. Each step is described below.

Step 1: 3D Capturing with the KIRI Engine. 3D models are captured, e.g., using the KIRI Engine, an AI-assisted smartphone application that implements Structure-from-Motion (SfM) photogrammetry. The user takes photos of the target object from multiple angles; the application automatically aligns the images, constructs a dense point cloud, and generates a textured mesh. The resulting model is exported in multiple formats (e.g., GLB, PLY, NXS, and NXZ) to ensure compatibility with different downstream visualisation and processing environments. The entire acquisition process requires no specialist equipment beyond a modern smartphone and can be completed in the field within minutes, making it genuinely accessible to citizen scientists and researchers without dedicated hardware budgets (Thiery, Schenk, & Thiery, 2025).

Step 2: 3D Publication. Prior to FDO packaging, the 3D model is published on one or more open visualisation platforms to ensure human-accessible presentation. The SquirrelBase workflow supports two primary publication targets: Sketchfab, a widely used interactive 3D platform accessible to broad audiences, and 3DHOP (Three-Dimensional Heritage Online Presenter), an open-source framework for scientific web-based 3D visualisation hosted on the Research Squirrel Engineers infrastructure at archaeosquirrels.cloud. Whilst Sketchfab offers broad discoverability, its proprietary nature introduces long-term sustainability risks; 3DHOP provides full institutional control over hosting and is therefore preferred for scientific archiving. Both platform URLs are stored as qualified statements in the SquirrelBase with full acquisition qualifiers.

Step 3: FDO Packaging. The core methodological contribution of the workflow is the transformation of the 3D artefact into a FAIR Digital Object using the fdo-squirrel reference implementation FDO*x*. The input is a self-contained ZIP archive bundling the binary model files together with two lightweight metadata files: *MD.cff*, which encodes descriptive object metadata including FDO type (fdo:3DDataFDO), persistent identifier, title, spatial coordinates, temporal extent, acquisition technique, object type, material, condition, and conservation urgency; and *CITATION.cff*, which encodes attribution and citation metadata including authors, licence, and version. The fdo-squirrel toolchain ingests and validates these inputs, classifies each file within the archive according to a role vocabulary (fdo:role = model, fdo:role = metadata, fdo:role = documentation), and maps metadata fields to established RDF vocabularies via explicit crosswalk rules: DCAT for dataset description, CodeMeta for software and dataset attribution, PROV-O for provenance, CIDOC CRM and CRMdig for heritage object semantics, and GeoSPARQL for spatial representation. The output is a structured RDF serialisation (fdo-metadata.ttl) together with a human-readable modelling report. The complete FDO package is deposited on Zenodo, receiving a persistent DOI that serves as the canonical identifier for the object across all downstream systems. The structure of this packaging process is shown in Fig. 3, whilst a concrete example of the resulting MD.cff structure is illustrated in Fig. 4.

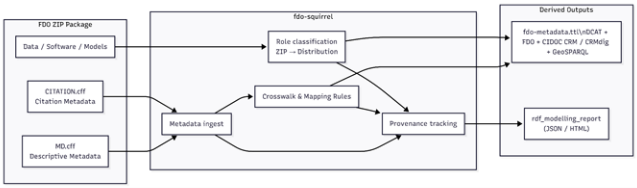

Figure 3. The FDO*x* Workflow. Florian Thiery, CC BY 4.0.

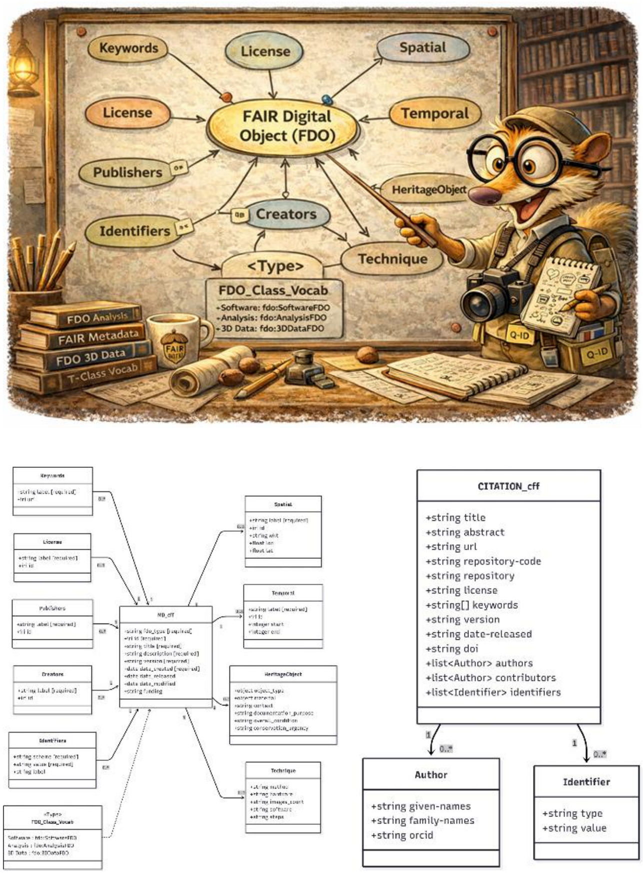

Figure 4. The FDO*x* Metadata. Florian Thiery, CC BY 4.0, top created using OpenAI's DALL·E.

Step 4: SquirrelBase Ingestion. Once the FDO has been deposited and its DOI confirmed, the object is registered in the SquirrelBase. Each item receives a persistent Q-identifier and is populated with two categories of statements. The Identifier & Metadata section stores the Wikidata Q-ID of the documented object, its OpenStreetMap node, way, or relation identifier, and its representative geographic point as a WKT geometry. The ThreeDDataAsURL section stores qualified links to the KIRI Engine model, the 3DHOP viewer URL, and the Sketchfab URL, each annotated with acquisition qualifiers. The FAIRDigitalObject section stores the Zenodo DOI of the FDO package together with its type, format, licence, and release version. Finally, SKOS-based alignment statements connect each item to terms in external knowledge bases: each AlignedWithTerm statement records the target URI, the mapping property type, a seven-star alignment score, the source repository, and the alignment rationale, making the degree of semantic connection explicit and queryable.

Step 5: Federated SPARQL Queries. The final step demonstrates the analytical potential of the integrated workflow. Because all SquirrelBase items expose their geometry via GeoSPARQL-compatible WKT literals and their semantic alignments via SKOS properties, they can be queried in conjunction with Wikidata, OpenStreetMap-derived datasets, and other Wikibase instances using federated SPARQL. The *SPARQLing Unicorn QGIS Plugin* (Thiery, Schenk, & Thiery, 2025) provides a practical interface for executing such federated queries and visualising the results as georeferenced layers within a GIS environment, enabling spatial analysis across heterogeneous knowledge graph sources without requiring custom integration code.

4 Use Cases

The following five case studies illustrate the workflow across a range of object types and documentation contexts. All objects are registered in the SquirrelBase with FDO packages deposited on Zenodo, grouped into three thematic categories.

4.1 Ephemeral Natural Formations

The first two case studies document spontaneously encountered, inherently temporary formations in the South Tyrolean Dolomites, captured in January 2026. Both objects ceased to exist within days, leaving their FDO representations as the sole surviving records.

Lago di Anterselva: Steinmännchen (Q60). A hand-built cairn (a "Steinmännchen") was encountered on the frozen surface of the Lago di Anterselva (Antholz/Anterselva, South Tyrol) on 3 January 2026. The object was captured using a Samsung Galaxy S22 with the KIRI Engine application, producing a photogrammetric model from a series of photographs taken in the field. The resulting FDO package (DOI: 10.5281/zenodo.18732892) contains 64 files, including GLB model data, acquisition metadata in MD.cff and CITATION.cff, and 61 photographic documentation images. In the SquirrelBase (Q60), the object is registered as a temporal object with a representative point at 46°53′18.1032″N, 12°10′11.568″E, aligned to the Wikidata concept of Steinmännchen (wd:Q7321974) via skos:exactMatch at seven stars, to the Getty AAT concept of cairns (aat:300006960) via skos:exactMatch at seven stars, and to the Antholzer See as a temporal site in both Wikidata and OpenStreetMap via skos:relatedMatch. The temporal extent is recorded using ChronOntology (dfwAgTD5WMEV, start: 2026, end: 2026), indicating that the object exists as a single-season phenomenon (Fig. 5).

Figure 5. Q60. Florian Thiery, CC BY 4.0.

Lago di Braies: Eismännchen (Q20, Q21). Two ice formations, spontaneous sculptures assembled from blocks of ice along the frozen shore of the Lago di Braies (Prags/Braies, South Tyrol), were documented during a fieldwork visit on 5th January 2025. Q20 captures a larger composite formation resembling a stacked figure, whilst Q21 documents a tall, tower-like ice column balanced on a rock. Both were captured with the KIRI Engine and are registered as individual SquirrelBase items with separate FDO packages, spatial coordinates, and temporal alignments. As with Q60, the physical objects no longer exist; the 3D models, together with their semantic FDO representations, constitute the only durable record of these formations.

Taken together, Q20, Q21, and Q60 exemplify that low-cost smartphone SfM, when combined with FDO packaging and SquirrelBase registration, enables the preservation of objects that would otherwise leave no trace in any research infrastructure (Fig. 6).

4.2 Urban & Conceptual Art

The second group of case studies documents objects from two established artistic contexts in German cities, demonstrating the workflow's applicability to modern cultural heritage with rich existing documentation in external knowledge bases.

Figure 6. Q20 & Q21. Florian Thiery, CC BY 4.0.

Cologne: Heinzelmännchen "Heinz Eau" (Q55). The Heinz Eau is one of the Heinzelmännchen figures distributed throughout Cologne as part of the Heinz Welt urban art project, a series of small bronze sculptures that reference the Cologne legend of the Heinzelmännchen as retold by August Kopisch. The figure, a gnome seated in a bathtub holding a bottle of Eau de Cologne, is located at OSM node/12848270361 in the Glockenstraße. It was captured on 25 July 2025 using a Samsung Galaxy S22 with the KIRI Engine, and its FDO package (DOI: 10.5281/zenodo.18740523) contains 32 files. In the SquirrelBase (Q55), the object is aligned to the Wikidata concept of Heinzelmännchen (wd:Q537513) via skos:exactMatch at seven stars, to the specific Kölner Heinzelmännchen Weg trail (wd:Q138425168) via skos:relatedMatch at three stars, and to the Heinzelmännchen poem by Kopisch (wd:Q330568801) via skos:relatedMatch at three stars, reflecting the layered cultural context of the object (Fig. 7).

Figure 7. Q55. Florian Thiery, CC BY 4.0.

Kassel: Beuys-Stele B 1036, "7000 Eichen" (Q56). The second urban art case study documents one of the 7,000 oak tree-basalt stele pairs planted across Kassel as part of Joseph Beuys's landmark conceptual art project 7000 Eichen, initiated at documenta 7 in 1982. Stele B 1036 is located at OSM node/3647679932 (51°18′47.2471″N, 9°29′53.569″E). It was captured on 14 July 2025 using a Samsung Galaxy S22 with the KIRI Engine, producing an FDO package (DOI: 10.5281/zenodo.18742693) containing 46 files with an OBJ model. The SquirrelBase item (Q56) carries four alignment statements: to the 7000 Eichen OSM relation (relation/4629093) via skos:closeMatch at six stars with the description "art project" and source "Literature"; to the Wikidata item for 7000 Eichen (wd:Q261274) via skos:closeMatch at six stars; to the Wikidata item for Beuys Basaltstele (wd:Q138426002) via skos:exactMatch at seven stars as object type; and to Joseph Beuys (wd:Q53065) via skos:relatedMatch at four stars as artist. This layered alignment, connecting the physical stele, the artwork series, the artist, and the geographic infrastructure, demonstrates how the SquirrelBase model supports nuanced semantic description of objects embedded in complex cultural contexts.

4.3 Permanent Sculptural Installation

Graz: "Das Erforschen der Dauer" by Manfred Erjautz (Q59). The final case study documents a permanent sculptural installation at the Universalmuseum Joanneum in Graz: a life-sized marble snowman with coal eyes, a carrot nose, and a puddle of water cast around its base, created by the Austrian artist Manfred Erjautz (Fig. 8).

Figure 8. Q59. Florian Thiery, CC BY 4.0.

The work, whose title translates as "Exploring the Duration", deliberately interrogates the boundary between the ephemeral and the permanent: a snowman rendered in marble, eternally melting yet never gone. It was captured on a visit to Graz using the KIRI Engine and is registered in the SquirrelBase as Q59. Whilst this object, unlike the Dolomites formations, does physically persist, its conceptual subject matter, duration, impermanence, and the tension between material and idea, make it a fitting conclusion to the case study sequence. Its FDO representation connects the 3D scan to the artist's Wikidata entity, the museum's geographic location in OpenStreetMap, and the broader discourse on ephemeral art through SKOS-aligned semantic statements. Together with the preceding four case studies, it demonstrates that the workflow is equally applicable to permanent, temporary, and entirely vanished objects, and that the semantic richness of the resulting knowledge graph entries scales with the availability of external reference data.

5 Discussion & Conclusions

The five case studies presented in Section 4 demonstrate that the pathway from a smartphone in a jacket pocket to a semantically interconnected node in the Federated Knowledge Graph Ecosystem is not only technically feasible but practically reproducible across a wide range of object types, cultural contexts, and documentation motivations. From a frozen cairn at the Lago di Anterselva to a marble snowman in Graz, the workflow consistently produces machine-actionable, persistently identified, and semantically aligned research outputs from nothing more than a consumer smartphone and a sequence of open-source tools. Several methodological observations merit discussion. The FDO packaging step, which transforms a ZIP archive containing binary mesh files and lightweight metadata into an RDF representation aligned with DCAT, CIDOC CRM, and GeoSPARQL, is the critical bridging operation in the workflow. Without this step, the 3D models remain isolated binary artefacts, accessible for human inspection via Sketchfab or 3DHOP but invisible to the semantic query infrastructure. The fdo-squirrel reference implementation FDO*x* makes this transformation explicit, reproducible, and auditable through provenance tracking, lowering the barrier for adoption considerably. The MD.cff metadata schema, extended with heritage-specific fields for object type, material, condition, acquisition technique, and spatial and temporal extent, is sufficiently expressive to cover the full range of case-study objects without requiring domain-specific ontology engineering at the point of capture. The SquirrelBase SKOS alignment model adds a further layer of analytical value that goes beyond simple identifier linking. By recording not only the target URI of an alignment but also its mapping type, a graduated seven-star score, the source repository, and a human-readable rationale, the model makes the epistemological basis of each semantic connection explicit and queryable. This is particularly relevant for objects embedded in complex cultural contexts, as demonstrated by the Beuys-Stele case study, where a single physical object carries meaningful semantic relationships to an artwork series, an artist, a specific object type, and a geographic infrastructure, each at a different degree of connection. The ability to express and query these graduated alignments federatedly across SquirrelBase, Wikidata, and OpenStreetMap simultaneously represents a significant advance over simple same-as linking.

The comparison between ephemeral and temporal/permanent objects in the case study sequence also yields an important conceptual insight. For the ice formations at the Lago di Braies and the cairn at the Lago di Anterselva, the FDO representation is not merely a convenient supplement to the physical object: it is the only surviving record. In these cases, the workflow fulfils a preservation function that no amount of metadata enrichment after the fact could replicate. This argues for integrating FDO packaging into the acquisition workflow from the outset, rather than treating it as a post-processing step, and reinforces the practical value of low-cost, in-field documentation tools for citizen science communities engaged in heritage recording. Several limitations deserve acknowledgement. The fdo-squirrel implementation does not yet address persistent identifier resolution or data type registries, and DOI-based identification depends on Zenodo's continued operation. SfM model quality remains variable and sensitive to lighting and photographic coverage, without automated quality assessment. SKOS alignment scores rely on human judgment and lack automated suggestion support. SquirrelBase depends on sustained curatorial effort to maintain long-term data quality.

Looking ahead, several directions for future development emerge naturally from the present work. The integration of persistent identifier services and richer FDO type registries would strengthen the machine-actionability of the generated objects and bring the implementation closer to the full FDO framework specification. Automated quality metrics for SfM mesh outputs could be incorporated into the MD.cff schema as additional technique fields, enabling downstream filtering by geometric accuracy. AI-assisted semantic annotation, for instance, automatic suggestion of Wikidata alignment candidates based on object type and geographic context, would reduce the manual effort required for SquirrelBase ingestion and improve consistency across contributors. The workflow is also well-positioned for integration into larger research data infrastructures such as NFDI4Objects (von Rummel et al., 2025), where FDO-based 3D data could participate directly in the FAIR Object Biography lifecycle alongside other object-related research data.

In conclusion, this paper has shown that low-cost smartphone-based 3D acquisition, when combined with FDO packaging and semantic registration in a dedicated Wikibase instance, can produce research outputs that are genuinely findable, accessible, interoperable, and reusable – not as an aspiration, but as a demonstrable, reproducible outcome. The journey from pocket to knowledge graph is short, open, and well-signposted. The squirrel approves.

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Author Contributions

Florian Thiery – Conceptualisation, Data curation, Formal analysis, Methodology, Project administration, Software, Visualisation, Writing – original draft, Writing – review & editing.

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