

Interpretable Uncertainty in Colonial Collection Research: User-Informed Requirements and a Lightweight Modelling Pattern for Semantic Infrastructures

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Abstract

Uncertainty annotations such as "*confidence = 0.7*" are increasingly prevalent in semantic infrastructures for Cultural Heritage and Digital Humanities, where they render uncertainty machine-readable and support ranking, filtering, and aggregation processes. In collection and provenance research, however, attributions frequently rest on fragmentary evidence, competing interpretations, and ongoing scholarly debates, such that numerical precision without an explicit reference frame remains semantically underdetermined. This paper investigates how uncertainty in RDF-based knowledge graph infrastructures can be modelled and published in ways that make it not only machine-readable but also interpretable, revisable, and responsibly reusable. The guiding thesis is that uncertainty is not a property of an object but a feature of a research judgment. We formulate a typology of uncertainty forms relevant to DH and CH research and show why each resists scalar representation. To ground requirements in practice, we report insights from an exploratory workshop with 15 professionals from Galleries, Libraries, Archives, and Museums (GLAM), analysed using Reflexive Thematic Analysis in light of an Human-Computer Interaction-informed perspective on interpretability, from which recurring requirements emerge concerning transparent uncertainty marking, authorship, temporality, revisability, and the visibility of alternatives. On this basis, we propose a lightweight modelling pattern that represents uncertainty as an attributed, contextualised, and referenceable evaluation of a claim. We illustrate it with a case of conflicting narratives from *Sammlung Kulturen der Welt* in Lübeck, where at least five epistemically incompatible claims coexist, a complexity no scalar value can capture.

Keywords

Uncertainty Representation, Information Transparency, Human-Centred Design

1. Introduction

"*Confidence = 0.7*". Such values appear precise. Percentages and decimal figures suggest measurability and objectivity. In data-driven infrastructures, they seem well suited to rendering uncertainty machine-readable and amenable to algorithmic processing. Yet in many humanistic knowledge contexts, and particularly in collection and provenance research, the stable reference frame that would support such precision is frequently absent [1, 2, 3]. This uncertainty is not a marginal phenomenon but a constitutive one. Acquisition contexts are often only fragmentarily documented, attributions are contradictory [4], interpretations are perspectively situated [5], and normative evaluations are subject to ongoing scholarly and societal negotiation [6, 7]. In collections shaped by colonial histories, polyvocality [8], conflicting narratives [6], and ethical sensitivities [9] are especially pronounced. In this context, we define uncertainty not as a lack of information or a quantifiable probability, but as a structural feature of the epistemic situation in which research judgments are made. It arises where knowledge claims cannot be fully grounded in available evidence, whether due to source gaps, competing interpretations, methodological constraints, or unresolved normative questions [10, 11]. In parallel, Cultural Heritage (CH) and Digital Humanities (DH) have increasingly adopted semantic technologies [12], ontologies [13], and knowledge graphs [14]. This shift raises questions that extend beyond technical implementation.

SemDH 2026: Third International Workshop of Semantic Digital Humanities. Co-located with ESWC 2026, May 10, 2026, Dubrovnik, Croatia

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What matters is not merely the digital availability of data, but how modelling decisions shape their future researchability [15, 16], traceability [4, 17], and accountability [16]. Semantic infrastructures are not merely technical carriers. They stabilise interpretations and orders of relevance, embedding assumptions that become invisible precisely because the infrastructure continues to function [3, 18]. In such infrastructures, uncertainty is frequently operationalised through numerical confidence or probability values that govern ranking and filtering processes [19], threshold-based workflows [20], and automated enrichment pipelines [21]. What originates as a provisional research judgment is received as stable data [5, 17]. A single confidence score cannot capture the documented coexistence of competing interpretations. This becomes evident in the case of a Byeri/Nyamodo figure from the *Sammlung Kulturen der Welt (SKW)* discussed in Section 6, where at least five epistemically distinct and partially incompatible narrative frames coexist. Confidence scores thus become a new form of formalised definiteness [22], rendering multivocal, provisional, or contested knowledge situations [6] as apparently stable numerical values [17]. The issue is not quantification itself, but the reduction of epistemic complexity to context-free scalar values, a move that embeds assumptions into infrastructure and stabilises them over time [7, 23].

Our research question is therefore: How should uncertainty annotations in semantic infrastructures be modelled and published so that they are not only machine-readable but also interpretable, revisable, and responsibly reusable? As contributions, we formulate (1) a typology of uncertainty forms relevant to collection and provenance research and the structural reasons why scalar representation fails, (2) a requirements inventory for interpretable uncertainty representation derived from theoretical analysis and practitioner perspectives, and (3) a lightweight modelling pattern representing uncertainty as a referenceable, attributed, and versioned evaluation of a claim, demonstrated through a colonial collection case. This paper builds on prior applied work developed in collaboration with Stella Barsch, collection researcher at *Sammlung Kulturen der Welt* in Lübeck, through which more than 105 cases of structurally complex uncertainty in colonial collections were identified and categorised [24]. The case material underlying this study includes sacred and culturally sensitive objects from colonial collections. Unrestricted publication would conflict with source communities' sovereignty over their own knowledge and heritage, a tension this research takes seriously rather than resolves. In our prior work, we address this directly, presenting four visualisation solutions for the three case types at stake here: historical place designations, conflicting narratives, and secret and sacred objects [24]. Further development and publication of these approaches is subject to a dedicated research project currently in preparation.

2. Related Work

Uncertainty in RDF-based knowledge graphs has been addressed through named graphs [25], RDF reification, and RDF-star [26], which allow statements to be annotated with confidence scores or provenance information. Probabilistic extensions of the Semantic Web stack offer formal grounding for uncertainty quantification but typically presuppose well-defined probability spaces and repeatable measurement conditions that are rarely available in humanities contexts [27]. Within CH and DH, uncertainty tends to be epistemically, interpretively, or ontologically structured rather than probabilistically framed [23, 28]. The CIDOC Conceptual Reference Model [29, 14] and its extensions, including CRMsci [30] and CRMinf [31], as well as related vocabularies such as HiCO [32] and PROV-O [33], provide dedicated constructs for modelling epistemic states, inference acts, authorship, and derivation chains. While CIDOC CRM allows the representation of multiple statements and inference events, it does not prescribe an infrastructure-level modelling pattern for bundling versioned and competing narrative claims as first-class, mutually referential entities [7, 34]. Recent work demonstrates that combining these vocabularies enables more differentiated representations of uncertainty in provenance research [35]. In practice, uncertainty is represented either as free-text annotation, which is contextually rich but difficult to process automatically, or as a scalar value, which is easily indexable but semantically underdetermined without an explicit reference frame, authorship, and temporal context [17, 23]. Scalar confidence values have become a de facto standard in CH and DH infrastructures, often without explicit

reference frames. In large-scale knowledge graphs, they feed into automated enrichment [19], linking [20], and ranking workflows, where numerical comparability is operationalised as epistemic comparability [21, 17]. Other approaches, including evidentiality vocabularies and argumentation-based models remain sparsely adopted in GLAM knowledge graph practice [28, 36]. The closest precedent to the design requirements articulated here is the nanopublication framework, which models attributed, referencable, and versioned claims as first-class entities [37, 38]. This structural emphasis on provenance and attribution resonates with current calls for responsible data publication under the FAIR principles. However, while FAIR compliance can often be achieved at a syntactic level, the semantic conditions for reusing interpretation-laden humanistic data remain undertheorised.

3. Why Scalar Scores Fail: Typology and Structural Tensions

Not all uncertainty is alike. We orient our typology towards Boukhelifa et al. (2017), who describe uncertainty as incompleteness, ambiguity, incorrectness, or variability in data, models, and analytical processes [11], and Panagiotidou et al. (2023), who emphasise the inherent uncertainty of humanistic knowledge production [10]. Table 1 extends these accounts by identifying, for each type, the structural reasons why it resists quantitative representation (column 3) and by providing domain-specific CH and DH instantiations (column 4). This analytical extension frames uncertainty as a problem of epistemic architecture rather than one of measurement precision.

Uncertainty Type	Basis	Structural Problem	CH/DH Example
Source Data Gaps [11]	Gaps, contradictions, or quality issues in source data	No stable reference space, contradictions are substantively meaningful	Conflicting inventory entries for the same object acquisition
Documentation Decisions [10]	Interpretive decisions made during documentation	Process- and decision-dependent, not separable from epistemic choices	Transcription of damaged archival documents
Algorithmic Assumptions [11]	Assumptions built into algorithms or classifications	Calibration and transfer problem, data may be sparse, biased, or domain-shifted	Automated attribution of artefacts to cultural groups
Visual Mapping [11]	Transformation of data into visual variables	Representation-induced trust, effects are context- and design-dependent	Choropleth maps of provenance routes
Interpretive Reading [11]	Subjective reading of visualised or structured data	Not objectifiable, meaning depends on context, expertise, and ethical framing	Divergent expert readings of the same provenance chain
Purpose Ambiguity [11]	Ambiguity about the purpose of an analysis	Thresholds are normative and decision-dependent	Defining “sufficient” evidence for restitution claims

Table 1

Uncertainty types and structural limits of quantitative representation in CH/DH

Across these six uncertainty types, four recurring structural tensions emerge that cut across individual categories:

- (1) **Unstable reference frames**, as numerical values often lack a clearly specified referent, whether evidence density [17], consensus, model confidence, or subjective assessment [23];
- (2) **Open possibility spaces**, as historical research operates in evolving hypothesis spaces and quantifications therefore represent situated snapshots rather than stable probability distributions [10, 1];
- (3) **Absent evaluative provenance**, as undocumented criteria [21] and authorship compress complex decision processes into opaque numbers [37];
- (4) **Limited action-guiding capacity**, as isolated values increase interpretive effort [11] while encouraging unwarranted confidence [39].

These tensions are compounded by two further problems. From an HCI perspective, uncertainty representations must be action-guiding. Isolated numerical values rarely fulfil this condition, as they reduce context without replacing it [11, 40, 39]. A related FAIR problem compounds this further. Numerical values may be syntactically interoperable while remaining epistemically opaque. A value such as 0.7 may designate evidence density, expert consensus, heuristic alternative counting, or model confidence, distinctions that remain invisible without explicit modelling. The choice of 0.7 is deliberate: unlike 0.5, which intuitively suggests equipoise, this value carries no self-evident meaning, making visible precisely the interpretive gap that scalar representations create. Formal interoperability thus becomes mere pseudo-compatibility [41, 42]. Unlike errors in print scholarship, which remain localised and correctable, errors embedded in semantic infrastructures [22] propagate silently across systems and automated pipelines, while remaining invisible as long as the infrastructure functions [6]. Without an explicit reference frame, a second-order uncertainty emerges, concerning not only the object itself but also the meaning of the uncertainty value [3, 22, 6].

4. Requirements for Interpretable Uncertainty

Machine-readability alone guarantees neither comprehensibility nor auditability. Uncertainty representations shape trust and risk perception [39], decision-making behaviour [11], and interpretability therefore requires structural compatibility with users' mental models [40, 43]. To ground the requirements in practice, we conducted an exploratory workshop with 15 GLAM professionals representing diverse disciplinary backgrounds including musicology, art history, and history. Three guiding questions examined expectations toward digital object information, uncertainty visibility, and trust in collection data. Notes were analysed using Reflexive Thematic Analysis, a qualitative method developed by Braun and Clarke [44], in which themes are actively constructed through a structured, recursive engagement with the data rather than discovered within it, treating researcher positionality as a resource for interpretation rather than a source of bias. The corpus consisted of approximately 15 pages of anonymised notes, which were iteratively coded and thematically clustered.

Five thematic complexes emerged:

- (1) **Transparent uncertainty**, knowledge gaps should be made visible rather than smoothed over;
- (2) **Multiplicity and alternatives**, as competing narratives should coexist;
- (3) **Currency**, as knowledge is inherently time-bound and its limits should be explicitly marked;
- (4) **Authorship**, since trust is linked to disclosed authorship and traceable reasoning;
- (5) **Context and scope**, since the relevance and permissibility of information vary by audience and cultural context, including normative access restrictions.

Together with the theoretical analysis, these themes support the claim that interpretable uncertainty representation requires explicit documentation of the dimensions consolidated in Table 2.

Dimension	Key Question
Reference frame	What is the basis of the evaluation?
Evaluative dimension	Which type of uncertainty does this instance belong to?
Authorship	Who produced the assessment?
Temporality	When did this evaluation apply, and is it revisable?
Alternatives	What competing hypotheses or narratives exist?
Scope	In what context and for which audience is the claim made?
Justification	What sources or arguments ground the assessment?
Access context	Are there normative or ethical constraints on use?

Table 2

Information dimensions required for interpretable uncertainty representation

These dimensions make visible what a confidence score compresses into a single number. An object is not “70% certain”. Rather, a specific attribution is connected, under specific conditions, to a specific assessment [38].

5. A Lightweight Modelling Pattern

Building on the dimensions identified above, the pattern represents uncertainty as a referenceable, attributed, and versioned entity by structurally separating three levels: domain claim, research judgment concerning that claim, and uncertainty assessment of that judgment. This prevents uncertainty from being treated as an intrinsic property of an object rather than as a feature of an epistemic act.

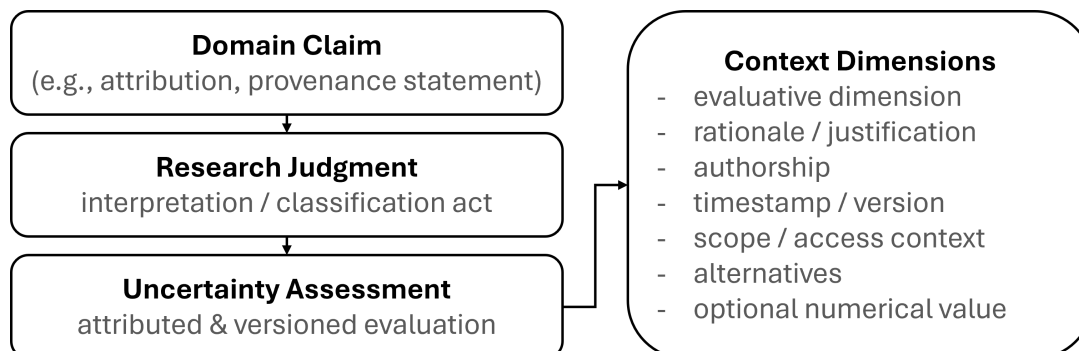


Figure 1: Structural separation of domain claim, research judgment, and uncertainty assessment

The pattern comprises three components. **First**, the claim is modelled as a referenceable entity, either as a reified statement, an RDF-star embedded triple, or a dedicated resource such as `prov:Entity`, so that it can serve as the target of further annotations. **Second**, the uncertainty assessment is modelled as a distinct entity pointing to the claim rather than annotating an object attribute directly. **Third**, this assessment carries the contextual dimensions required for interpretability: Uncertainty type, rationale, authorship, timestamp, scope, alternatives, and access context. Properties such as `:hasRationale` can be aligned with HiCO [32] or `:hasAlternative` with PROV-O [33]. The pattern is implementation-agnostic and can be realised through RDF reification, RDF-star, or dedicated resource structures within existing CRM and PROV deployments. It builds on PROV-O, HiCO, and CIDOC CRM, but is explicitly tailored to interpretability requirements in GLAM infrastructures. Its contribution lies in modelling uncertainty as a referenceable, attributed entity rather than as an annotation attached to individual statements or object attributes. To illustrate the added value of the pattern, we apply it to a case from prior applied work conducted in collaboration with Stella Barsch at *Sammlung Kulturen der Welt* in Lübeck [24]. The case concerns a Byeri/Nyamodo figure from Equatorial Guinea, collected around 1900 as part of the Günther Tessmann collection. It exemplifies what we term a conflicting narratives case. While the concept often denotes two parallel interpretations [45], this object carries at least five epistemically distinct and partially incompatible knowledge claims: a modernist-aesthetic narrative, a ritual-emic perspective, a colonial-postcolonial framing, a museological-curatorial interpretation, and local and syncretic narratives including internal community plurality modelled via `:hasInternalPlurality` and `:hasSubPosition`. In current database practice, this object is reduced to a small set of fixed fields that cannot accommodate contradiction. The following listings model Claims A and B as the two epistemically most opposed narrative frames, the museological-curatorial interpretation and the ritual-emic perspective, to illustrate how the pattern handles structurally incompatible knowledge orders. Claims C–E follow the same structural pattern. Full serialisation is omitted here for space.

```
@prefix : <http://example.org/byeri/> .
@prefix prov: <http://www.w3.org/ns/prov#> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
# NOTE: All : properties are locally defined and would be
# aligned with HiCO or PROV-O in deployment.
# :validFrom indicates date of documentation, not of the
# original knowledge claim.
```

Listing 1: Claim A: Museological-curatorial

```
# CLAIM A: Museological-curatorial
:claim_byeri_curatorial
  a :ProvenanceClaim ;
  :hasContent
    "Object acquired by Guenther
    Tessmann ca. 1900; classified
    as ancestor reliquary figure
    (Byeri/Nyamodo); Fang people,
    Equatorial Guinea."@en ;
  :hasApproximateDate
    "ca. 1900"^^xsd:string ;
  prov:wasAttributedTo
    :curatorSKW ;
  prov:wasDerivedFrom
    :tessmannCollectionRecord .

:u_curatorial
  a :UncertaintyAssessment ;
  :aboutClaim
    :claim_byeri_curatorial ;
  :hasType
    :conflictingNarrativeUncertainty
    ;
  :hasRationale
    "Curatorial classification
    reflects Western typological
    categories; acquisition
    circumstances under colonial
    conditions underdocumented;
    context of removal not
    recorded."@en ;
  :hasAlternative
    :claim_byeri_ritual,
    :claim_byeri_aesthetic,
    :claim_byeri_postcolonial,
    :claim_byeri_syncretic ;
  :hasScope
    "Western museum documentation
    context."@en ;
  :hasAccessContext
    "Object held in storage at SKW,
    Luebeck; not currently on
    public display; access subject
    to collection policy."@en ;
  :hasRestitutionStatus
    "Contested; no formal
    restitution claim filed
    as of 2024."@en ;
  :isRevisable
    true^^xsd:boolean ;
  :revisionCondition
    "New archival evidence or
    community consultation may
    revise this assessment."@en ;
  :validFrom
    "1900"^^xsd:gYear ;
  prov:wasAttributedTo
    :curatorSKW .
```

Listing 2: Claim B: Ritual-emic

```
# CLAIM B: Ritual-emic narrative

:claim_byeri_ritual
  a :ProvenanceClaim ;
  :hasContent
    "Object is a sacred intermediary between
    living and deceased; public display
    constitutes desecration; object retains
    active ritual agency."@en ;
  :hasApproximateDate
    "ca. 1900"^^xsd:string ;
  prov:wasAttributedTo
    :fangCommunityPerspective_ritual ;
  prov:wasDerivedFrom
    :sourcePlaceholder_B ;
  rdfs:comment
    "Source reference to be linked in
    implementation."@en .

:u_ritual
  a :UncertaintyAssessment ;
  :aboutClaim
    :claim_byeri_ritual ;
  :hasType
    :conflictingNarrativeUncertainty ;
  :hasRationale
    "Epistemically incompatible with
    curatorial claim; not resolvable through
    archival evidence; reflects a knowledge
    order structurally excluded from
    database documentation. Positions within
    Fang communities range from reclamation
    to Christian-influenced distancing."@en ;
  :hasAlternative
    :claim_byeri_curatorial,
    :claim_byeri_aesthetic,
    :claim_byeri_postcolonial,
    :claim_byeri_syncretic ;
  :hasScope
    "Fang community knowledge context;
    internal plurality acknowledged."@en ;
  :hasAccessContext
    "Display and digital publication may be
    restricted for certain cultural
    groups."@en ;
  :hasRestitutionStatus
    "Object considered wrongfully removed;
    repatriation sought by parts of Fang
    community."@en ;
  :isRevisable
    true^^xsd:boolean ;
  :revisionCondition
    "Community consultation required to
    update this assessment."@en ;
  :validFrom
    "2024"^^xsd:gYear ;
  prov:wasAttributedTo
    :fangCommunityPerspective_ritual .
```

```
# Claims C-E follow the same structural pattern.  
# All five claims reference each other via :hasAlternative,  
# establishing a non-hierarchical polyphonic graph structure.
```

The pattern addresses six recurring database problems through targeted modelling decisions. **(1) Ontological reduction** is countered by multiple `:ProvenanceClaim` entities per object typed via `:hasType`. **(2) Semantic rigidity** is addressed through `:hasAlternative`, which allows competing claims to coexist without hierarchy. **(3) Epistemic asymmetry** is made visible via `prov:wasAttributedTo` per individual claim, with `:fangCommunityPerspective_ritual` as a non-singular attribution. **(4) Political tension** is rendered explicit through `:hasRationale` and `:hasRestitutionStatus`. **(5) Curatorial translation loss** is addressed by `:hasRationale` and `:hasAccessContext`. **(6) Missing decolonial defaults** are countered by modelling non-Western claims as first-class entities with `:hasRestitutionStatus` and `:hasInternalPlurality`.

The pattern does not resolve competing narratives, nor is that its purpose. Its contribution lies in rendering them simultaneously present, attributed, and referenceable, operating at the infrastructural level where decisions are made about which forms of difference and coexistence can be modelled at all.

6. Conclusion

This paper addresses a structural problem in how uncertainty is represented in semantic infrastructures. Scalar confidence values compress epistemically heterogeneous situations into context-free numbers, enabling syntactic interoperability while obscuring the research judgments that produced them. Values travel across systems without carrying the conditions of their production. Uncertainty is not a property of an object but a feature of a research judgment, and semantic infrastructures should reflect this distinction. Drawing on Boukhelifa et al. [11] and Panagiotidou et al. [10], the typology developed here identifies six forms of uncertainty relevant to CH and DH research and shows why each resists scalar representation. These theoretical findings are confirmed in practice by the practitioner workshop, which indicates that GLAM professionals consistently require visible contextual dimensions including reference frame, authorship, temporality, alternatives, scope, and access context. The proposed lightweight modelling pattern responds directly by separating domain claim, research judgment, and uncertainty assessment into distinct, mutually referential entities. The application to the Byeri/Nyamodo figure from *Sammlung Kulturen der Welt* demonstrates what this separation achieves: five epistemically incompatible narrative frames modelled simultaneously, attributed, and made referenceable without collapsing into a single value, a result not achievable through scalar confidence scores. The case functions as a stress test. If structurally incompatible knowledge orders can be modelled simultaneously, the pattern is viable for less complex cases as well. Infrastructural modelling decisions determine which forms of epistemic difference, cultural plurality, and contested ownership are representable and which remain invisible. Uncertainty representation therefore emerges as a design task at the infrastructural level rather than merely a question of ontological modelling. By demonstrating that referenceable, attributed uncertainty assessment is implementable within existing RDF and PROV-based architectures, this paper argues for its wider adoption. A productive direction for further development lies in replacing free-text fields such as `:hasRationale` and `:hasAccessContext` with controlled vocabularies, which would improve computational processability while preserving contextual depth. While the pattern has been illustrated through a single, structurally complex case, broader validation across diverse collection contexts remains a necessary next step. What semantic infrastructures currently lack is not numerical precision, but referenceability.

Declaration on Generative AI

During the preparation of this work, the author(s) did not use any GenAI tools or services.

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