IBE meets AIR: a framework for structured archaeological reasoning and digital reconstruction

Danilo Marco Campanaro (\httpsAddr{//orcid.org/0000-0001-9962-6879})[1], Paola Derudas (\httpsAddr{//orcid.org/0000-0003-2700-4143})[1], Mikkel H. Thomsen (\httpsAddr{//orcid.org/0000-0002-7432-3246})[2], Brendan Foley (\httpsAddr{//orcid.org/0000-0002-8226-4098})[1], and Federico Nurra (\httpsAddr{//orcid.org/0000-0001-6100-8151})[3]

[1] Department of Archaeology and Ancient History, Lund University, Sweden

[2] Viking Ship Museum, Roskilde, Denmark

[3] French National Institute for Art History (INHA), Paris

Abstract

The increasing use of digital tools in archaeology has vastly expanded our capacity to document and visualise the past, yet the reasoning that connects evidence to interpretation often remains implicit or undocumented. This paper addresses that gap by integrating Inference to the Best Explanation (IBE)—a philosophical model of hypothesis evaluation—into the Archaeological Interactive Report (AIR), a semantic platform for managing and visualising archaeological data. We demonstrate how this integration enables transparent, iterative, and reproducible archaeological interpretation by structuring hypotheses, linking them to evidence, and assessing them against explanatory virtues. Two case studies illustrate the potential of this framework: the systematic reconstruction of the House of the Greek Epigrams in Pompeii, and an experimental application to the Gribshunden shipwreck, where reasoning evolves alongside data collection. The result is a replicable method that formalises archaeological argumentation and embeds it directly within digital infrastructure, making interpretation not only visible, but critically assessable and reusable.

CCS Concepts

• Visualization → Visualization systems and tools; • Human computer interaction (HCI) → Interactive systems and tools;

1.Introduction

The challenge of building transparent, rigorous, and reproducible archaeological interpretations remains a central concern in contemporary archaeological practice. As the discipline increasingly embraces digital tools for documentation and analysis, a paradox has emerged: while the amount of data and the sophistication of digital models have grown exponentially, the underlying reasoning processes that lead from evidence to interpretation often remain opaque. In many cases, the logical chains connecting observations, hypotheses, and conclusions are fragmented or entirely absent from digital outputs. This situation complicates both critical evaluation and the long-term reusability of archaeological knowledge.

This study proposes a solution by bringing together two distinct but complementary strands: Inference to the Best Explanation (IBE) and the Archaeological Interactive Report (AIR). IBE, a methodological framework rooted in philosophical logic and scientific inquiry, structures reasoning by evaluating competing hypotheses based on their explanatory power. Despite its recognised relevance to archaeological interpretation, IBE has remained largely theoretical and underutilised in practical digital workflows. AIR, on the other hand, is an innovative online platform for archaeological data management, visualisation, and reporting. It provides an integrated environment for managing diverse datasets — from 3D models to textual metadata — while supporting dynamic and interactive documentation processes.

The aims of this paper are to demonstrate how embedding IBE principles within AIR can enhance interpretative transparency, foster iterative reasoning, and promote the reproducibility of archaeological knowledge. Through the alignment of structured inferential reasoning with semantic data management and interactive visualisation, we propose a replicable framework that formalises archaeological argumentation and makes it visible, editable, and reusable. To validate this integrated approach, the paper presents two case studies: a fully mapped application of the framework in the reconstruction of the House of the Greek Epigrams in Pompeii, and an experimental extension to the ongoing archaeological investigation of the *Gribshunden* shipwreck.

2. Theoretical Framework

2.1. Inference to the Best Explanation (IBE)

IBE is a pattern of reasoning widely acknowledged in philosophy of science and epistemology as a fundamental method for making sense of incomplete or fragmentary evidence. First conceptualised by Charles Sanders Peirce under the term “abduction”, IBE was later elaborated by Gilbert Harman [Har65] and Peter Lipton [Lip04] among others. In contrast to deduction, which guarantees the truth of its conclusions given true premises, and induction, which generalises from observed instances, IBE infers the hypothesis that best explains the available evidence. In this model, hypotheses are not only evaluated on their internal consistency or empirical support but also on their comparative ability to account for a broader and more coherent range of observations: "The cheese in the larder has disappeared, apart from a few crumbs / Scratching noises were heard coming from the larder last night / Therefore, the cheese was eaten by a mouse" [Oka02:29].

Within archaeology, IBE has been recognised as a particularly suitable framework for structuring inferential reasoning [Fog07]. As demonstrated in recent studies [Cam21] [Cam22] 3D reconstruction emerges as a natural and integral consequence of the IBE process, functioning not as a final product but as a dynamic reasoning tool to spatially test, refine, and visualise competing hypotheses. In this approach, archaeological reasoning can be mapped into a systematic pipeline informed by IBE principles: it begins with the selection of relevant records from the archaeological archive, moves to the formulation of hypotheses that aim to explain these records, organises these hypotheses into contrast sets of competing alternatives, and then applies an evaluation phase based on explanatory virtues (Fig. 1).

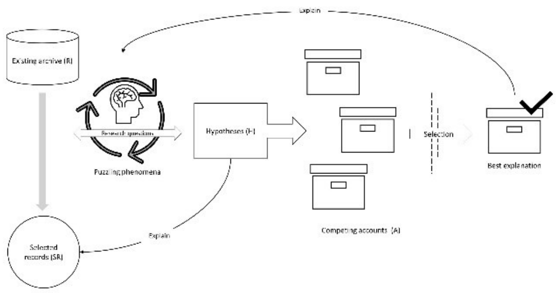

Figure 1: *The IBE-based model for the recording of archaeological argumentation.*

Through this structured process, archaeologists can systematically manage multiple, often conflicting lines of evidence and critically assess competing interpretations.

IBE's strength in archaeology lies precisely in its flexibility in dealing with fragmentary, multivariate, and heterogeneous evidence — defining features of archaeological inquiry. Material remains are often incomplete, contexts are complex, and multiple interpretations are usually plausible. By adopting an IBE-based approach, archaeologists can explicitly structure their reasoning processes, ensuring that interpretations are not only grounded in evidence but also comparatively evaluated for their explanatory coherence and robustness. This makes IBE not merely a theoretical model but a pragmatic guide for navigating the inherent uncertainties of archaeological interpretation.

Despite the centrality of reasoning in archaeological interpretation, structured, digital approaches to modelling inference remain rare — highlighting the need for further work in this direction. Recent work by Guillem et al. (2024) demonstrates the growing importance of formalising reasoning in virtual reconstruction. While their system effectively enables rule-based validation and justification of hypotheses using *Prolog* programming language, *Prolog* is not specifically designed to support IBE. Moreover, our approach benefits from being embedded within the AIR platform, which is based on the CIDOC CRM ontology [Doe03] [BBD*21]. This foundation allows reasoning processes to be not only transparently documented, but also dynamically structured, semantically linked to evidence, and open to iterative refinement within a shared and extensible conceptual framework.

2.2. Digital Archaeology and AIR

Current archaeological practice has been dramatically transformed by the use of digital technologies, which have also increased the volume and heterogeneity of data produced during fieldwork [Hug16] [BK17]. However, this proliferation has often led to fragmentation, with datasets scattered across siloed archives and repositories, and documentation lacking explicit connections to interpretative reasoning [LL20]. As a consequence, there are limits to both the accessibility and the long-term reuse of archaeological information.

AIR was developed in response to these issues [DNS23]. AIR is a web-based system for integrated documentation, 3D visualisation, and interactive reporting of archaeological investigations. Built by combining the online 3D visualisation platform 3DHOP (3D Heritage Online Presenter, [PCD*15]) with the modular platform Omeka S and structured around semantic relationships, AIR ensures compliance with the FAIR principles (Findable, Accessible, Interoperable, Reusable, [Wil16]) and supports sustainable management of excavation data.

One of the key strengths of AIR is the integration of a semantic data model with 3D models. Archaeological features, contexts, finds, and samples are not only captured and represented in 3D, but also linked through an ontological framework based on CIDOC CRM and its extensions. In AIR, 3D models are embedded in this semantic structure and become active tools for documenting, comparing and verifying archaeological hypotheses.

By connecting structured documentation with interactive visualisation, AIR transforms archaeological archives into open, dynamic resources. This solution facilitates not only the recording and publication of excavation data but also the continuous reinterpretation and reuse of archaeological information across different research contexts.

3. Embedding IBE into AIR

3.1 Conceptual Framework

The integration of IBE within AIR involves a deliberate alignment of AIR's digital architecture with the logical structure of archaeological reasoning. To support this alignment, we adopted the CIDOC-CRM semantic model. The CIDOC-CRM extension, CRM-inf, was deliberately excluded because its inference framework does not accommodate the abductive reasoning that underpins our IBE approach.

Each phase of the IBE pipeline corresponds to specific functionalities within AIR, enriching the platform with an active environment for structured interpretative reasoning. The first phase, record selection, is addressed in AIR through semantic data ingestion. AIR allows users to input, and curate selected archaeological records — including 3D models, images, texts, and metadata — into a structured, interoperable framework based on linked data principles. This curated archive forms the evidential basis upon which hypotheses are formulated. In the second phase, hypothesis generation, AIR facilitates the creation of dynamic interpretative narratives. Using AIR's paragraph-based architecture, users can generate multiple hypotheses linked to specific data subsets. Each paragraph or interpretation block can be associated with selected records and visualised through tailored 3D scenes, enabling users to structure their arguments explicitly and spatially. The third phase, contrast set construction, is operationalised through AIR's capacity to manage competing models and scenarios within its 3D interface. Alternative accounts can be encoded as parallel narratives, linked to distinct sets of visual and textual evidence. Through this mechanism, AIR supports the comparative evaluation of interpretations, encouraging a dynamic, non-linear understanding of archaeological reasoning.

Finally, the evaluation phase, essential to IBE, is embedded within AIR through its emphasis on transparency and documentation of the reasoning trail. Each interpretative step, from data selection to hypothesis formulation, is explicitly recorded and linked to the underlying material evidence. This structured, traceable approach allows for systematic application of explanatory virtues such as generality, simplicity, and empirical breadth, thereby enhancing both the credibility and reproducibility of archaeological interpretations.

By semantically structuring and mapping the IBE model and implementing it into AIR, archaeological reasoning becomes an integrated, transparent, and iterative process within the digital environment.

3.2 Why This Matters

Embedding IBE principles into AIR has significant implications for archaeological practice. First, it formalises the structure of argumentation, moving interpretation from an implicit, often opaque process into an explicit, documented workflow. This enhances the scientific rigour of archaeological reasoning by making hypotheses, evidence, and evaluation criteria visible and examinable. Second, it makes archaeological reasoning editable and dynamic. Interpretations can evolve as new evidence is integrated or as alternative contrast sets are explored, reflecting the inherently provisional nature of archaeological knowledge. AIR thus supports a living model of interpretation, where revisions, critiques, and refinements are not only possible but structurally encouraged. Finally, by tightly linking data, hypotheses, and reasoning processes, AIR ensures that archaeological knowledge is reusable and reproducible. Future researchers can trace the inferential pathways behind conclusions, critically evaluate them, and build upon them with new data or perspectives, contributing to a more open and reflexive archaeological practice.

Through the synthesis of IBE and AIR, archaeological interpretation is no longer a final statement, but an ongoing, transparent dialogue between evidence, hypotheses, and explanatory judgment.

4. Mapped Case Study: The House of the Greek Epigrams, Pompeii

The House of the Greek Epigrams (Regio V, Insula 1, 18) in Pompeii offers a compelling testbed for applying the full IBE pipeline within archaeological reasoning (Fig. 2-3).

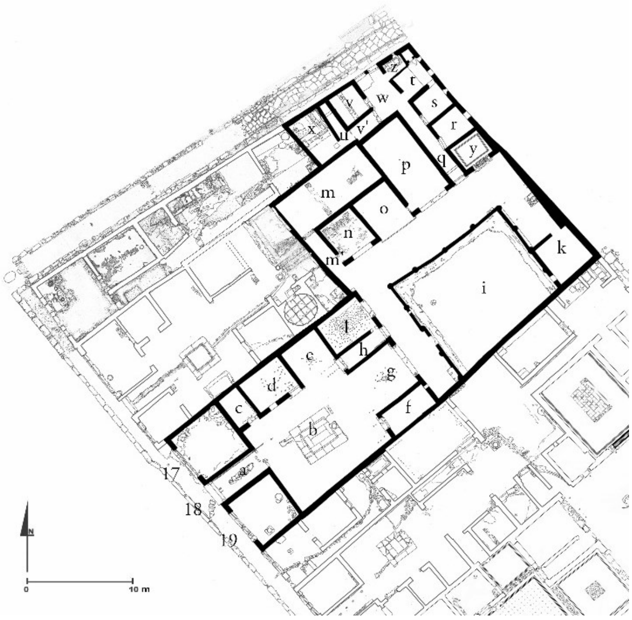

Figure 2: *The plan of the House of the Greek Epigrams ([Cam22]: Fig 3, courtesy of the Swedish Pompei Project)*

Figure 3: *House of the Greek Epigrams, view from the atrium ([Cam22]: Fig 4, courtesy of the Swedish Pompei Project).*

In this case study, an IBE-based model was employed to investigate whether the *atrium* was roofed or open at the time of the eruption of Vesuvius ([Cam22], Fig. 4).

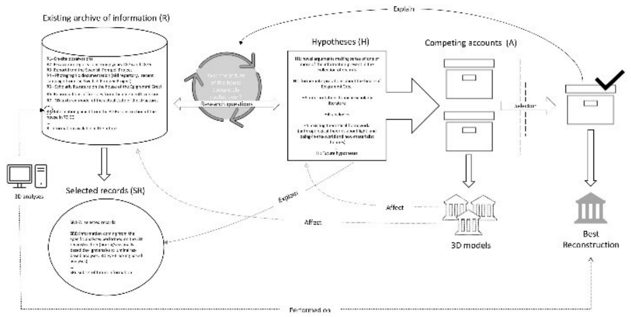

Figure 4: *The IBE pipeline applied to the case study of the House of the Greek Epigrams ([Cam22]:Fig 5).*

Following a systematic compilation of selected records — including excavation reports, historical photographs, architectural drawings, and legacy documentation — a set of detailed hypotheses was formulated to explain various aspects of the material evidence. These hypotheses addressed questions such as the intended viewing distance of wall paintings, the architectural expression of social prestige, the function of the tufa *impluvium* and cistern for water collection, the effects of war damage and weathering, and the use of the *atrium* space for activities such as circulation, storage, display, and religious rituals. Building on these hypotheses, two principal interpretative accounts were developed: the first proposed that the *atrium* was covered with a *tuscanicum*-type compluviate roof, while the second suggested that it remained open or only partially roofed during its final phase.

Each account was operationalised through the construction of a corresponding three-dimensional model, allowing for the visualisation and critical assessment of each proposed configuration. These 3D models were not final products but rather tools embedded within the reasoning process, enabling the refinement of hypotheses through spatial validation and the critical exploration of architectural feasibility. These accounts were systematically evaluated through the application of explanatory virtues — generality, modesty, refutability, conservatism, simplicity, empirical breadth, and multiplicity of foils — following the methodological framework articulated by Quine and Ullian [QU78] and Fogelin [Fog07] and adapted to archaeological inference [Cam22]. Through this structured assessment, the account proposing a roofed *atrium* with a *tuscanicum* structure was identified as the best explanation given the available evidence. The iterative use of 3D modeling thus supported a dynamic, transparent, and critically reflexive interpretative workflow, rather than serving as a static representation of a final conclusion.

In AIR, the inferential reasoning process was formalised through a structured semantic mapping aligned with CIDOC CRM principles, following a staged and traceable workflow (Fig. 5).

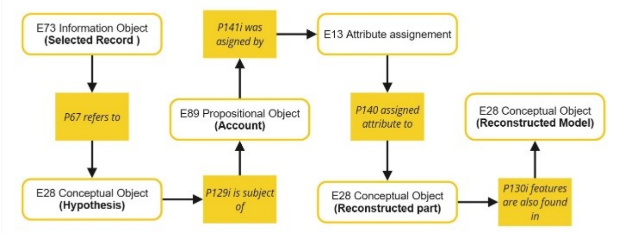

Figure 5: *The IBE-based semantic model for the recording of archaeological argumentation.*

In the first stage, specific records were selected from the available documentation archive, comprising photographic, textual, visual, and analytical materials. For the House of the Greek Epigrams, elements from recent and historic excavation reports, photographic campaigns, and nineteenth-century reproductions were curated, focusing on evidence relevant to the question of whether the atrium was roofed over in its final phase.

Each selected record was registered within AIR as an Information Object (E73) and semantically linked to specific hypotheses (E28 Conceptual Objects) through the property P67 (“refers to”), establishing the evidential foundation for inferential reasoning. Based on these selected records, hypotheses were formulated to explain the available evidence, drawing both from new interpretations generated during analysis and from critical engagement with past archaeological, architectural, and historical theories. Each hypothesis was documented individually, assigned a unique identifier, detailed descriptive metadata, and a classification according to its nature and origin. This structured mapping thus formalised the transition from curated evidence to inferential propositions within the AIR environment.

Following the formulation and documentation of individual hypotheses, these inferential propositions were structured into broader accounts (E89 Propositional Objects) through the property P129i ("is subject of"), organising sets of hypotheses into coherent explanatory frameworks. For instance, an account was developed supporting the presence of a *tuscanicum* roof over the *atrium*, while an alternative account proposed the *atrium* remained open. Each account aggregated multiple hypotheses and their supporting records, providing a transparent structure for managing competing interpretations.

The accounts were then linked to specific reconstructed parts (E28 Conceptual Objects) through an E13 attribute assignment using the properties P141i ("was assigned by") and P140 ("assigned attribute to"), each reconstructed part representing an individual architectural component or spatial feature based on the preferred explanatory model for that section. For example, the reconstructed part corresponding to the *atrium* roofing was generated according to the account supporting the *tuscanicum* hypothesis. In AIR, these accounts are not only documented textually but are also associated with interactive 3D models, allowing users to visualise and directly explore the alternative reconstructions proposed by each account. This visualisation capability enables a dynamic, spatial comparison of competing interpretations, reinforcing the critical engagement with the reasoning process.

Crucially, the workflow extended beyond the level of individual parts. The reconstructed part(s) are subsequently assembled into a comprehensive reconstructed model (E28 Conceptual Object), in the specific case, the entire house of the Greek Epigrams. This integration was formalised using the property P130i ("features are also found in"), establishing hierarchical relationships between individual parts and the full model. The process of assembling the reconstructed model is not a straightforward summation of parts. Rather than simply aggregating independent reconstructions, the integration stage introduces an additional critical phase of reasoning that can reveal 'emergent' properties [Joh01] — new spatial or structural patterns that are not predictable from the independent parts alone. These discrepancies necessitate a return to earlier stages of the inferential process, prompting the reassessment of selected records, the revision of hypotheses, or the reformulation of accounts to achieve a coherent and plausible reconstruction. Although visually represented as a linear semantic graph, the actual inferential process is dynamic, iterative, and reflexive.

Through this expanded semantic structuring, AIR accommodates the full complexity of archaeological reasoning. It ensures that reconstructions are not static end products but living documents of interpretative processes, supporting transparency, adaptability, critical engagement, and epistemic responsibility in the creation of archaeological knowledge. This semantic structuring ensures that each inferential step is explicitly documented, allowing users not only to visualise the final reconstruction but also to critically interrogate the reasoning processes that support it. In this way, AIR operationalises the IBE pipeline, ensuring that archaeological interpretations are grounded, transparent, and open to iterative refinement.

4. Experimental Extension: *Gribshunden*

The IBE/AIR methodology was also experimentally tested on an ongoing and discontinuous project, producing a very diverse archaeological record as methodology has evolved over the years: that of the medieval shipwreck, *Gribshunden* (Blekinge, Sweden).

This late 15th-century royal flagship (c. 1485–1495) presents a compelling case study for the integration of IBE and AIR. The shipwreck is the earliest known example of a carvel vessel purpose-built to carry artillery. This is the style of ocean-going ship embraced by early European explorers, and which came to dominate naval fleets for centuries after 1500. In addition to its service as a warship, and perhaps uniquely among European monarchs, the Danish-Norwegian King Hans used *Gribshunden* extensively as a seagoing castle and mobile seat of government. The king and senior nobility sailed on the ship throughout its career and on its final voyage, living in close proximity to their servants and the crew while fulfilling the military, economic, political, and cultural requirements of their offices [Fol24] [FH24] [FSHf] [HLF22] [DF24]. Medieval society was strictly hierarchical; the presumed co-mingling of social classes forced by the realities of shipboard life prompts our investigations into the social use of space within *Gribshunden*'s confined dimensions. IBE analysis of the data coordinated in AIR grants the opportunity to test a variety of configurations of the extant wooden elements of the hull, superstructure, and equipment. These are extensive due to the environmental conditions of the Baltic Sea, but partially disarticulated and occluded by sediments. The range of possible configurations is constrained by the factors usual in any archaeological reconstruction, including construction materials, physical requirements for structural integrity, architectural style, and intended use. Successive data collection campaigns on the wreck site generate iterative photogrammetric data of not only exposed elements, but also features key to the reconstruction, observable upon limited excavation.

5.1 Research questions

The selection of records for analysis was guided by a structured set of research questions, which aligned with the sequential logic of the reconstruction process. First-order questions addressed the fundamental physical characteristics of the ship, including its main dimensions, hull shape, and the number and height of its decks. Second-order questions focused on less well-preserved but historically significant aspects of the vessel, particularly its superstructure. Here, the inquiry centred on the configuration of the sterncastle — a zone presumed to have accommodated royal and noble passengers. Given the rigidly hierarchical structure of medieval society, the spatial arrangements aboard *Gribshunden* raise critical questions about how social distinctions were negotiated within the ship's confined layout.

5.2 Selection of the records

The records were selected in direct response to the first- and second-order research questions. The full set of selected records — including their descriptions, types, and relevance to specific aspects of the reconstruction — is presented in Figure 6 and accessible on AIR at this link:

\httpsAddr{dev.air.ht.lu.se/s/gribshunden/item?submit=Search&resource_template_id[]=35}

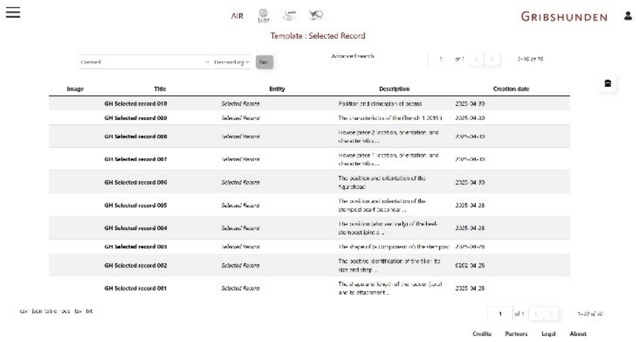

Figure 6: *Records selected within the Gribshunden experiment.*

5.3 Hypotheses

The generation of hypotheses followed the logic of the IBE framework, in which interpretative propositions are formulated to explain selected records and are structured according to their explanatory potential. Hypotheses were formulated to account for specific material observations, drawing on both direct evidence and contextual knowledge, including comparative analysis, historical analogy, and theoretical perspectives. While the reasoning process was structured sequentially, it remained dynamic and iterative, allowing for hypotheses to be refined or discarded as new relationships between evidence and interpretation emerged. A complete overview of the hypotheses generated during this phase is provided in Figure 6 and accessible on AIR at this link:

\httpsAddr{dev.air.ht.lu.se/s/gribshunden/item?submit=Search&resource_template_id[]=36}.

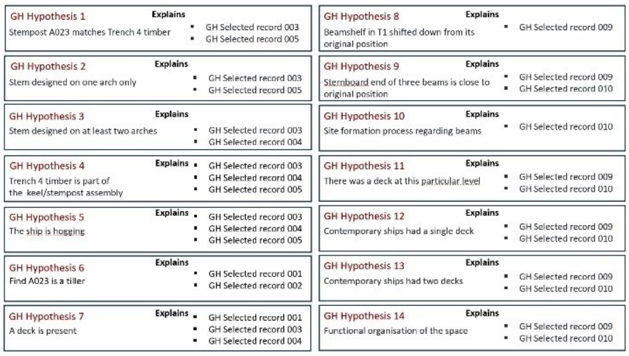

Figure 7: *The Hypotheses formulated within the Gribshunden experiment and the Selected Records explaining them.*

5.4 Accounts

All interpretative accounts of the *Gribshunden* site are informed by a set of hypotheses that aim to explain specific observed archaeological phenomena (Fig. 8).

Figure 8: *The four Accounts built out of the Hypotheses formulated listed in the AIR platform.*

Many of these hypotheses appear across multiple accounts, as they relate to broadly accepted interpretations or general observations. However, it remains possible to formulate distinct accounts that diverge on specific aspects of the ship's reconstruction. In the example presented here, the point of divergence concerns the number of decks originally present on the vessel:

Account 1 (Fig.9). This account proposes that the ship featured a single continuous deck extending from bow to stern, anchored to the hull at points defined by hypotheses concerning the positions of crossbeams, the beam shelf, and the reconstructed height of the tiller. In this scenario, the space beneath the deck would have formed a single, vertically undivided volume.

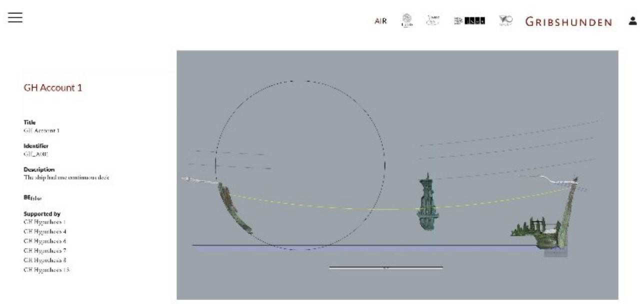

Figure 9: *3D Visualisation of Account 1 in the AIR platform.*

Account 2 (Fig. 10). This version proposes that the ship was built with two continuous decks. While sharing some of the underlying structural hypotheses of Account 1, this interpretation implies a different configuration of internal space.

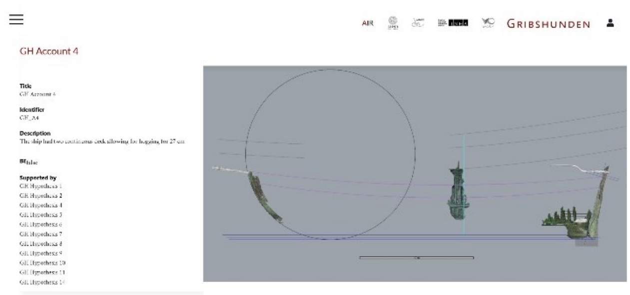

Figure 10: *3D Visualisation of Account 2 in the AIR platform.*

In both Account 1 and Account 2, the bow structure is reconstructed based on a hypothesis of a single-arc stem design. However, this configuration does not fully explain the apparent misalignment between the stem arc and the observed keel line. To address this, an additional hypothesis was introduced: that the ship may have experienced hogging — a condition in which the fore and aft ends of the hull gradually deflect due to structural and loading stresses in combination with the buoyancy acting on the ship's hull. This led to the development of two additional accounts:

Account 3. A continuation of Account 1, incorporating the hypothesis of hogging by rotating the forward end of the hull upward around the midpoint of the keel.

Account 4. A continuation of Account 2, likewise integrating the hogging hypothesis with an upward rotation of the forward hull section around the keel's midpoint.

Three-dimensional models were produced for each interpretative account, not as final products, but as tools within the reasoning process. By visualising the implications of each hypothesis, the models supported the refinement of interpretations and helped identify potential inconsistencies. This process may, in turn, lead to the revision of hypotheses or even the reconsideration of selected records, highlighting the iterative and non-linear nature of the IBE framework. Specifically, with the 2-decked Accounts the height between the two decks seems a bit low, perhaps suggesting that there was a now missing topmost sternpost section (or fragment), allowing for a higher position of the weather deck, hawse pieces, figurehead beam, and the entire superstructure above it. This could very well be the target of a future, focused fieldwork campaign.

5.5 Selection of the best explanation

The four interpretative accounts were experimentally evaluated using the framework of explanatory virtues adapted from Quine and Ullian [QU78], which include generality, simplicity, conservatism, modesty, empirical breadth, and refutability. In addition, the virtue of multiplicity of foils, introduced by Fogelin [Fog07], was considered to ensure that each account was assessed against a sufficiently diverse set of plausible alternatives. Each account was thus examined for its coherence, empirical adequacy, and openness to critical testing. Through this structured comparison, Account 4 — proposing a two-deck configuration incorporating the hypothesis of hogging — was identified as the best explanation based on currently available data. It accounted for a wider range of observed phenomena, aligned with structural and spatial evidence, and did so without invoking unnecessary or far-fetched assumptions. While the evaluation remains open to future revision, Account 4 currently provides the most comprehensive and coherent interpretative model based on the available data and. While one might be tempted to describe Account 4 as the version that simply "feels right" or "looks best," our aim is precisely to move beyond such intuitive judgments. By applying a structured inferential framework based on IBE, the reasoning behind the reconstruction is made explicit, allowing future researchers to critically evaluate, revise, or build upon the interpretative process—even in the context of discontinuous or evolving research projects. Through the AIR platform

(\webLink{https://air.ht.lu.se/s/reports/page/home}),

each interpretative account can be visualised alongside its assessed degree of compliance with the explanatory virtues (Fig. 11).

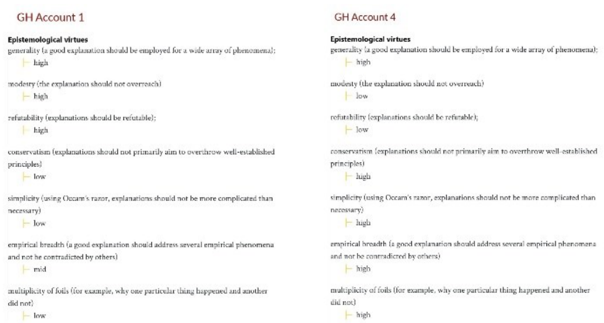

Figure 11: *Epistemological Virtues of Account 1 and Account 4 in the AIR platform.*

6. Discussion

The application of the IBE pipeline within AIR across two distinct case studies — the House of the Greek Epigrams and the *Gribshunden* shipwreck — offers critical insights into the strengths, challenges, and broader implications of this combined framework.

In the Pompeii case study, the integration of structured reasoning within AIR demonstrated the full potential of the system: selected records were systematically linked to hypotheses, competing accounts were visualised as dynamic 3D reconstructions, and a final interpretation was selected through transparent application of explanatory virtues. This structured approach enabled a level of analytical traceability rarely achieved in traditional archaeological publications, ensuring that interpretations remained open to critical interrogation and future refinement.

By contrast, the *Gribshunden* project served as an experimental testing ground, where the adaptability of the integrated approach to an underwater and only partially excavated site was evaluated. In particular, during the phase of hypothesis construction and account generation, a diverse set of tools and data sources was employed. In addition to the documentation already available within the AIR platform from previous investigative campaigns — including multiple 3D models — new materials such as 3D-printed components of recovered ship parts and interactive 3D modelling software were used to support the development and testing of interpretative scenarios (Fig. 12-13).

This marked a significant advance over the House of the Greek Epigrams case, where AIR was used primarily to map IBE-based interpretations previously elaborated in [Cam21] [Cam22]. In the *Gribshunden* study, by contrast, AIR functioned as an active platform for generating hypotheses, refining accounts, and iteratively linking them to both existing and newly produced digital and physical data.

Figure 12: *Hypotheses construction and accounts generation.*

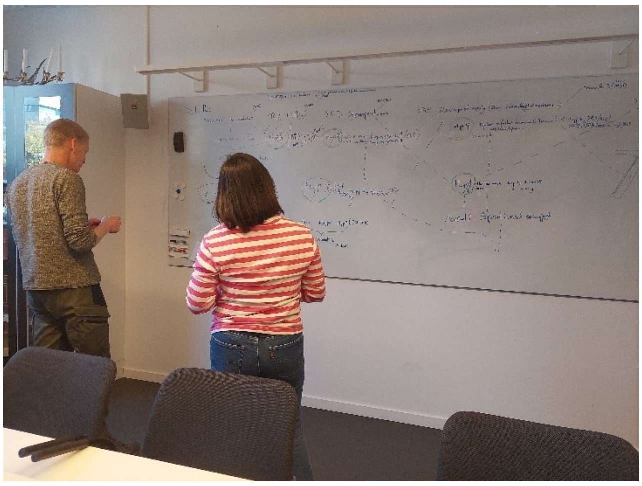

Figure 13: *Hypotheses refinement.*

Across both contexts, the embedding of IBE within AIR yielded several key benefits: it enhanced transparency by explicitly documenting the inferential chain from evidence to interpretation; it fostered knowledge reuse by structuring data and reasoning in a manner conducive to future investigation; it supported interdisciplinary collaboration by providing a common platform for archaeologists, historians, and digital specialists; and it facilitated public engagement by making complex reasoning processes accessible through interactive visualisations.

The complexity of constructing the semantic model, handled once by archaeologists and data specialists, is not exposed to users using IBE within AIR. The main challenge for users is to manage and interpret the complex relationships within the data and the associated inference layer. The system's advanced interface, essential for navigating such complexity, can also present usability challenges, highlighting the need for ongoing refinement and user-centred improvements.

Theoretically, the combination of IBE and AIR proposes a model of archaeological practice grounded in epistemic responsibility: interpretations are not only presented but justified, linked to their evidential bases, and made available for critical evaluation and reuse. This represents a significant step toward more transparent, reflexive, and collaborative forms of digital archaeology.

6. Conclusion

This study has demonstrated that the integration of IBE within AIR provides a replicable model for structured, transparent, and dynamic archaeological reasoning. By aligning semantic data management with inferential logic, AIR operationalises the interpretative process, making it navigable, editable, and subject to critical scrutiny. Through application to both terrestrial and maritime case studies, the framework has proven versatile and adaptable, capable of enhancing archaeological documentation and interpretation across diverse environments. It ensures that digital reconstructions are not merely visual outputs but are embedded within explicit chains of reasoning that can evolve as new evidence emerges.

As Fogelin [Fog07] notes, statistical induction — relying on the extrapolation of patterns from repeated occurrences — can be of limited use in archaeology, where evidence often relates to singular, non-replicable historical contexts. The Pyramids of Giza, for instance, do not constitute a statistically representative sample of ancient monumental construction; rather, they represent singular achievements embedded within highly specific cultural, technological, and historical contexts. In this regard, while the rise of big data approaches and the application of machine learning and generative AI to cultural heritage offer substantial opportunities, their implementation must be approached critically and reflectively [Gat25]. Merely accumulating large datasets does not inherently ensure robust historical inference, particularly when the available evidence is fragmentary, biased, or non-representative. Rather than prioritising the quantity of data — which, as in the Giza example, is often inherently limited — archaeological research should aim toward training machines and AI systems to reason within structured inferential frameworks such as the one outlined by IBE and operationalised within AIR. Practically, this involves developing systems capable of explicitly recording each interpretative step, the specific evidential sources consulted, and the logical rationale underpinning every inferential choice. By embedding this structured reasoning capability, archaeological interpretations become not only transparent and traceable but also open to scholarly critique, iterative refinement, and meaningful reuse. Consequently, machines could transition from passive generators of digital surrogates to active participants in an ongoing, rigorous dialogue about the human past.

Looking forward, this structured approach opens pathways toward the responsible and informed integration of intelligent systems in archaeology — systems capable of supporting hypothesis management, multimodal argumentation, and seamless integration within broader ecosystems of linked open heritage data. By grounding archaeological reasoning in explicit methodological frameworks like IBE, digital archaeology can evolve into a discipline that leverages technological innovation while maintaining methodological rigor, epistemic responsibility, and critical reflexivity.

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