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RESEARCH ARTICLE

# REVISED Designing a FAIR Catalogue of Services for the Heritage Science community

[version 2; peer review: 2 approved, 2 approved with reservations]

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## Abstract

### Background

The European Research Infrastructure for Heritage Science (E-RIHS), recently granted with European Research Infrastructure Consortium (ERIC) legal status, aims to advance research by facilitating access to cutting-edge scientific services and tools in the domain of heritage science. One of the major challenges and achievements during its implementation phase (2022–2024, G.A. 101079148) was the creation of the Catalogue of Services (CoS)—a digital platform that helps users find, request, and manage access to both physical and digital services offered by E-RIHS partners.

### Method

This paper introduces the concept, design, and development of the E-RIHS CoS, emphasising how it follows FAIR (Findable, Accessible, Interoperable, Reusable) and Open Science principles. Built with a strong focus on real research needs, the platform features a flexible and scalable architecture. It includes tools like semantic search, automated workflows, and customized dashboards based on user roles. The paper also places the CoS in the broader context of similar platforms from other research infrastructures, and point out its novel features—such as a recommendation engine, multilingual support, and advanced data analytics.

### Results and Conclusions

Now, the E-RIHS CoS is online, providing a single access entry to E-RIHS ERIC services and making easy to find and select the most

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adequate scientific services based on the users' research questions. It is a solid and forward-thinking digital tool designed to support high-quality research, foster collaboration, and make heritage science more inclusive and accessible.

**Plain language Summary**

Heritage Science is an interdisciplinary domain focused on the scientific study of cultural and natural heritage, bridging the humanities and the sciences. Researchers in this field require access to scientific laboratories and services to better understand, study, interpret, analyze, and intervene on cultural or natural objects.

Many of these services are now accessible thanks to E-RIHS, the European Research Infrastructure for Heritage Science. Its online Catalogue of Services provides an easy, research-need-oriented way to explore and access these resources.

The Catalogue was developed as a standalone FAIR (Findable, Accessible, Interoperable, Reusable) platform, integrated with automated workflows and an AI-based recommendation engine designed to assist even non-expert users in identifying the most suitable services for their projects.

Created through a co-creation process, the platform has become one of the most advanced tools available to the heritage science community and continues to evolve based on user feedback.

**Keywords**

Catalogue of services, Heritage Science, Research Infrastructure, FAIR, Open Science, Data Management, E-RIHS

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**REVISED** **Amendments from Version 1**

This revised version incorporates all the suggestions provided by the reviewers, including enhancements to the user experience design—specifically, the strategy for engaging researchers and potential users in the development of the catalogue. We have expanded the description of the AI driven recommendation system and included additional technical details. As requested, we further elaborated on the potential applicability of the model to other research infrastructures. In addition, we have added more information on the heritage science community and integrated an analysis of how the different components of the data system align with the FAIR principles.

**Any further responses from the reviewers can be found at the end of the article**

## Introduction

Heritage Science – a broad and multidisciplinary field that focuses on the scientific study, interpretation, conservation, and preservation of cultural and natural heritage, operates across different contexts with heterogeneous domains of knowledge and stakeholders, including non-experts and the public. In the last few decades, research on both tangible and intangible heritage has gained interest worldwide,[1,2] drawing on a wide range of disciplines from the humanities (art history, archaeology, history), sciences (chemistry, physics, biology), and engineering (materials science, digital tools).[3] Heritage Science has progressively strengthened its collaborative nature. These efforts to enhance scientific cooperation among the different specialists involved have led to the establishment of a dedicated European Research Infrastructure (E-RIHS).[4]

E-RIHS, included in the ESFRI roadmap in 2016 under the Social Sciences and Humanities domain and which recently became an ERIC, brings together laboratories, scientific archives, and institutions across Europe and beyond, providing integrated access to resources that support heritage-related research. Like other European RIs, E-RIHS aims at providing resources and services for research and innovation.[5] The services include access to facilities and expertise, data, and state-of-the-art analytical instrumentation, as well as online tools for data management and processing, to support heritage research in advancing scientific discovery and enabling collaboration across disciplines and borders.

Interdisciplinarity is a persistent challenge in the heritage science domain due to the different methods and languages employed to analyse, study, interpret, and intervene in cultural and natural heritage. The E-RIHS scientific community has worked to overcome the fragmentation of different approaches by creating three integrated platforms to offer its services:

- ARCHLAB, providing access to scientific archives and collections of heritage-related data, including access to samples, datasets, or scientific reports from historical or artistic artefacts preserved in scientific archives.[6]
- FIXLAB, offering large and medium-scale cutting-edge laboratory instrumentation, such as synchrotrons or particle accelerators, to analyse samples coming from the artefacts under investigation.[7]
- MOLAB, enabling the use of mobile instrumentation for on-site heritage non-invasive analysis, such as the study of an artwork directly inside the museum exhibition room.[8]

Many online catalogues of services and marketplaces created by European and non-European research infrastructures primarily focus on digital tools, data, and related services. The E-RIHS CoS represents one of the few initiatives that effectively aligns services with user needs for access to archives, laboratories, and instrumentation. By prioritizing physical access, this approach introduces additional conceptual and operational complexity in both the design and implementation of the catalogue. To complement this framework with digital resources, E-RIHS is developing DIGILAB, a dedicated platform for digital tools and data that will provide a comprehensive, FAIR-compliant knowledge base for heritage digital twins.

To ensure effective access to scientific services, it is crucial to present the relevant information in a comprehensive, structured, and harmonized manner. This approach enhances both their visibility and discoverability. Additionally, users should be able to compare similar services easily and identify those best suited to their specific research needs. Such capabilities support a unified access model across RIs, a crucial goal also in heritage science, where users (e.g., conservators, heritage professionals, and other stakeholders) play an active role in knowledge co-creation and its translating into practice.[2] A Catalogue of Services (CoS) is a crucial tool for achieving these goals. In brief, it can be defined as an organized portfolio (i.e., list of services), accessible to the users (i.e., external researchers accessing the RIs services). It includes information regarding the service offered, the contact persons, and the access process.[9,10]

The CoS acts as a showcase and a single-entry point for managing users' interactions among the internal and external researchers (i.e., service managers and users). Given the diversity of the disciplines involved in heritage science, as well as the widely variable expertise level of the potential users, clarity, accessibility, and guidance through co-creation and interaction with experts are critical.

This article outlines the process undertaken by the E-RIHS community over the past ten years to transition from a static, email-managed catalogue to a smarter, dynamic system powered by modern digital technologies and aligned with international standards. The development of the new E-RIHS CoS builds on prior initiatives, such as the IPERION HS European project (G.A.871034), which laid the groundwork for organizing service data and provided valuable insights into the complex, real-world needs of the heritage science community. This article documents the initial phases of the E-RIHS CoS development. Subsequent updates and future enhancements are out of the scope of this work.

The E-RIHS CoS provides a single-entry point to explore physical and digital services organized into four platforms: ARCHLAB (scientific archives), FIXLAB (fixed laboratories), MOLAB (mobile laboratories), and DIGILAB (digital data and tools). The CoS supports E-RIHS's mission to enable Open Science practices and foster interoperability among research infrastructures around Europe and beyond. Additionally, by integrating a semantic metadata model, natural language search capabilities, and a system of dashboards, it offers a streamlined and FAIR-compliant pathway from service discovery to access implementation.

## Background for the development of E-RIHS CoS

Several RIs in Europe have developed digital CoS, and marketplaces to provide researchers with access to scientific services, datasets, and software. These platforms enhance resource visibility and usability while exploiting the benefits of data reusability and advanced analytical technologies. To this aim, one of the most challenging aspects of creating a reliable CoS, suitable for a wide range of potential users, is setting interoperable systems, and standardised and normalised metadata concerning datasets and services.[11]

To assess the current landscape within RIs and to address the challenges associated with developing a heritage science CoS, a mapping of existing solutions at the European level was undertaken starting from the E-RIHS PP project (2017–2020, G.A. 739503).[12] The mapping employed two complementary methodologies: direct interviews with RIs managers and hands-on testing of other catalogues from the user perspective. Although structurally different from traditional CoS, marketplaces were also included to provide comparative insights. In the ESFRI landmark, E-RIHS is one of the 11 RIs in the Social Science and Humanities domain. Among these, only two offer physical services in addition to digital resources. Besides, E-RIHS is the only one that currently primarily offers access to physical services.

Among the different catalogues revised, several well-developed CoS that support access to both physical and digital services were identified for an in-depth examination: ELIXIR,[13] and CORBEL,[14] in the life sciences domain, the Virtual Unified Office of CERIC-ERIC,[15] in materials science, CESSDA in social sciences,[16] and the ELVIS portal of DISSCo in biodiversity research.[17] These CoS include advanced functionalities such as proposal management, reviewer assignment, and service usage tracking, capabilities that are essential also for E-RIHS.

Another example of advanced CoS represents the ARIA software developed by Instruct-ERIC, a European RI in the biology field, a cloud-based tool that facilitates access to the RIs' scientific services. It is currently used by at least nine RIs, demonstrating its versatility.[18] However, the unique complexity and interdisciplinary nature of the heritage science domain required the development of a tailored model to effectively support the specific requirements of scientific services within E-RIHS.

Furthermore, the interviews with the CoS managers/developers provided key insights into the underlying workflows, as well as the processes used to manage evaluation of the research proposals. For example, the dashboard system employed by ARIA software allows for managing different proposal evaluations and monitoring the project visit in the premises of the host institution, while facilitating the communication among all the actors involved.

The following CoS key characteristics were identified for its successful implementation: a) adequate service description, b) metadata quality, c) harmonised data structure, d) user interface clarity, and e) search functionalities to facilitate discoverability. In this respect, the first E-RIHS CoS was developed during the E-RIHS Preparatory Phase (2017–2020), marking a significant step forward for the heritage science community in creating a dynamic, online catalogue.

The initial conceptual data model was informed by the knowledge and outcomes of previous European projects – particularly PARTHENOS,[19] IPERION CH,[20] and ARIADNE.[21,22] It was implemented as a Relational Database

Management System, developed in SQL technology, and represented a major improvement over existing tools and frameworks available at the time for managing heritage science services.[12] One of the main challenges was to structure the database to reflect the multi-valued attributes to conform the specific entities created to cover the extensive information at the base of the CoS. Over the last few years, a dedicated coordination group within the heritage science community has defined a shared conceptual framework for service description, metadata representation, and data structuring. This framework was iteratively discussed and refined in close cooperation with service managers (then referred to as "providers") responsible for the delivery of individual services, ensuring both domain relevance and operational feasibility.

The first online catalogue, conceived as a sort of e-commerce website, was released during the IPERION HS project in 2020.[23] In coordination with the ARCHLAB, FIXLAB, and MOLAB platform leaders, services were clustered into high-level functional categories (e.g. spectroscopic analysis, spot analysis, etc.), leading to the formalisation of a coherent data model.[12] In the absence of a consolidated domain ontology or standardized controlled vocabularies for heritage science, service managers were invited to populate the model fields and contribute domain-specific terminology reflecting established practices within their scientific communities. The coordination group subsequently carried out an extensive, tricky process of data curation, harmonisation, and standardisation, validating semantic consistency and structural coherence across the catalogue. The scientific services offered by 100 institutions were delivered through three platforms: ARCHLAB, FIXLAB, and MOLAB. Users and service managers tested the first version of the catalogue, allowing for fixing bugs and unclear submission processes, and criticalities for future improvements were identified and registered.

The process to access the scientific services is illustrated in Figure 1: users create a profile, then browse the catalogue to select the most adequate service(s) that best match their research needs, and finally submit a proposal. Successful proposals were granted based on the technical feasibility (evaluated by the provider) and subsequently on scientific excellence, reviewed by an international and independent panel of experts. A system of dashboards in the CoS backend was created with different levels of permission according to specific roles: platform coordinator, helpdesk, provider, and user. All notifications were managed through an automatic email system throughout the entire process. Finally, the user was responsible for completing two surveys and uploading a report (referred to as "post-access duties"). All data and files could be downloaded and analysed to monitor the IPERION HS access performance.

Despite its pioneering role, the platform developed within E-RIHS PP and IPERION HS faced challenges related to lack of metadata standardization, user interface complexity, and scalability. For example, many scientific techniques included

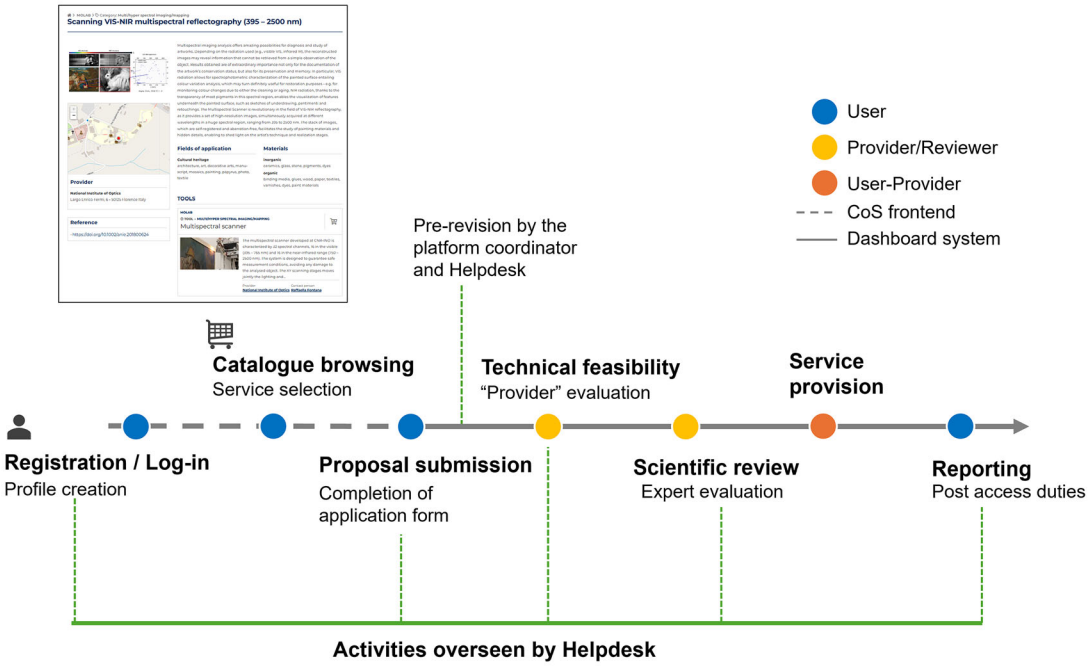



**Figure 1. Scheme of the CoS system released during the IPERION HS project.** The different phases and actors involved are indicated.

in the catalogue had no standard designation, and scientists used different ways to refer to the same instrumentation. Similar issues were connected with complex methodologies or the targeted materials investigated by a single technique. All these factors made the selection of the most adequate service for a non-expert difficult.

Building on the experience of IPERION HS and informed by the launch of the SSHOC and EOSC marketplaces in 2021 and 2022, respectively, the E-RIHS community undertook an update of its CoS model starting from 2022. This revision aligned the model with emerging interoperability and FAIR data standards, while integrating innovative features aimed at improving service discoverability and enhancing the user experience. The redesign of the data model was made possible through regular meetings of a group dedicated to the catalogue's development, during which different perspectives were discussed and iterative revisions were necessary. The users' point of view was also considered and was included via targeted questionnaires distributed to experienced users and, more broadly, to the heritage science community through dedicated mailing lists. The resulting new E-RIHS CoS draws upon the heritage science community's prior work and incorporates key advancements from other research infrastructures, delivering a more robust, interoperable, and user-friendly system.

### FAIR-by-design methodology

ESFRI has emphasized the central role of RIs in advancing Open Science, specifically advocating for the adoption of FAIR principles and the provision of quality-assured open data. According to ESFRI,[24] RIs are key actors in driving cultural change, enhancing data quality, and broadening access within the evolving EOSC ecosystem.

In this framework, E-RIHS has developed its CoS in alignment with this vision, FAIR-by-design and fully interoperable with other RIs marketplaces in other scientific fields, such as EOSC, SSHOC, and H2IOSC, acting both as a data and service provider. It enables seamless data integration and discovery, fostering the practice of Open Science in heritage science. This is achieved through the curation of service data displayed, facilitating the findability and interoperability. Each service is described using a detailed metadata schema that includes technical specifications, associated platforms, hosting institutions, service managers, and relevant references. The embedded policies and tools, such as machine-actionable Data Management Plans (DMPs), Creative Commons licensing, and the assignment of persistent identifier systems contribute to ensure metadata quality. The FAIR compliance of the features of the new E-RIHS CoS is summarized in the Table below (Table 1).

**Table 1. Key components of the E-RIHS CoS and the relative FAIR principles.** F = Findable, A = Accessible, I = Interoperable, R = Reusable. Details on the FAIR principles are reported in GO FAIR.[25–27]

| CoS component | FAIR principle |
|---|---|
| Structured and semantically enriched metadata | F2, F3, I1, R1 |
| Data indexed via a semantic engine powered by Elasticsearch | F1, R1 |
| Free text search powered by Elasticsearch | F3 |
| Unique persistent identifiers for data | F1, F3 |
| Existence of Open APIs | A1 |
| Controlled vocabularies and multilingual thesauri (developed in OpenTheso) | I2, R1.3 |
| Cross-platform and cross-community service discovery | F4 |
| Collaborative dashboard with a different access rights system | A1 |
| Secure single sign-on system (e.g. ORCID) | F1 |
| JSON-based schemas that model entities (service, person, organisation, technique, tool, method, KPIs) | I1, I3 |
| Adherence to EOSC and CORDRA standards | I1 |
| Data ingestion and exchange with external platforms (EOSC, SSHOC, H2IOSC) | F4 |
| Machine-actionable metadata, knowledge representation, and harmonisation | F2 |
| Research outputs (Reports, Datasets) available on Zenodo | F1 |
| Research outputs identification via DOI | F1, F3, I3 |
| Open-source software | R1.1 |
| Data export in different formats | I1 |

All these elements reflect the new approach to a "research need-oriented catalogue".[28] Through rigorous schema design, semantic enrichment, federated authentication, and open dissemination mechanisms, E-RIHS facilitates Open Science practices and promotes reproducibility, transparency, and collaboration in heritage science research.

## Architecture, structure, and functions of the system

The development of the E-RIHS CoS was preceded by the creation of its digital environment. A dedicated GitHub workspace,[28–30] hosts schemas (Table 2) and documentation, while a metadata knowledge base,[31] powered by CORDRA.[32] serves as the central repository for service-related digital objects.

The data model for the CoS is based on the knowledge based created for E-RIHS.[33] A selection of metadata fields was considered in order to respond to the requirements of the model centered on the service entity (Figure 2a–b), which acts as the main aggregation point and entry within the CoS. Each service is linked to one provider (i.e. an organization and a service managers) through explicit object properties that define responsibility for its implementation and delivery. Services are also associated with one or more platforms, representing the operational environments where they run, as well as with one or more tools and methods entities that describe the scientific approaches and technical capabilities they offer. These relationships ensure semantic consistency, interoperability, and machine-actionable service descriptions.

The inclusion of a service in the CoS aligns with the broader E-RIHS access policy and infrastructure governance,[34] which defines the eligibility criteria for platforms and services within the RI's operational framework. Services enter the E-RIHS CoS through a provider-driven submission process and must demonstrate compliance with the relevant access and platform eligibility requirements. Service information is then populated via the dashboard system (Figure 2c), which captures all required metadata fields, followed by editorial and metadata-quality validation by the User Helpdesk. An ongoing review and integration process ensures consistency and homogeneity across service records. After initial inclusion, services remain subject to regular review, managed through an internal versioning system. This workflow ensures that new or evolving service offerings, for example as newly developed techniques or digital tools can be added and updated over time in response to technological advancements and the needs of service managers.

An innovative addition with respect to the first CoS model implemented during IPERION HS is represented by the "Method" schema. This new entity captures the procedural knowledge required to conduct services across different service managers. The "Method" describes the way a specific equipment is employed by a service manager to offer a particular service. This could be the same for different service managers (Figure 2), yet its preparation needs a certain level of standardisation and the designation of the actor or institution in charge of the definition of this entity. This schema enhances reproducibility and supports the harmonisation of service offerings across the E-RIHS network.

**Table 2. List of the schemas available on GitHub.[28]**

| Schema | Description |
|---|---|
| Service | This schema is intended to model the metadata and details required to document and describe service or access providers within E-RIHS. These services will be offered by one or more funding programmes and exploited in one or more research projects. |
| Organisation | It represents the research institution, museum, etc., to which one or more persons can be affiliated. It contains information regarding the name, address, geographical coordinates, website, etc. |
| Person | It represents a person affiliated with a specific organisation. It contains information such as name, biography, country, role, etc. The role is particularly important since it defines who will be contacted (Contact person or Service Manager) when a User selects a service. |
| Technique | This schema is intended to model the metadata and details required to document and describe techniques that are used within access offerings in E-RIHS. |
| Tool/Equipment/ Software | It represents the Equipment, Tool or Software from more than one equipment employed. It describes the potential results obtained (output). |
| Method | It describes the procedure on how the Tool/Equipment/Software is set-up and used. It is expected to be a default standardized description reusable to define the service offered by different Service Managers. |
| KPI | It represents the Equipment, Tool or tool form from more than one equipment employed. It describes the potential results obtained (output). |

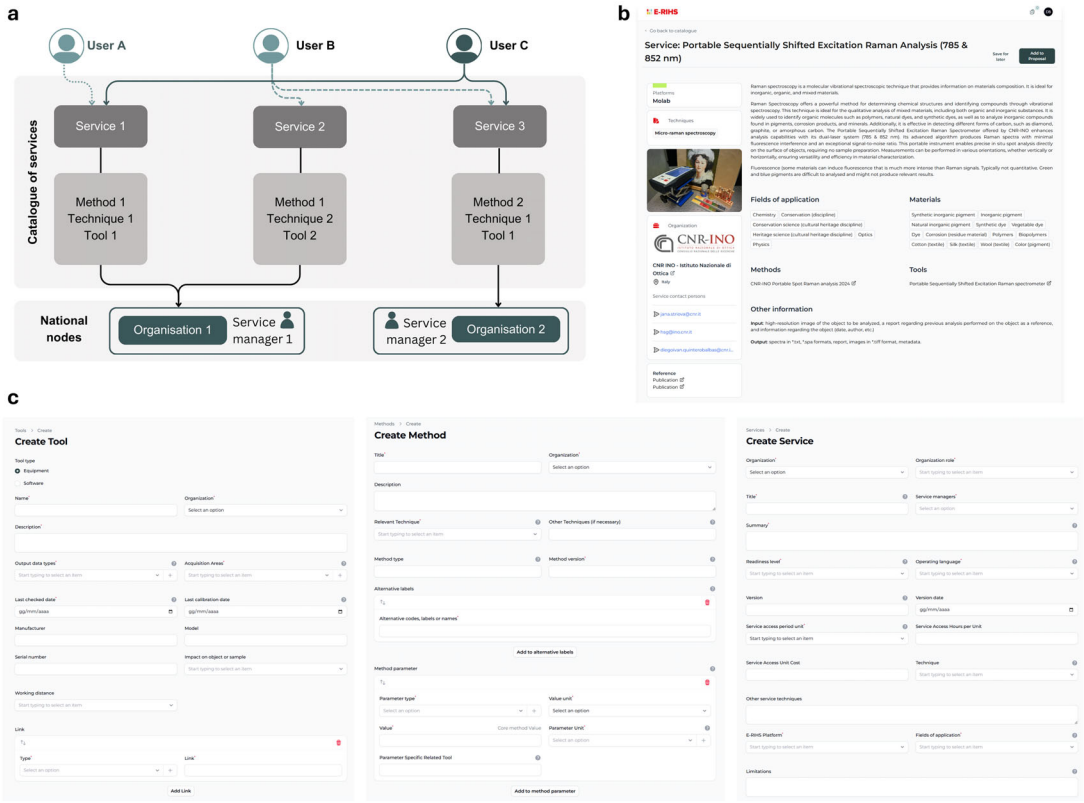



**Figure 2. a) Simplified schema of the architecture of the E-RIHS CoS and its interaction with the potential users. The frontend of a service included in the CoS is shown in b) along with the dashboard system for compiling its metadata in c).**

The combination of the schemas allows for a modular and scalable representation of services. The OpenTheso-based vocabulary platform – a multilingual and multi-hierarchical thesaurus manager that follows the ISO-25964 standard,[35,36] – further supports multilingualism and semantic clarity. Its integration with the CoS via open APIs ensures dynamic vocabulary management.

The new architecture and the use of open APIs increased interoperability with other tools developed within E-RIHS (DIGILAB) and with systems created in the context of other research infrastructures or projects at European and national level (e.g. EOSC, SSHOC, Resinfra, H2IOSC). As a result, all the data in the E-RIHS catalogue can be easily harvested and reused by the European marketplaces, expanding its accessibility. Furthermore, the catalogue system is fully released as open-source software, enabling its reuse and adaptation by other research infrastructures.

This CoS has been developed following two main guiding principles: responsiveness to the research needs of users and a co-creation approach involving service managers, users, and ICT experts. This marks a strategic transition from a "technique-oriented" to a "research need-oriented" catalogue. A key aspect was the creation of an independent platform built on a scalable, modular architecture, in collaboration with Net7 ICT company,[37] which is particularly important for a domain in constant change and for an RI in its initial operational phase. This design allows the platform to adapt and grow with the evolving needs of the RI and can be integrated with new features and emerging technologies. The E-RIHS CoS *scalability* resides in its core architectural and conceptual requirements since it is designed to accommodate growth in users, service records, and access requests without performance degradation, while supporting the progressive extension of functionalities through modular components and open APIs. At the same time, the data and semantic levels are handled through an extensible data model and controlled vocabularies that can evolve without compromising coherence or interoperability, facilitating the inclusion of new services originating from disciplines progressively incorporated into the scientific community, such as architecture, bioarchaeology, and related domains.

The architecture and requirements were defined through extensive consultations with stakeholders, including researchers, service managers, and infrastructure administrators. Interviews and iterative user experience (UX) testing cycles enabled the project team to identify key pain points and user expectations. The insights gained informed the creation of a detailed specification document that guided system development.

The new E-RIHS CoS.[38,39] is a standalone platform composed of two primary components: (1) a frontend interface serving as the entry point for users, and (2) a backend system dedicated to managing and monitoring proposals and access activities. Its implementation relied on contemporary web technologies, including the Laravel PHP framework for the backend and the Elasticsearch engine for semantic and faceted search. Laravel supports a robust, maintainable codebase including role-based access, workflow automation, and secure data handling. On the other hand, Elasticsearch enables robust and scalable search functionality, combining natural language processing with structured filtering. It also supports high-performance querying across large datasets, delivering fast and precise results essential for navigating extensive research service catalogues.

Advanced filters have been incorporated into the search functionality, to filter services for example, by type, research domain, geographic location, and availability. This feature enables users to precisely target relevant services, significantly improving search efficiency and user experience. The Elasticsearch-based implementation fosters an intuitive discovery process, even for unfamiliar users employing specific keywords or terminology and ensures that the system can scale effectively as the number of services and users grows, maintaining consistent performance and reliability.

The CoS involves four key actors (Figure 3): the User, the Service Manager (previously "provider"), the Reviewer, and the User Helpdesk. Access level varies according to the role and the dashboard system is tailored for each actor. The User Helpdesk is responsible for overseeing and managing the entire process, from submission to post-access activities, and for assigning roles to the other actors involved.

Behind the CoS, a detailed workflow (Figure 4) was embedded in the system and reflects the access model.[40] defined by E-RIHS: proposals are submitted through periodic cut-off calls, undergo technical feasibility checks by service managers, and are subsequently evaluated by independent reviewers.

The procedure is simple; users can browse the catalogue, even without creating a profile, which makes the service information open. To select services and add them to a research proposal, the users must register and log in, enrich their profile with detailed information on their scientific background and experience, fill down the online application form, and submit it within the deadline of the call for proposals.

The on-line form guides users through the proposal process and functions as a metadata generator. It feeds both the backend analytics, by extracting performance metrics, and the recommendation algorithm, by capturing comprehensive data on research needs, access requirements, and project contexts. Once the application has been submitted, service

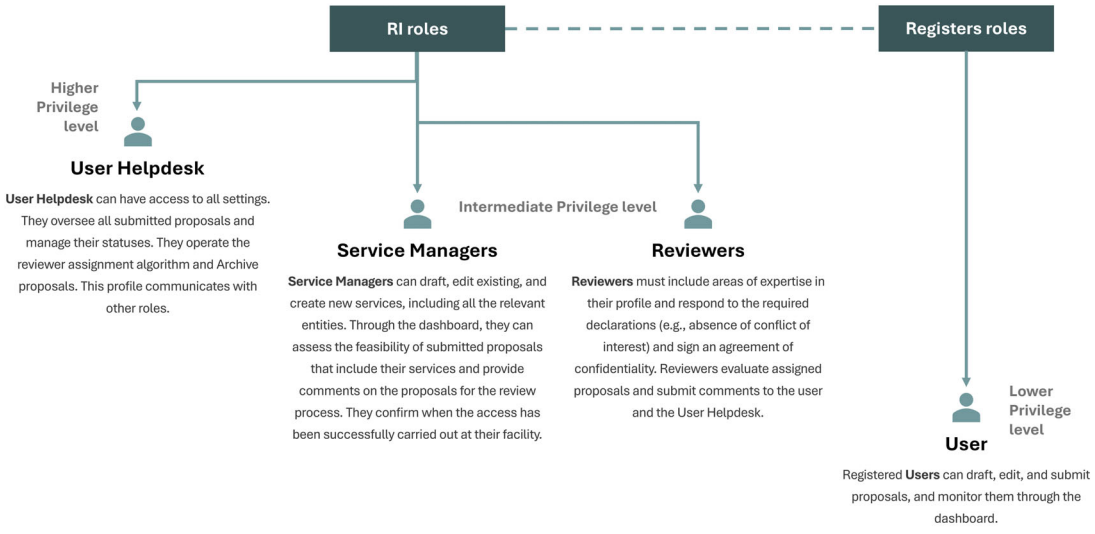



**Figure 3. List of roles involved in the E-RIHS CoS and their corresponding dashboard functionalities.**

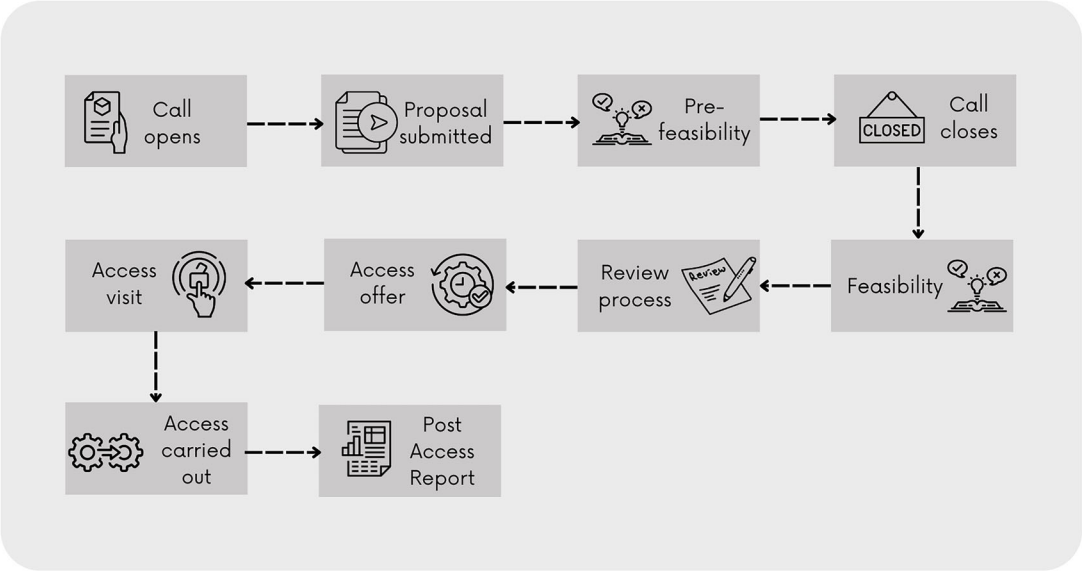



**Figure 4. CoS workflow as defined by the E-RIHS Access Policy.[40]**

managers assess the proposal's feasibility. This step represents a co-creation phase between users and service managers, since the service manager can provide comments to improve the proposal. Should the application be partially feasible or unfeasible, it returns to the draft phase, and users are encouraged to improve the proposal, change, or remove services, and resubmit the application before the established deadline. Feasible proposals undergo a review phase. An algorithm within the CoS system selects three reviewers based on the declared areas of expertise in the metadata of the profiles and the keywords of the proposal. Reviewers score the application based on defined criteria and provide comments to the users. Top-rated applications are granted access to the services. Following this phase, users and service managers agree on the access modalities and timeline, carry out the access, and collaboratively discuss and interpret data and results. At the end of the process, users are required to submit a final report.

The dashboard system helps monitor the entire process from the submission of a proposal to the post-access duties and gathers useful information that can be used to improve the CoS system and user experience. Their design focused on usability and intuitiveness, offering users a streamlined experience that makes it easy to access all key features. To this aim, a system of tabs is used to browse different pages where all the components are stored, such as the list of applications, the list of documents, and the application history.

As outlined in the E-RIHS Access Policy,[34] the RI provides continuous access through open calls for excellence-driven access, by ranking the proposals submitted and guaranteeing the maintenance of high-level standards. Two cut-off deadlines are expected by the year, one every six months. Additionally, the system can manage also market-driven and fast-track accesses.

At the time this work was developed (2020-2025), a major innovation in development was the integration of a recommendation engine within the CoS, inspired by recommender systems used in e-commerce and media platforms. This AI driven component was designed to support users in identifying the most appropriate services based on their research needs, having in mind that the community is broad and that not all users are experts in the scientific fields or equipment characteristics and methodological applications. The system is based on a Retrieval-Augmented Generation (RAG) architecture that integrates language models with a vector indexing infrastructure.[41] By generating high-dimensional embeddings and leveraging a vector database (Elasticsearch), the system performs similarity search operations to semantically map user queries to indexed content. The various strategies adopted – ranging from classical semantic similarity to multi-vector and multi-querying approaches – enable increased contextual granularity, improved robustness of information retrieval, and mitigation of model hallucination phenomena.

The engine was designed to analyse a broad array of data, including equipment characteristics, methodological applications, past project outcomes, and user feedback, to generate personalized recommendations. Natural language queries are supported to increase accessibility and inclusiveness, especially for non-experienced users looking for the best

solution for their research question. However, the AI-driven recommendation engine is not intended to replace the expertise of heritage scientists or the fundamental relationship between users and service managers. Rather, it serves as an initial orientation tool to guide users through the complex landscape of services and to build a more structured data foundation for this multifaceted sector. Data for training the algorithm are being collected through pilot applications distributed among the community and from E-RIHS service managers, with all processing conducted in full compliance with EU data protection regulations. Additionally, a dedicated working group identified representative research needs, compiling standardized controlled vocabularies and classification schemes to be used in service descriptions.

The contribution of researchers has been critical in enhancing the robustness and reliability of the system. Questions automatically generated by the Large Language Model (LLM) underwent manual validation, transforming a synthetic dataset into a golden dataset of reference, essential for rigorous endpoint evaluation. This intervention significantly impacted not only the improvement of retrieval quality but also the establishment of a structured feedback framework, which is fundamental for calibrating embedding techniques and optimizing the entire RAG pipeline according to E-RIHS's operational requirements.

The effectiveness of the recommendation engine depends on the quality and volume of structured metadata collected via the application form and backend monitoring tools. Users' engagement through input and feedback directly contributes to refining the system, allowing it to function as a dynamic, self-improving resource that supports decision-making, increases efficiency, and enhances the scientific impact of access activities. In a context marked by the rapid evolution of AI-driven technologies, targeted financial investments will be necessary to ensure future system updates and scalability.

## Current state of the CoS

The new E-RIHS CoS platform marked a milestone in delivering integrated access to heritage science services. Its first version, including the dashboard system, was released in October 2024. This release followed an intensive phase of design, prototyping, testing, and iteration, culminating in the transition from development to operational deployment. From the earliest stages, service managers were engaged in the co-design of the system, contributing to data modelling, the selection of controlled vocabularies, and the definition of access procedures. To support the operational rollout, training sessions for service managers of the different platforms were conducted from October to December 2024, involving a total of 32 representatives from E-RIHS National Nodes to start inserting services (Figure 5). They also served as validation environments, highlighting formal and functional requirements. Among the issues and changes identified in this phase can be listed the inclusion of a comment section from service managers to users following the feasibility evaluation to enhance the co-creation and collaboration between the user and the scientists. Also, the specialist involved identified the need to enable proposal revision and resubmission which required a revision in the functioning workflow.

The sessions, which were recorded and distributed to reach a wider audience, also allowed to identify concepts that were not completely clear to the service managers and represented an opportunity to adjust, when necessary, and explain the data model at the foundation of the CoS. Moreover, guidelines were prepared and made publicly accessible through the E-RIHS Zenodo community.[40,42,43] In parallel, technical support facilitated user onboarding and encouraged early engagement with the platform. At the moment this work was written (June 2025), 124 services are included in the CoS across three of the four platforms, involving ten E-RIHS national nodes (Figure 5). Their data are under revision by the Users Helpdesk to ensure consistency and homogeneity, a process that will be constantly and regularly updated. Also, digital services from the DIGILAB platform are progressively integrated through APIs to allow their discoverability.

Intermediate testing phases involved a significant number of participants, covering multiple dimensions of the user experience, such as intuitiveness of the dashboard, filtering and search mechanisms in the catalogue, as well as the effectiveness of the proposal submission workflow. Reviewers and the User Helpdesk assessed the peer-review system, focusing on proposal evaluation and approval processes. Several users (>50) were interviewed on usability, performance, and overall satisfaction, generating both qualitative and quantitative insights that directly informed development cycles.

The iterative UX testing approach resulted in concrete enhancements across the platform. Navigation structures were improved, visual elements were optimized, and user journeys were made more intuitive. To ensure methodological coherence in user-centred design, the IT company formally integrated a professional UX designer into the development team, supporting evidence-based design decisions and consistency across interfaces. UX testing was conducted in multiple iterative sessions involving different user profiles: (i) expert users already familiar with the IPERION HS catalogue, engaged to optimise task efficiency and reduce interaction latency; (ii) heritage science practitioners without prior exposure to the catalogue, involved to assess general usability and cognitive load; and (iii) non-specialist users with no previous experience of the system, recruited to evaluate navigability, onboarding effectiveness, and critical friction points within the access workflow. System performance and security were validated through comprehensive testing,

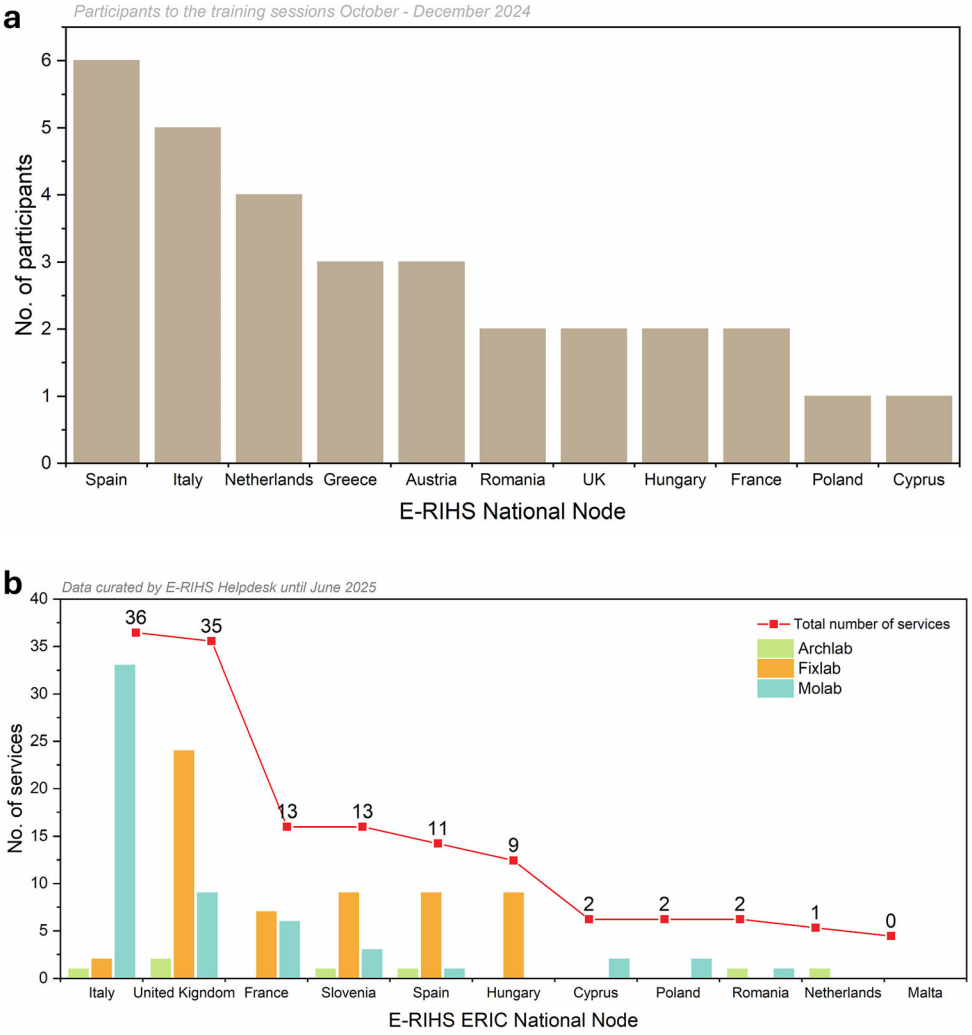



**Figure 5. a) Participants from E-RIHS nodes trained; b) E-RIHS ERIC Curated services catalogue across three platforms (by June 2025).**

including penetration tests and code reviews. Feedback collected through UX testing and real-time usage analytics continues to inform system updates. The co-creation philosophy embedded in the development process has proven essential for achieving a usable and adaptable platform.

To support continuous monitoring and decision-making, the CoS includes a Business Intelligence tool integrated into the User Helpdesk dashboard. This tool enables KPIs tracking and supports strategy adjustments based on platform usage data. The analytics module provides detailed insights across several dimensions:

- Proposals: total number and number per call/country; acceptance and reserve list rates; gender-disaggregated data; type classification (new, long-term, resubmission); status tracking.
- Scientific Disciplines: submission and acceptance breakdowns by discipline.
- Users: total number of users; submission activity; user-to-proposal ratios.
- Tools: request frequency per tool and call.

The resulting data can be visualised through graphs and maps and is available for download. Regular updates, based on the iterative engagement process with users and service managers, ensure that CoS remains aligned with the expectations and workflows of its users, consolidating its role as a central component in E-RIHS access provision.

## Conclusions and future perspectives

The development of the E-RIHS CoS demonstrates how a service-oriented digital platform can be used to structure and formalise the knowledge of a highly interdisciplinary research community through shared standards, common conceptual frameworks, controlled vocabularies, and FAIR-aligned data practices. Beyond the management of access to the scientific services, from proposal submission to delivery, the catalogue's workflow acts as an enabling mechanism for knowledge co-creation, fostering collaboration among researchers with diverse expertise and objectives, highlighting how an interoperable user-centered framework can overcome disciplinary barriers and support sustainable and cross-domain research ecosystems for scientists and other specialists.

The E-RIHS CoS is contributing significantly to the adoption of Open Science practices within the heritage science community. Through its adherence to FAIR data principles, support for reproducible research workflows, and user-centered design, the CoS promotes accessibility, transparency, and knowledge sharing. It also fosters cross-disciplinary collaboration and co-creation, enriching research at all stages—from project planning to reporting.

The CoS stands as a flagship initiative in digital heritage science infrastructure, showcasing how modular design, AI integration, semantic interoperability, and community co-creation can converge to deliver impactful, sustainable, and inclusive research services.

The E-RIHS CoS has been designed with a modular architecture to ensure long-term extensibility and maintainability. A core area of ongoing development will concern the further refinement of an AI-based recommendation engine. Although the current version of the CoS includes basic personalised suggestions, further enhancements will leverage structured metadata and behavioural analytics to support dynamic service recommendations. Powered by machine learning and natural language processing techniques, context-aware recommendations for individual research goal will improve with previous usage patterns. This capability, powered by growing number of available training data, will enhance discoverability and increase the efficiency of service selection processes. The AI-driven metadata analysis will progressively enhance the following features:

- Automated enrichment of metadata through natural language processing.
- Resource indexing and improved catalogue navigation.
- Predictive analytics for user behaviour and resource utilisation trends.

The application of non-generative AI technologies contributes to efficient data management and consistent metadata updates, forming the backbone of a scalable and intelligent digital infrastructure. The CoS is constantly aligned with the EOSC ecosystem and other domain-specific RIs, such as CLARIN, CERIC ERIC, and DARIAH. Currently available in English; however, a multilingual expansion to support broader accessibility and inclusiveness could be implemented. To this purpose, for example in collaboration with the CLARIN RI, a multilingual metadata management and query translation could include:

- Metadata Translation: Automated and manually validated translation of metadata fields, beginning with languages of the E-RIHS National Nodes, using semantic frameworks and controlled vocabularies (e.g., SKOS, AAT, and EDM).
- Query Translation: Implementation of multilingual search capabilities using CLARIN tools to ensure terminological consistency and user-friendly query interfaces.

CLARIN's expertise in domain-specific term extraction, translation, and controlled vocabulary creation could guide this process, ensuring high-quality, interoperable multilingual support for both human-readable and machine-actionable metadata.[44,45] Moreover, the semantic annotation of resources could allow a more precise classification and linking of information across domains.

The ERIC legal framework of E-RIHS is reinforcing governance structures and long-term sustainability of the CoS. Under E-RIHS ERIC, responsibilities for catalogue maintenance, technological evolution, user support, and policy

compliance has been formally allocated, ensuring continuity and accountability. This governance model supports the long-term operation and strategic development of the platform in alignment with international standards and community needs.

## Ethics and consent

Ethical approval and consent were not required.

## Abbreviations

| | |
|---|---|
| **AAT** | Art and Architecture Thesaurus |
| **AI** | Artificial Intelligence |
| **API(s)** | Application Programming Interface(s) |
| **ARIA** | Access to Research Infrastructure Administration |
| **ARIADNE** | Advanced Research Infrastructure for Archaeological Data Networking in Europe |
| **CERIC** | Central European Infrastructure Consortium |
| **CLARIN** | Common Language Resources and Technology Infrastructure |
| **CORBEL** | Coordinated Research Infrastructure Building Enduring Life-science services |
| **DARIAH** | Digital Research Infrastructure for the Arts and Humanities |
| **E-RIHS** | European Research Infrastructure on Heritage Science |
| **E-RIHS IP** | European Research Infrastructure on Heritage Science – Implementation Phase |
| **E-RIHS PP** | European Research Infrastructure on Heritage Science – Preparatory Phase |
| **EDM** | European Data Model |
| **ELIXIR** | European Life-science Infrastructure for Biological Information |
| **EOSC** | European Open Science Cloud |
| **ERIC** | European Research Infrastructure Consortium |
| **ESFRI** | European Straregy Forum on Research Infrastructures |
| **FAIR** | Findable, Accessible, Interoperable, Reusable |
| **H2IOSC** | Humanities and cultural Heritage Italian Open Science Cloud |
| **ICT** | Information and Communication Technology |
| **IPERION CH** | Integrated Platform for the European Research Infrastructure on Cultural Heritage |
| **IPERION HS** | Integrating Platforms for the European Research Infrastructure ON Heritage Science |
| **ISO** | International Organization for Standardization |
| **KPIs** | Key Performance Indicator(s) |
| **PARTHENOS** | Pooling Activities, Resources and Tools for Heritage E-research Networking, Optimization and Synergies |
| **ResInfra** | EU-CELAC Joint Initiative for Research and Collaboration – Research Infrastructure |
| **RI(s)** | Research Infrastructure(s) |
| **SKOS** | Simple Knowledge Organization System |
| **SQL** | Structured Query Language |
| **UX** | User Experience |

## Data availability

### Underlying data

The E-RIHS CoS is online, available at the link: https://catalogue.e-rihs.eu/catalogue.

The dataset was derived from the database of the E-RIHS ERIC Catalogue of Services and is available at Zenodo: CNR INO Dataset for the E-RIHS CoS: https://doi.org/10.5281/zenodo.16532272.[39]

The project contains the following underlying data:

- E-RIHS CoS_CNR INO_Dataset.xlsx

The dataset is available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

## Software availability

- Source code available from: https://github.com/net7/ERIHS_catalogue/tree/v.1.0
- Archived software available from: https://zenodo.org/records/16362229
- License: GPL v3

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to enhance the readability and language. After using the tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Acknowledgment

The authors acknowledge the following partners for their contribution to develop the E-RIHS CoS: Net7 Srl, Silvia Manconi, David Buti, Alberto Bucciero, Brenda Doherty, Wim Fremout, Joseph Padfield, Sophia Sotiropoulou, Vania Virgili.

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# Open Peer Review

## Current Peer Review Status: ✔ ? ? ✔

**Version 2**

Reviewer Report 18 June 2026

https://doi.org/10.21956/openreseurope.24784.r70336

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✔ **Sonja Herres-Pawlis**
RWTH Aachen University, Aachen, Germany

This article describes the design, implementation, and deployment of the E-RIHS Catalogue of Services (CoS), a FAIR-compliant digital platform that serves as the main access point to scientific services offered by the European Research Infrastructure for Heritage Science (E-RIHS). The platform aims to help researchers identify, request, and manage access to heritage science facilities, archives, instruments, expertise, and digital resources.

A central challenge addressed by the authors is that heritage science is highly interdisciplinary, bringing together chemists, physicists, conservators, archaeologists, art historians, and engineers. Many users are not experts in analytical techniques and therefore struggle to identify appropriate facilities or methods for their research questions.

The paper traces the evolution of the catalogue from earlier E-RIHS and IPERION projects to a more sophisticated platform built around:

- FAIR and Open Science principles
- Structured metadata and controlled vocabularies
- Semantic search using Elasticsearch
- Workflow management for proposal submission and peer review
- Role-specific dashboards
- Open APIs and interoperability with EOSC and other research infrastructures
- An emerging AI-based recommendation engine to help users identify suitable services

A major conceptual shift is from a "technique-oriented" catalogue (listing instruments and analytical methods) to a "research-need-oriented" catalogue that starts from the user's scientific problem. This is really good for the community!

The architecture is based on modular schemas (Service, Organization, Person, Technique, Tool, Method, KPI) and a knowledge-based infrastructure intended to support interoperability and future scalability. The contribution also describes the workflow through which users submit

proposals, receive feasibility feedback from service managers, undergo peer review, and ultimately gain access to E-RIHS facilities.

The strongest technical contribution is the explicit attempt to apply FAIR principles not only to datasets but also to service descriptions and service discovery. The authors provide a mapping between catalogue features and FAIR principles and describe metadata structures, identifiers, APIs, controlled vocabularies, and interoperability mechanisms.

***Small point for a potential revision:*** *The authors improved the table but still do not provide a systematic FAIR maturity assessment.*

The catalogue was developed through sustained engagement with service managers, users, platform coordinators, and ICT developers over several years and I would like to point out that this iterative refinement, testing, and community involvement is crucial for a good CoS. I would like to note that heritage science includes many users who are not specialists in analytical instrumentation and that the report´s emphasis on usability, recommendation support and co-creation is therefore well justified.
The AI recommendation engine based on RAG architecture is innovative and potentially useful for non-expert users. In my view, the authors correctly position it as a support tool rather than a replacement for expert consultation.

This report documents a real operational system that supports a major European research infrastructure, and the practical impact is evident. The catalogue reflects nearly a decade of development work, beginning with E-RIHS Preparatory Phase and IPERION HS. Hereby, the report captures valuable lessons from infrastructure-building that are rarely documented systematically. The platform's code, metadata schemas, datasets, and documentation are openly available. This increases reproducibility and allows reuse by other infrastructures.

In summary, this is a valuable and timely infrastructure report documenting the creation of an important FAIR-oriented service platform for heritage science. Its major strength lies in its practical implementation and community-driven design.

**Is the work original in terms of material and argument?**

Yes

**Does it sufficiently engage with relevant methodologies and secondary literature on the topic?**

Yes

**Is the work clearly and cogently presented?**

Yes

**Is the argument persuasive and supported by evidence?**

Yes

**If any, are all the source data and materials underlying the results available?**

Yes

**Does the research article contribute to the cultural, historical, social understanding of the field?**
Yes

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Chemistry, FAIR data, Research data management

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.**

Reviewer Report 05 March 2026

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**Katrina Exter**
Flanders Marine Institute (VLIZ), Oostende, Belgium

The authors have improved the manuscript and I have no further comments to make on the manuscript: fully approved.
As an FYI to the authors, I would again suggest that they exposed their schemas on GH as json-ld as well (which they did say they were considering), as this will make those schemas interoperable wtih the wider research (or any other) community...following, for example, the ODIS (Ocean Data Information System) approach of schema.org+json-ld, consideing mapping to CodeMeta for software schemas, etc.
Good luck with future evolutions.

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Open science, data management

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.**

**Version 1**

Reviewer Report 06 January 2026

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?

**Brian Matthews**
STFC, Rutherford Appleton Laboratory, Didcot, Oxfordshire, UK

The article is well-written and a good summary of the work undertaken to implement the E-RIHS CoS.
However, I find the title of the paper misleading as the emphasis of the paper is not the design of the Catalogue itself, but rather how it supports users in a proposal submission, evaluation and service access workflow. This is broader than the Catalogue itself and would thus be of interest to a different audience - service managers rather than catalogue developers. This is nicely presented and of value in itself, but as a consequence how services are actually catalogued, how service metadata is chosen and presented in the system, and how in particular new services are onboarded are only briefly touched upon. A fuller treatment of this would give better insight into the scope and usability of the system.

Table 1 is curious and I am not convinced that all features are correctly classified against the FAIR criteria. Particularly some of the Accessibility criteria seem misplaced. Perhaps a more detailed assessment against the specific criteria would be of value. Have the authors undertaken a FAIR evaluation?

Figure 3 seems to take a lot of space - could this be made more compact? I am not certain of the meaning
of the Access Level arrow from - to +.

The use of AI for recommendation services is interesting, but is brief and seems an afterthought. Is it in response to user demand? Do users find it hard to navigate around the system - currently 124 services are included - significant but not overwhelming. Could search be enhanced in other ways? (better keywords, user reviews and recommendations etc).

**Is the work original in terms of material and argument?**
Partly

**Does it sufficiently engage with relevant methodologies and secondary literature on the topic?**
Yes

**Is the work clearly and cogently presented?**
Yes

**Is the argument persuasive and supported by evidence?**
Yes

**If any, are all the source data and materials underlying the results available?**

Yes

**Does the research article contribute to the cultural, historical, social understanding of the field?**
Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Data management, metadata, data infrasructure, data catalogues, FAIR research, workflows, service management

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 21 Jan 2026

**Laura Benassi**

We thank you for the careful reading of the manuscript and for the constructive comments, which helped us to better clarify the scope, focus, and presentation of the work.

**Request 1**: *This is nicely presented and of value in itself, but as a consequence how services are actually catalogued, how service metadata is chosen and presented in the system, and how in particular new services are onboarded are only briefly touched upon. A fuller treatment of this would give better insight into the scope and usability of the system.*
**Answer**: We acknowledge your observation that the manuscript places strong emphasis on how the Catalogue supports proposal submission, evaluation, and service access workflows, rather than focusing exclusively on catalogue design in a narrow sense. This emphasis was intentional. That said, we agree that aspects such as service cataloguing, metadata selection, and onboarding of new services. We have added additional information to provide better insight into how services are described, harmonised, and operationally integrated into the system, while maintaining the workflow-oriented perspective of the paper. Also, we have modified Figure 2 to include a visual representation of the dashboard system used to populate the service metadata. p.3 “Interdisciplinarity is a persistent challenge in the heritage science domain due to the different methods and languages employed to analyse, study, interpret, and intervene in cultural and natural heritage. The E-RIHS scientific community has worked to overcome the fragmentation of different approaches by creating three integrated platforms to offer its services: • ARCHLAB, providing access to scientific archives and collections of heritage-related data, including access to samples, datasets, or scientific reports from historical or artistic artefacts preserved in scientific archives [2]; • FIXLAB, offering large and medium-scale cutting-edge laboratory instrumentation, such as synchrotrons or particle accelerators, to analyse samples coming from the artefacts under investigation [3]; • MOLAB, enabling the use of mobile instrumentation for on-site heritage non-invasive analysis, such as the study of an artwork directly inside the museum exhibition room [4]. Many online catalogues of services and marketplaces created by European and non-European research infrastructures

primarily focus on digital tools, data, and related services. The E-RIHS CoS represents one of the few initiatives that effectively aligns services with user needs for access to archives, laboratories, and instrumentation. By prioritizing physical access, this approach introduces additional conceptual and operational complexity in both the design and implementation of the catalogue. To complement this framework with digital resources, E-RIHS is developing DIGILAB, a dedicated platform for digital tools and data that will provide a comprehensive, FAIR-compliant knowledge base for heritage digital twins." p.5: "In coordination with the ARCHLAB, FIXLAB, and MOLAB platform leaders, services were clustered into high-level functional categories (e.g. spectroscopic analysis, spot analysis, etc.), leading to the formalisation of a coherent data model [5]. In the absence of a consolidated domain ontology or standardized controlled vocabularies for heritage science, service managers were invited to populate the model fields and contribute domain-specific terminology reflecting established practices within their scientific communities. The coordination group subsequently carried out an extensive, tricky process of data curation, harmonisation, and standardisation, validating semantic consistency and structural coherence across the catalogue." p.9: "The inclusion of a service in the CoS aligns with the broader E-RIHS access policy and infrastructure governance [8], which defines the eligibility criteria for platforms and services within the RI's operational framework. Services enter the E-RIHS CoS through a provider-driven submission process and must demonstrate compliance with the relevant access and platform eligibility requirements. Service information is then populated via the dashboard system (Figure 2c), which captures all required metadata fields, followed by editorial and metadata-quality validation by the User Helpdesk. An ongoing review and integration process ensures consistency and homogeneity across service records. After initial inclusion, services remain subject to regular review, managed through an internal versioning system. This workflow ensures that new or evolving service offerings, for example as newly developed techniques or digital tools can be added and updated over time in response to technological advancements and the needs of service managers."

**Request 2**: *Table 1 is curious and I am not convinced that all features are correctly classified against the FAIR criteria. Particularly some of the Accessibility criteria seem misplaced. Perhaps a more detailed assessment against the specific criteria would be of value. Have the authors undertaken a FAIR evaluation?*
**Answer**: Thank you for pointing this out. Indeed, this comment agrees with a suggestion by another reviewer. We have revised and simplified the table to make a more precise identification of the FAIR principles following the descriptions in GO FAIR: https://www.go-fair.org/fair-principles/

**Request 3**: *Figure 3 seems to take a lot of space - could this be made more compact? I am not certain of the meaning of the Access Level arrow from - to +.*
**Answer**: Thank you for this suggestion. Figure 3 has been modified accordingly, and the contents have been summarized to improve its interpretability.

**Request 4**: *The use of AI for recommendation services is interesting, but is brief and seems an afterthought. Is it in response to user demand? Do users find it hard to navigate around the system - currently 124 services are included - significant but not overwhelming. Could search be enhanced in other ways? (better keywords, user reviews and recommendations etc).*
**Answer**: Thank you for this comment, which again agrees with the suggestion by another

reviewer. The introduction of AI features emerged in response to the specific needs of the Heritage Science community users. We have included further information in the introduction to better contextualize the characteristics of the users involved in E-RIHS community. The challenge faced when working with a particularly heterogeneous user base, which includes not only scientists but also humanities scholars (e.g. art historians or archaeologists) who may seek scientific analyses without being familiar with available techniques or infrastructures, made it necessary to look for strategies to aid them during service selection. In this context, AI-based recommendations were intended to support user orientation and discovery, complementing search and filtering mechanisms, but not to replace human interaction. We have expanded the AI-driven system description in order to make clearer the goal of its use and characteristics. p.14 "The new E-RIHS CoS platform marked a milestone in delivering integrated access to heritage science services. Its first version, including the dashboard system, was released in October 2024. This release followed an intensive phase of design, prototyping, testing, and iteration, culminating in the transition from development to operational deployment. From the earliest stages, service managers were engaged in the co-design of the system, contributing to data modelling, the selection of controlled vocabularies, and the definition of access procedures. To support the operational rollout, training sessions for service managers of the different platforms were conducted from October to December 2024, involving a total of 32 representatives from E-RIHS National Nodes to start inserting services (Figure 5). They also served as validation environments, highlighting formal and functional requirements. Among the issues and changes identified in this phase can be listed the inclusion of a comment section from service managers to users following the feasibility evaluation to enhance the co-creation and collaboration between the user and the scientists. Also, the specialist involved identified the need to enable proposal revision and resubmission which required a revision in the functioning workflow. The sessions, which were recorded and distributed to reach a wider audience, also allowed to identify concepts that were not completely clear to the service managers and represented an opportunity to adjust, when necessary, and explain the data model at the foundation of the CoS."

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 31 December 2025

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**Yaxing Wei**
ORNL Distributed Active Archive Center, Oak Ridge, Tennessee, USA

This manuscript introduces the concept, design, and development of the new ERIHS CoS, emphasising how it follows FAIR and Open Science principles. This manuscript gives a well

introduction to the co-creation process and its novelty compared with similar platforms from European RIs. It highlights the two main guiding principles that the development process followed: 1) responsiveness to the research needs of users and 2) a co-creation approach involving service managers, users, and ICT experts. The flow of the manuscript is clear and it's easy to read.

But the manuscript can be potentially improved in multiple ways. Below are some suggestions and questions:

As someone who is not familiar with heritage science, I found it's hard to figure out what a "service" really means in this context or what "services" are really managed in this E-RIHS CoS. Suggest to add a few sentences to introduce heritage science at the beginning, especially its broad, multi-disciplinary, and heterogeneous nature. Also, provide a high-level categorization of "services" along with some examples of each category.

In Table 1, instead of simply using dots to indicate that a E-RIHS CoS' feature supports FAIR, be more specific and list what aspects of the FAIR principles (e.g., F1, F2, A1.1, I2, R1.3 found on https://www.go-fair.org/fair-principles/) are supported by each main CoS feature. This will better elaborate how the E-RIHS CoS supports FAIR and also help to identify gaps, if there is any.

How are the different schemas listed in Table 2 connected with each other to form an integrated data model?

How does this E-RIHS CoS fit into the overall E-RIHS system and the even broader European RIs? Are there use cases that users need to leverage E-RIHS CoS and other components of E-RIHS and/or European RIs to accomplish some objectives? Highlight its interoperability with other components of the E-RIHS system and/or the broader European RIs through those use cases.

"Scalability" is listed as one of the novelties of the E-RIHS CoS. But I can't seem to find information that elaborate what "scalability" means in this context, how scalability was achieved, and if there was any effort to quantify the scalability.

What are the lessons learned from E-RIHS CoS that can potentially benefit the broader communities, beyond heritage science and European RIs?

The manuscript doesn't sufficiently describe how the AI-driven recommendation engine works. It says "Users' engagement through input and feedback directly contributes to refining the system, allowing it to function as a dynamic, self-improving resource that supports decision-making, increases". But it's unclear how users' input and feedback are used to refine the system.

The "Current state of the CoS" section described how the training sessions and intermediate testing phases were conducted and "resulted in concrete enhancements across the platform". An elaboration of what feedback was collected during the training and testing and what enhancements were made based on these feedback would be helpful.

An Excel spreadsheet (E-RIHS CoS_CNR INO_Dataset.xlsx) is listed as a dataset associated with this manuscript. But I couldn't find this anywhere this dataset was described in the manuscript.

**Is the work original in terms of material and argument?**

Yes

**Does it sufficiently engage with relevant methodologies and secondary literature on the topic?**
Yes

**Is the work clearly and cogently presented?**
Partly

**Is the argument persuasive and supported by evidence?**
Partly

**If any, are all the source data and materials underlying the results available?**
Yes

**Does the research article contribute to the cultural, historical, social understanding of the field?**
Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** data science, remote sensing, data curation and management, geospatial information science, and environmental science

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 21 Jan 2026

**Laura Benassi**

We thank you for the positive evaluation of the manuscript, and we appreciate the detailed and constructive suggestions, which have helped us to improve the manuscript substantially. Below, we address each comment in turn.

**Request 1**: *As someone who is not familiar with heritage science, I found it's hard to figure out what a "service" really means in this context or what "services" are really managed in this E-RIHS CoS. Suggest to add a few sentences to introduce heritage science at the beginning, especially its broad, multi-disciplinary, and heterogeneous nature. Also, provide a high-level categorization of "services" along with some examples of each category.*
**Answer**: We thank you for highlighting the need to better contextualise our work. We have expanded the introductory section to describe heritage science as a broad, heterogeneous, and inherently multidisciplinary domain. pp.2-3: "Heritage Science – a broad and multidisciplinary field that focuses on the scientific study, interpretation, conservation, and preservation of cultural and natural heritage, operates across different contexts with heterogeneous domains of knowledge and stakeholders, including non-experts and the

public. In the last few decades, research on both tangible and intangible heritage has gained interest worldwide 1, 2 , drawing on a wide range of disciplines from the humanities (art history, archaeology, history), sciences (chemistry, physics, biology), and engineering (materials science, digital tools) [1]. Heritage Science has progressively strengthened its collaborative nature. These efforts to enhance scientific cooperation among the different specialists involved have led to the establishment of a dedicated European Research Infrastructure (E-RIHS)." To make the notion of "services" more concrete, we have introduced the three integrated E-RIHS platforms and provided examples of the services included for each category, including adequate examples in the reference. p.3 "Interdisciplinarity is a persistent challenge in the heritage science domain due to the different methods and languages employed to analyse, study, interpret, and intervene in cultural and natural heritage. The E-RIHS scientific community has worked to overcome the fragmentation of different approaches by creating three integrated platforms to offer its services: • ARCHLAB, providing access to scientific archives and collections of heritage-related data, including access to samples, datasets, or scientific reports from historical or artistic artefacts preserved in scientific archives [2]; • FIXLAB, offering large and medium-scale cutting-edge laboratory instrumentation, such as synchrotrons or particle accelerators, to analyse samples coming from the artefacts under investigation [3]; • MOLAB, enabling the use of mobile instrumentation for on-site heritage non-invasive analysis, such as the study of an artwork directly inside the museum exhibition room [4]".

**Request 2**: *In Table 1, instead of simply using dots to indicate that a E-RIHS CoS' feature supports FAIR, be more specific and list what aspects of the FAIR principles (e.g., F1, F2, A1.1, I2, R1.3 found on https://www.go-fair.org/fair-principles/) are supported by each main CoS feature. This will better elaborate how the E-RIHS CoS supports FAIR and help to identify gaps, if there is any.*
**Answer**: Thank you for the valuable suggestion to make the FAIR alignment more explicit. Table 1 has been revised to indicate which specific FAIR principles (e.g. F1, F2, A1.1, I2, R1.3) are supported by each main feature of the CoS, following the FAIR principles as defined by GO FAIR.

**Request 3**: *How are the different schemas listed in Table 2 connected with each other to form an integrated data model?*
**Answer**: In response to the question on how the schemas listed in Table 2 are connected, we clarified that they are components of a unified data model, simplified in Figure 2. We added a concise explanatory paragraph at p. 10 describing the semantic relationships among the main entities. p.9 "The data model for the CoS is based on the knowledge based created for E-RIHS [7]. A selection of metadata fields was considered in order to respond to the requirements of the model centered on the service entity (Figure 2a-b), which acts as the main aggregation point and entry within the CoS. Each service is linked to one provider (i.e. an organization and a service managers) through explicit object properties that define responsibility for its implementation and delivery. Services are also associated with one or more platforms, representing the operational environments where they run, as well as with one or more tools and methods entities that describe the scientific approaches and technical capabilities they offer. These relationships ensure semantic consistency, interoperability, and machine-actionable service descriptions."

**Request 4**: *How does this E-RIHS CoS fit into the overall E-RIHS system and the even broader European RIs? Are there use cases that users need to leverage E-RIHS CoS and other components of E-RIHS and/or European RIs to accomplish some objectives? Highlight its interoperability with other components of the E-RIHS system and/or the broader European RIs through those use cases.*
**Answer**: Thank you for requesting clarification on how the CoS fits within the wider E-RIHS system and European research infrastructures. To address this, we added a paragraph. We also clarify that all CoS data are harvestable and reusable by European research marketplaces, and that the Catalogue system is fully open source, enabling reuse and adaptation by other research infrastructures. Relevant references have been added. p. 11: "The new architecture and the use of open APIs increased interoperability with other tools developed within E-RIHS (DIGILAB) and with systems created in the context of other research infrastructures or projects at European and national level (e.g. EOSC, SSHOC, Resinfra, H2IOSC). As a result, all the data in the E-RIHS catalogue can be easily harvested and reused by the European marketplaces, expanding its accessibility. Furthermore, the catalogue system is fully released as open-source software, enabling its reuse and adaptation by other research infrastructures."

**Request 5**: *"Scalability" is listed as one of the novelties of the E-RIHS CoS. But I can't seem to find information that elaborate what "scalability" means in this context, how scalability was achieved, and if there was any effort to quantify the scalability.*
**Answer**: Thank you for this request for clarification of the scalability concept. We added a dedicated paragraph and contextualised scalability within a catalogue for the heritage science community. pp.10-11 "A key aspect was the creation of an independent platform built on a scalable, modular architecture, in collaboration with Net7 ICT company 31, which is particularly important for a domain in constant change and for an RI in its initial operational phase. This design allows the platform to adapt and grow with the evolving needs of the RI and can be integrated with new features and emerging technologies. The E-RIHS CoS scalability resides in its core architectural and conceptual requirements since it is designed to accommodate growth in users, service records, and access requests without performance degradation, while supporting the progressive extension of functionalities through modular components and open APIs. At the same time, the data and semantic levels are handled through an extensible data model and controlled vocabularies that can evolve without compromising coherence or interoperability, facilitating the inclusion of new services originating from disciplines progressively incorporated into the scientific community, such as architecture, bioarchaeology, and related domains."

**Request 6**: *What are the lessons learned from E-RIHS CoS that can potentially benefit the broader communities, beyond heritage science and European RIs?*
**Answer**: Thank you for this suggestion. We expanded the Conclusions by including some consideration describing how the CoS approach can impact other communities. p.16: "The development of the E-RIHS CoS demonstrates how a service-oriented digital platform can be used to structure and formalise the knowledge of a highly interdisciplinary research community through shared standards, common conceptual frameworks, controlled vocabularies, and FAIR-aligned data practices. Beyond the management of access to the scientific services, from proposal submission to delivery, the catalogue's workflow acts as an enabling mechanism for knowledge co-creation, fostering collaboration among researchers

with diverse expertise and objectives, highlighting how an interoperable user-centered framework can overcome disciplinary barriers and support sustainable and cross-domain research ecosystems for scientists and other specialists."

**Request 7**: *The manuscript doesn't sufficiently describe how the AI-driven recommendation engine works. It says "Users' engagement through input and feedback directly contributes to refining the system, allowing it to function as a dynamic, self-improving resource that supports decision-making, increases". But it's unclear how users' input and feedback are used to refine the system.*
**Answer**: Thank you for this observation. We have elaborated more on the AI-driven recommendation system and the interaction with the users, as well as the strategies undertaken to improve the AI-system by including the contribution of the community. pp.13-14 "At the time this work was developed (2020-2025), a major innovation in development was the integration of a recommendation engine within the CoS, inspired by recommender systems used in e-commerce and media platforms. This AI driven component was designed to support users in identifying the most appropriate services based on their research needs, , having in mind that the community is broad and that not all users are experts in the scientific fields or equipment characteristics and methodological applications. The system is based on a Retrieval-Augmented Generation (RAG) architecture that integrates language models with a vector indexing infrastructure [9]. By generating high-dimensional embeddings and leveraging a vector database (Elasticsearch), the system performs similarity search operations to semantically map user queries to indexed content. The various strategies adopted – ranging from classical semantic similarity to multi-vector and multi-querying approaches – enable increased contextual granularity, improved robustness of information retrieval, and mitigation of model hallucination phenomena. The engine was designed to analyze a broad array of data, including equipment characteristics, methodological applications, past project outcomes, and user feedback, to generate personalized recommendations. Natural language queries are supported to increase accessibility and inclusiveness, especially for non-experienced users looking for the best solution for their research question. However, the AI-driven recommendation engine is not intended to replace the expertise of heritage scientists or the fundamental relationship between users and service managers. Rather, it serves as an initial orientation tool to guide users through the complex landscape of services and to build a more structured data foundation for this multifaceted sector. Data for training the algorithm are being collected through pilot applications distributed among the community and from E-RIHS service managers, with all processing conducted in full compliance with EU data protection regulations. Additionally, a dedicated working group identified representative research needs, compiling standardized controlled vocabularies and classification schemes to be used in service descriptions. The contribution of researchers has been critical in enhancing the robustness and reliability of the system. Questions automatically generated by the Large Language Model (LLM) underwent manual validation, transforming a synthetic dataset into a golden dataset of reference, essential for rigorous endpoint evaluation. This intervention significantly impacted not only the improvement of retrieval quality but also the establishment of a structured feedback framework, which is fundamental for calibrating embedding techniques and optimizing the entire RAG pipeline according to E-RIHS's operational requirements. …. In a context marked by the rapid evolution of AI-driven technologies, targeted financial investments will be necessary to ensure future system

updates and scalability."

**Request 8**: *The "Current state of the CoS" section described how the training sessions and intermediate testing phases were conducted and "resulted in concrete enhancements across the platform". An elaboration of what feedback was collected during the training and testing and what enhancements were made based on these feedback would be helpful.*
**Answer**: Thank you for this suggestion. We have expanded the description of training sessions and UX testing results. p.14 "The new E-RIHS CoS platform marked a milestone in delivering integrated access to heritage science services. Its first version, including the dashboard system, was released in October 2024. This release followed an intensive phase of design, prototyping, testing, and iteration, culminating in the transition from development to operational deployment. From the earliest stages, service managers were engaged in the co-design of the system, contributing to data modelling, the selection of controlled vocabularies, and the definition of access procedures. To support the operational rollout, training sessions for service managers of the different platforms were conducted from October to December 2024, involving a total of 32 representatives from E-RIHS National Nodes to start inserting services ( Figure 5). They also served as validation environments, highlighting formal and functional requirements. Among the issues and changes identified in this phase can be listed the inclusion of a comment section from service managers to users following the feasibility evaluation to enhance the co-creation and collaboration between the user and the scientists. Also, the specialist involved identified the need to enable proposal revision and resubmission which required a revision in the functioning workflow. The sessions, which were recorded and distributed to reach a wider audience, also allowed to identify concepts that were not completely clear to the service managers and represented an opportunity to adjust, when necessary, and explain the data model at the foundation of the CoS." p. 15 "To ensure methodological coherence in user-centred design, the IT company formally integrated a professional UX designer into the development team, supporting evidence-based design decisions and consistency across interfaces. UX testing was conducted in multiple iterative sessions involving different user profiles: (i) expert users already familiar with the IPERION HS catalogue, engaged to optimise task efficiency and reduce interaction latency; (ii) heritage science practitioners without prior exposure to the catalogue, involved to assess general usability and cognitive load; and (iii) non-specialist users (e.g. art historians) with no previous experience of the system, recruited to evaluate navigability, onboarding effectiveness, and critical friction points within the access workflow."

**Request 9**: *An Excel spreadsheet (E-RIHS CoS_CNR INO_Dataset.xlsx) is listed as a dataset associated with this manuscript. But I couldn't find this anywhere this dataset was described in the manuscript.*
**Answer**: We are sorry if this was not completely clear. We have described the dataset in the Data Availability section. The dataset, derived from the operational database of the E-RIHS ERIC Catalogue of Services, is available via Zenodo as the CNR INO Dataset for the E-RIHS Catalogue of Services (DOI: 10.5281/zenodo.16532272).

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 25 November 2025

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**Katrina Exter**
Flanders Marine Institute (VLIZ), Oostende, Belgium

Nice arcticle, well written, very easy to read.
The audience focus for the paper is others creating catalogues of services. This article provides well for that audience: much appreciated.
The technical aspects are nicely introduced and summarised, and the GitHub space provides a lot of extra material for those who want to, to explore: much appreciated. (Tho a front-page README would be appreciated on that GH space)

Two things are lacking
- An explantion of the human side of the development. Often the biggest hurdle to creating anything new are the humans, not the IT. More detail on their experience on getting cooperation and good input from the service managers - what did and did not work - would be much appreciated. More detail on how the UX testing was designed, conducted, managed would also be appreciated, as user testing is crucial.
- AI: it is a little unclear how much of the AI-based "recommendations" part of the CoS is already in place and how much is still being tested. If this is still in development, will another article on that be written later? As this is the big novel part of this CoS, there will be a lot of interest in know how it was done. What did AI bring to the table - especially as AI is so resource intensive, it should be justitifed why the AI approach is superior to any tested/investigated non-AI methods. What algorithms were used in the AI? Will this be open source, once completed (and if not, why)?

A suggestion: JSON-LD would be superior to JSON for your schemas (as listed in Table 1), adding much machine-understandablity (semantics).

**Is the work original in terms of material and argument?**
Yes

**Does it sufficiently engage with relevant methodologies and secondary literature on the topic?**
Yes

**Is the work clearly and cogently presented?**
Yes

**Is the argument persuasive and supported by evidence?**
Yes

**If any, are all the source data and materials underlying the results available?**
Yes

**Does the research article contribute to the cultural, historical, social understanding of the field?**
Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Open science, data management

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 21 Jan 2026

**Laura Benassi**

Thank you for the positive and encouraging assessment of the article, as well as for recognising its relevance to communities involved in the design and implementation of catalogues of services. We also appreciate the comments regarding the clarity of the technical presentation and the availability of supplementary material through GitHub. We acknowledge the suggestion regarding the inclusion of a front-page README in the GitHub repository and will address this in a forthcoming update.

**Request 1**: An explanation of the human side of the development. Often the biggest hurdle to creating anything new are the humans, not the IT. More detail on their experience on getting cooperation and good input from the service managers - what did and did not work - would be much appreciated.
**Answer**: Thank you for this suggestion. We fully agree that the human dimension represents a critical factor in the development of complex digital infrastructures and that this aspect deserves explicit discussion. We have expanded the manuscript to include the coordination effort, stakeholder engagement, and iterative collaboration with service managers and users. p.6: “Over the last years, a dedicated coordination group within the heritage science community has defined a shared conceptual framework for service description, metadata representation, and data structuring. This framework was iteratively discussed and refined in close cooperation with service managers (then referred to as “providers”) responsible for the delivery of individual services, ensuring both domain relevance and operational feasibility. The first online catalogue, conceived as a sort of e-commerce website, was released during the IPERION HS project in 2020. In coordination with the ARCHLAB, FIXLAB, and MOLAB platform leaders, services were clustered into high-level functional categories (e.g. spectroscopic analysis, spot analysis, etc.), leading to the formalisation of a coherent data model [5]. In the absence of a consolidated domain ontology or standardized controlled vocabularies for heritage science, service managers were invited to populate the model fields and contribute domain-specific terminology reflecting established practices within their scientific communities. The coordination group

subsequently carried out an extensive, tricky process of data curation, harmonisation, and standardisation, validating semantic consistency and structural coherence across the catalogue." p.7 "The redesign of the data model was made possible through regular meetings of a group dedicated to the catalogue's development, during which different perspectives were discussed and iterative revisions were necessary. The users' point of view was also considered and was included via targeted questionnaires distributed to experienced users and, more broadly, to the heritage science community through dedicated mailing lists."

**Request 2:** *AI: it is a little unclear how much of the AI-based "recommendations" part of the CoS is already in place and how much is still being tested. If this is still in development, will another article on that be written later? As this is the big novel part of this CoS, there will be a lot of interest in knowing how it was done. What did AI bring to the table - especially as AI is so resource intensive, it should be justified why the AI approach is superior to any tested/investigated non-AI methods. What algorithms were used in the AI? Will this be open source, once completed (and if not, why)?*
**Answer:** Thank you for your consideration and suggestion. The adoption of AI within the E-RIHS Catalogue generated extensive discussion within the scientific community. On the one hand, it raised concerns regarding potential biases, such as the risk that the system might systematically recommend the same services. On the other hand, it also led to unrealistic expectations. Ultimately, the decision was to integrate a set of foundational AI functionalities to improve search performance and support the incremental development of the knowledge base required by the community. To clarify the role of AI, we integrated the text and included further discussion and information: p.13-14 "At the time this work was developed (2020-2025), a major innovation in development was the integration of a recommendation engine within the CoS, inspired by recommender systems used in e-commerce and media platforms. This AI driven component was designed to support users in identifying the most appropriate services based on their research needs, having in mind that the community is broad and that not all users are experts in the scientific fields or equipment characteristics and methodological applications. The system is based on a Retrieval-Augmented Generation (RAG) architecture that integrates language models with a vector indexing infrastructure [9]. By generating high-dimensional embeddings and leveraging a vector database (Elasticsearch), the system performs similarity search operations to semantically map user queries to indexed content. The various strategies adopted – ranging from classical semantic similarity to multi-vector and multi-querying approaches – enable increased contextual granularity, improved robustness of information retrieval, and mitigation of model hallucination phenomena. The engine was designed to analyse a broad array of data, including equipment characteristics, methodological applications, past project outcomes, and user feedback, to generate personalized recommendations. Natural language queries are supported to increase accessibility and inclusiveness, especially for non-experienced users looking for the best solution for their research question. However, the AI-driven recommendation engine is not intended to replace the expertise of heritage scientists or the fundamental relationship between users and service managers. Rather, it serves as an initial orientation tool to guide users through the complex landscape of services and to build a more structured data foundation for this multifaceted sector. Data for training the algorithm are being collected through pilot applications distributed among the community and from E-RIHS service managers, with all

processing conducted in full compliance with EU data protection regulations. Additionally, a dedicated working group identified representative research needs, compiling standardized controlled vocabularies and classification schemes to be used in service descriptions. The contribution of researchers has been critical in enhancing the robustness and reliability of the system. Questions automatically generated by the Large Language Model (LLM) underwent manual validation, transforming a synthetic dataset into a golden dataset of reference, essential for rigorous endpoint evaluation. This intervention significantly impacted not only the improvement of retrieval quality but also the establishment of a structured feedback framework, which is fundamental for calibrating embedding techniques and optimizing the entire RAG pipeline according to E-RIHS's operational requirements. ... In a context marked by the rapid evolution of AI-driven technologies, targeted financial investments will be necessary to ensure future system updates and scalability."

**Request 3**: More detail on how testing was designed, conducted, managed would also be appreciated, as user testing is crucial.
**Answer**: Thank you for this suggestion. We have added and expanded several paragraphs describing the UX methodology and evaluation process (pp. 14–15), describing how providers were involved from the earliest stages in the co-design of the system, contributing to data modelling, controlled vocabulary selection, and access procedure definition. Additionally, we expanded the description of the iterative UX testing strategy. p.14: "From the earliest stages, service managers were engaged in the co-design of the system, contributing to data modelling, the selection of controlled vocabularies, and the definition of access procedures. To support the operational rollout, training sessions for service managers of the different platforms were conducted from October to December 2024, involving a total of 32 representatives from E-RIHS National Nodes to start inserting services (Figure 5). They also served as validation environments, highlighting formal and functional requirements. Among the issues and changes identified in this phase can be listed the inclusion of a comment section from service managers to users following the feasibility evaluation to enhance the co-creation and collaboration between the user and the scientists. Also, the specialist involved identified the need to enable proposal revision and resubmission which required a revision in the functioning workflow. The sessions, which were recorded and distributed to reach a wider audience, also allowed to identify concepts that were not completely clear to the service managers and represented an opportunity to adjust, when necessary, and explain the data model at the foundation of the CoS." p.15: "To ensure methodological coherence in user-centred design, the IT company formally integrated a professional UX designer into the development team, supporting evidence-based design decisions and consistency across interfaces. UX testing was conducted in multiple iterative sessions involving different user profiles: (i) expert users already familiar with the IPERION HS catalogue, engaged to optimise task efficiency and reduce interaction latency; (ii) heritage science practitioners without prior exposure to the catalogue, involved to assess general usability and cognitive load; and (iii) non-specialist users with no previous experience of the system, recruited to evaluate navigability, onboarding effectiveness, and critical friction points within the access workflow."

**Request 4:** JSON-LD would be superior to JSON for your schemas (as listed in Table 1), adding much machine-understandability (semantics).

**Answer:** Thank you for the suggestion. We agree that JSON-LD would significantly enhance machine-understandability by enabling explicit semantics and linked data interoperability. In the current implementation, standard JSON was adopted to ensure simplicity and broad adoption during the initial operational phase. However, the data model has been intentionally designed to support semantic extensions, and the adoption of JSON-LD, potentially through tools such as the *Dynamic Modeller* for improved formatting and JSON-LD handling, is being considered as part of future developments.

***Competing Interests:*** No competing interests were disclosed.