Knowledge-driven E-Business in cultural heritage: a framework for design and evaluation*

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Abstract

Cultural heritage institutions implement e-business information systems to integrate enjoyment, economic sustainability, and public purpose. This study presents a comprehensive framework that systematically connects cultural data (shared models and vocabularies, digitally described content) with operational processes (bookings, online sales, membership, and public relations) through integration utilising documented interfaces and event exchange. This approach produces a distinctive information model that connects objects, individuals, locations, and events, while also quantifying the impact of architectural decisions on measurable outcomes: data quality and alignment, service response times, booking completion rates, membership renewal rates, and decreased absenteeism. The methodological component establishes reproducible protocols for collecting and analysing evidence, considering seasonality and contextual factors, while incorporating data protection and accessibility standards throughout the design process. We examine the anticipated outcomes and ramifications for sustainability, experiential quality, and system governance.

1 Introduction

Cultural heritage institutions, including museums, archives, libraries, and archaeological sites, are currently operating in a context where digital technology increasingly influences economic sustainability models and cultural enjoyment(Colace et al., 2025). Beyond the basic digitization of collections, there is an increasing demand for E-Business Information Systems (EBIS) that can amalgamate cultural content, transactional processes, and analytical tools into a unified ecosystem: encompassing time-slot ticketing, e-commerce, copyright management, subscriptions/memberships, image licensing, and online educational programs(Cantone et al., 2023; Grimaldi et al., 2022; Vega-Gorgojo, 2024). Notwithstanding the advancement of standards for asset description (e.g., CIDOC

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CRM, IIIF, SKOS/RDF), technical and scientific literature remains deficient in providing a comprehensive framework for orchestrating the complete life cycle of data and services in a composable, measurable, and reproducible manner, while integrating cultural interfaces and e-business subsystems amidst compliance constraints (privacy, accessibility) and resource limitations (capacity, budget, skills) (Colace et al., 2018; Nishioka & Nagasaki, 2021).

Two fundamental reasons exist for this. Cultural institutions must diversify their revenue streams and optimize operational processes while maintaining their public mission; concurrently, they must guarantee the quality of cultural data and semantic consistency, essential for interoperability, discovery, knowledge reuse, and research (Casillo, Colace, Gaeta, et al., 2025). The conflict between these two goals is evident in the amalgamation of disparate silos (repository/DAM, IIIF servers, LOD graphs, ticketing, e-commerce, CRM, LMS), frequently characterized by incompatible technologies and data models. This leads to elevated integration expenses, inadequate traceability of information flows, challenges in assessing impact (both cultural and economic), and, often, technological lock-in (Pellegrino et al., 2022).

This article presents a cohesive architectural and methodological framework for applying EBIS to cultural heritage. The initial step involves implementing an API-first and event-driven architecture, segmented into specialized layers (cultural, transactional, integration, channels, governance) and interconnected via formal contracts and semantic mappings. Consequently, we develop a formal graph model that integrates cultural entities and transactional events with explicit typology and temporality, facilitating cross-analysis (provenance ↔ visitor journey) while maintaining compliance with museum standards (Sanderson, 2024). We propose an evaluation workflow that delineates datasets (public, synthetic, and anonymized real cases), metrics, and experimental protocols to assess: integration effort; query performance; operational outcomes (conversion, membership renewal, no-shows); and adherence to accessibility and privacy standards(De Simone et al., 2022; Yap et al., 2024).

Economic sustainability, interoperability, privacy and regulatory compliance, and scientific reproducibility are the four project constraints against which our approach is evaluated. Interoperability necessitates precise alignment with ontologies and vocabularies (e.g., mapping IIIF to CIDOC CRM, SKOS for thesauri), whereas privacy mandates minimization, granular consent, and privacy-preserving analytical methodologies. Sustainability necessitates explicit cost models and the minimization of integration debt; reproducibility demands the availability of shared datasets, pipelines, and metrics to facilitate equitable comparisons among architectural alternatives (e.g., monolithic versus composable) (Gaeta et al., 2025a; Huang et al., 2023). Notwithstanding the existing research on digital libraries, knowledge graphs, and descriptive standards, the following domains remain underexplored: the systematic integration of the cultural semantic layer with e-business subsystems; the cohesive formalization of entities and events for cross-domain analytics; the quantitative evaluation of architectural impacts on KPIs under realistic constraints (capacity, seasonal demand, queue management); and the intentional incorporation of ethical-legal requirements (GDPR, accessibility) into technical workflows (Clarizia et al., 2020; Gaeta et al., 2024; Zhang, 2022).

This work seeks to establish a cohesive framework for E-Business Information Systems in cultural heritage, wherein semantic content modelling underpins the integration of transactional subsystems and facilitates subsequent analysis and reporting. This context presents a composable architectural framework with API-first and event-driven integration, incorporating roles, permissions, and comprehensive traceability. It also establishes a typed and temporal graph model that aligns with CIDOC CRM and IIIF, enhancing them with events throughout the user journey (booking, visit, purchase, renewal) (Davis & Heravi, 2021). The work presents an experimental protocol featuring operational and interoperability metrics, underpinned by a controlled synthetic dataset and guidelines for utilizing anonymized real cases. Ultimately, it examines the anticipated outcomes and their ramifications for sustainability, governance, and the ethical design of systems, emphasizing how the tenuous connection between the semantic domain and the operational domain can enhance

information quality and service performance. This methodology facilitates the systematic and reproducible examination of the correlation between architectural decisions and quantifiable results (e.g., enhancement in conversion rates prompted by time slots and contextual upselling). Practically, it offers cultural institutions a framework to minimize the total cost of ownership, enhance user experience (particularly regarding accessibility), and facilitate content circulation within national and international ecosystems (e.g., aggregators, thematic portals) while maintaining control and compliance.

The document is organized as follows: the "Related Work" section delineates standards, architectural patterns, and contemporary practices within the field; the "Proposed Workflow" section narratively outlines the phases, participants, and artifacts, supplemented by a diagram illustrating data and event flows; the "Expected Results and Discussion" section articulates testable hypotheses and examines their technical and ethical ramifications; lastly, the "Conclusions and Future Developments" section encapsulates the contributions and suggests a research roadmap, emphasizing online optimization, inter-institutional federation, and bias auditing.

2 Related Work

The digital transformation of cultural heritage arises from three converging elements: semantic modelling and interoperability of cultural data; advanced digital applications (imaging/annotations, federated discovery); and integration with e-business subsystems (ticketing, e-commerce, membership/CRM). The body of work on digital libraries and knowledge organisation has established standards and practices for description; however, the operational integration of the semantic layer with transactional processes continues to be the primary technical and organisational challenge. CIDOC CRM advocates for event-centric modelling of works, agents, places, and processes at the reference ontology level, facilitating alignment among diverse archives and maintaining provenance throughout the data transformation and mediation process. This method is deemed essential for achieving semantic interoperability in museum metadata.

SKOS formalises concepts, hierarchical and associative relationships for thesauri and taxonomies with minimal ontological commitment, a design rationale facilitating its adoption and interoperability between various systems, which is essential in cultural heritage aggregation pipelines. The RDF/OWL expression and the presence of SPARQL endpoints constitute the technological framework for LOD/knowledge graphs within the cultural domain (Baker et al., 2013; Casillo, Colace, Lorusso, et al., 2025).

IIIF has emerged as the definitive standard for disseminating high-resolution images, multi-resource sequences/manifests, and interoperable annotations in imaging and advanced applications. The literature in this domain outlines its objectives, APIs, and advantages for interoperability and application reuse, with extensive implementation in prominent libraries and museums. IIIF facilitates zooming, comparison, storytelling, and extensions to audiovisual and three-dimensional content; however, it does not inherently address licensing and the integration of transactional metadata, which are persistent architectural challenges (Haller et al., 2018; Snydman et al., 2015).

Regarding knowledge graphs and open aggregation, Europeana has provided metadata as Linked Open Data in EDM, showcasing tangible benefits (dereferenceable URIs, SPARQL, connections to external resources such as GeoNames/GEMET/DBpedia) while simultaneously confronting the challenges of quality and heterogeneity characteristic of large-scale aggregation (granularity, coverage, licenses) (Cecere et al., 2025; Isaac & Haslhofer, 2013).

Recent studies in CH + KG demonstrate that relational search methodologies on semantic graphs can provide elucidated connections and discovery pathways that surpass mere keyword retrieval, featuring explanation patterns that identify intriguing connections and facilitate explanations in

natural language — a valuable viewpoint for cultural discovery and engagement (Hyvönen & Rantala, 2021).

Cultural institutions employ e-business information systems, including ticketing suites for time-slot and capacity management, e-commerce platforms for bookshops, merchandising, and print-on-demand services, CRM and marketing automation for segmentation and multi-channel journeys, and Learning Management Systems for educational purposes. The trend in information systems/software architecture is transitioning from monolithic structures to microservices and event-driven architecture (EDA) to attain decoupling, targeted scalability, and diminished time-to-market. Mapping studies on microservices encapsulate patterns, taxonomies, and trade-offs (such as service granularity, observability, and versioning) and apply to CH domains characterized by frequent integrations and multiple suppliers (Pahl & Jamshidi, 2016). Recent empirical evidence regarding EDA in enterprise information systems demonstrates quantifiable effects on performance and scalability during real-time and fluctuating traffic conditions, such as those encountered in advance ticket sales or major exhibitions, thereby supporting bus/event streaming implementation to mitigate strong interdependencies among components (Cabane & Farias, 2024).

The implementation of EBIS in CH necessitates privacy-by-design and accountability in compliance with the GDPR (including granular consent, data minimization, DPIA, and retention), as well as digital accessibility of platforms (websites/apps) in accordance with WCAG 2.2 (W3C Recommendation of 5 October 2023, featuring new success criteria). In the cultural sector, accessibility constitutes a public obligation: recent research indicates inconsistent implementation and persistent obstacles at museum locations, advocating for ongoing evaluations and collaborative design with individuals with disabilities (Kruczek et al., 2023). Technical literature suggests employing privacy and data protection by design tools utilising knowledge graphs to depict consent and autonomously verify compliance (regulatory obligations → technical/organisational measures → code), yielding reproducible results in analogous domains and transferable to EBIS processes (bookings, accounts, telemetry) (Chhetri et al., 2022).

Traditionally, digital libraries have assessed metadata quality and search efficacy; from an EBIS standpoint, operational KPIs (conversion rates, membership renewals, absenteeism) and impact metrics (accessibility, reach, and reuse) are relevant. It is advisable to employ online controlled experiments (A/B) for features/UI and quasi-experiments, such as Difference-in-Differences (DiD) with staggered treatments, adhering to established guidelines and econometric updates to prevent negative weights and prohibited comparisons. These methods are pertinent for isolating the impact of architectural or policy decisions (e.g., implementation of time slots, reminders) on observed outcomes (Callaway & Sant'Anna, 2021; Kohavi et al., 2020; Roth et al., 2023).

The technological foundation is established (CIDOC/SKOS/RDF, IIIF, EDM; microservices/EDA; WCAG 2.2; GDPR-compliant tools), yet the literature identifies four operational deficiencies: an absence of unified models that systematically connect cultural entities and e-business events within a queryable and provenance-aware graph; a lack of vendor-agnostic guidelines for transitioning from monolithic to composable systems in the public sector; insufficient shared benchmarks and replicable datasets addressing interoperability, performance, and outcomes under realistic constraints (capacity, seasonality, queues); and the need for technical-organizational playbooks that incorporate accessibility and privacy by design into the DevOps cycle and KPI assessment. The proposed workflow in the subsequent section addresses these deficiencies through reproducible phases (semantic ingestion, mapping, API/event integration, analytics, reporting), standardised metrics, and integrated compliance controls.

3 Proposed Workflow

The suggested workflow is predicated on the notion that the digital value chain in cultural heritage arises from the tenuous interconnection between two historically distinct domains: the semantic-cultural domain (models, vocabularies, manifests) and the transactional domain (bookings, payments, membership). The glue is an API-first, event-driven integration layer that disseminates stable identifiers, versioned messages, and reproducible transformations. This results in an observable and measurable ecosystem that adheres to ethical and legal standards. Figure 1 illustrates these blocks and their interactions.

The initial focus is on the semantic structuring of the informational legacy. Descriptive catalogues and authority files explicitly delineate entities and events (works, agents, places, processes) and are supplemented by interoperable manifests for multimedia resources. This standardization is not an ultimate goal; it renders content citable and composable by other subsystems by offering shared keys, temporal context, and interpretative rules. The cultural graph and manifests serve as a "common lexicon" for the architecture, providing a clear reference point.

The operational domain is integrated into this lexicon. Slot reservation, e-commerce, membership frameworks, and communication channels reveal public, versioned interface agreements and disseminate domain events (e.g., booking.created, order.fulfilled, membership.renewed). Their responsibility is not to reproduce cultural knowledge, but to utilize it as necessary (e.g., to create a contextual offering) and to transmit signals when notable transactions or interactions occur. In this interaction, the minimization of personal data and the traceability of consent are constant principles: only essential information is conveyed, and the purposes are restricted.

The integration layer serves as a pivotal connection between the two domains. Operational events are aligned with cultural entities via semantic-operational transformations and linking protocols: a booking is not an isolated occurrence but is connected to the pertinent object, exhibition, and location; a membership renewal may be correlated with usage patterns and preferences, consistently in pseudonymized form. This layer contains a registry of schemas for messages and events, along with compatible versioning practices, enabling the ecosystem to evolve seamlessly while ensuring the reproducibility of experiments and measurements.

The user experience on public channels (website, app, kiosks) is enhanced by this unification: interoperable visualizers utilize manifests, search merges facet-based navigation with graph projections, and purchase processes amalgamate content and services. Every significant interaction produces events that revert to the integration layer, completing an initial learning cycle. Simultaneously, a measurement pathway converts events into pre-established indicators (conversion, renewal, no-show, mapping coverage, adherence to accessibility standards), maintaining the connection with versions of schemas, vocabularies, and contracts. This link is essential: it enables us to differentiate the impacts of an architectural modification from those resulting from seasonality or content, and to retroactively reconstruct the circumstances under which a specific measurement was generated.

The cycle concludes with ongoing enhancement driven by empirical evidence. New features or policies, such as modifications in time-slotting, contextual suggestions, and messaging alterations, are implemented in a regulated manner (feature flags, canary). The effects are assessed using suitable experimental designs (controlled experiments for localized changes; quasi-experiments for process alterations), and the resultant decisions exert a retroactive influence on both the semantic domain (mapping updates, enrichments, vocabulary restructuring) and the operational domain (contract evaluation, new orchestration protocols). Compliance constraints—data protection, consent management, accessibility—are not assessed retrospectively at each stage, but are embedded as process controls: transformation logs, consent ledgers, and accessibility audits integrated into software delivery.

The workflow is a cyclical process governed by contracts and standards: structured content renders transactions significant; transactions produce evidence that enhances content, orchestration, and interfaces; measurement provides methodological consistency to the cycle; compliance, integrated by design, ensures its legitimacy. Figure 1 encapsulates these relationships: from the cultural and operational strata that converge at the integration level, to the channels and metrics that complete the cycle and drive the system's evolution.

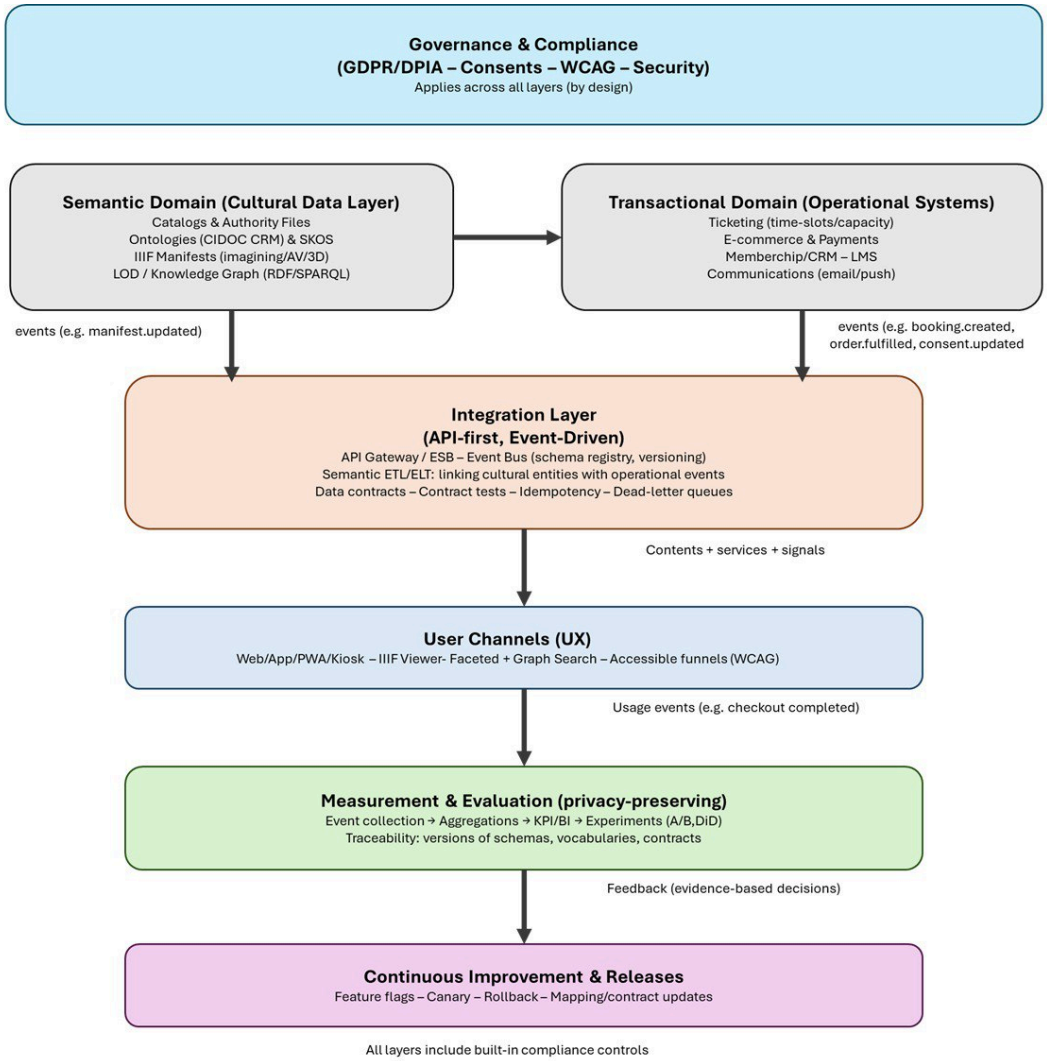

Figure 1: The proposed workflow scheme has an API-first, event-driven integration layer with versioned schemas that lets the semantic-cultural domain (graph and manifest) and the transactional domain (reservations, e-commerce, membership) exchange identifiers and events. Public channels use content and services and send usage signals. A measurement subsystem turns events into reproducible indicators and helps with continuous improvement, with compliance checks built in at every process step.

4 Expected results and discussion

The proposed workflow is expected to have measurable effects on two closely related levels: first, the quality and interoperability of cultural information (semantic consistency, traceability, observability); second, the operational results related to use and economic sustainability (conversion, capacity management, loyalty). The idea is that semantic formatting of content, which is linked to API-first and event-driven integration, is not just a technological change but a change in the information model. Identifiers and relationships become shared contracts between the cultural and transactional domains, and events in the usage channels are reported in the knowledge graph with context and provenance.

In the near future, we expect semantic mapping coverage to go up and integration costs to go down. The first can be measured by the ratio of fields mapped to reference ontologies or vocabularies to the subset of fields that are relevant to use cases. The second can be measured by the number of person-days needed for connectors, mapping, and testing for the same functional scope. Once fully operational, stable contracts and a registry scheme are available to lower integration debt and allow for gradual evolution without any problems. This has indirect benefits for time-to-market and pipeline reliability. In systems with peaks in demand, like pre-sales and temporary exhibitions, event-driven orchestration also aligns to reduce perceived latency along the funnel. Architectural decoupling lets critical parts be isolated and selectively scaled, stabilising the p95 latency of queries that combine cultural content and transactional data.

When semantic modelling and consumption channels come together, they change how people act. Systematically using interoperable manifests and search engines that use faceted navigation and graph projections makes it easier to make informed decisions about buying and participating, reducing friction during the selection and payment phases. The conversion rate can be defined in numbers as

$$\mathrm{Conv} = \frac{order}{unique\ visitors},$$

while no-show for slot reservations is

$$\text{No-show} = \frac{missed\ reservations}{total\ reservations}$$

An anticipated rise in conversion is attributed to contextual suggestions and enhanced clarity of information. At the same time, a decrease in no-shows results from reminders and more transparent presentations of capacity and schedules. A favourable effect on loyalty is also conceivable: the (pseudonymized) integration of events throughout the journey facilitates pertinent communications and membership proposals that correspond with actual usage trends, potentially enhancing the renewal rate in the medium term. Accessibility functions as a systemic quality variable: intentionally incorporating WCAG criteria into release cycles typically diminishes abandonment at crucial stages (such as forms and payment), broadening the effective user base without imposing technical obstacles.

Empirical validation necessitates an experimental design aligned with the characteristics of the intervention. For localised modifications to the interface or messaging, a controlled online experiment is suitable; for process alterations (e.g., the introduction or restructuring of slots), a quasi-experiment utilising temporal or cohort control groups is advisable, such as in the form of difference-in-differences (DiD). In a basic two-period framework, the mean impact of the treatment can be articulated as

$$\hat{\tau} = \left(\bar{Y}_{\text{treated, post}} - \bar{Y}_{\text{treated, pre}}\right) - \left(\bar{Y}_{\text{control, post}} - \bar{Y}_{\text{control, pre}}\right),$$

Y represents the principal metric (e.g., conversion) and the bars denote averages across observational units. Results reporting must encompass point estimates and 95% confidence intervals, alongside effect sizes articulated in percentage points or relative reduction, with adjustments for multiple comparisons when assessing various variants. The traceability of schema, vocabulary, and contract versions guarantees the replicability of analyses and the accurate interpretation of deviations and regressions.

The anticipated effects rely on specific operational assumptions: demand is not entirely restricted by capacity during most observation periods; the initial quality of semantic mapping is adequate to prevent interpretative leakage; and the levels of consensus permit minimal orchestration (reminders, confirmations) without surpassing data minimisation limits. Estimating effects of exogenous shocks (such as blockbuster exhibitions, tariff alterations, or weather conditions) necessitates appropriate controls, including homogeneous cohorts, temporal blocking, or available instrumental variables. Threats to validity persist and require meticulous consideration, notably selection bias (experiments conducted on more digitised segments) and semantic drift resulting from vocabulary evolution. Both issues can be alleviated through ex-ante stratification, subgroup analysis, intent-to-treat methodologies, and automatic mapping validation.

Integrating enhanced interoperability, adaptive orchestration, and stringent measurement aligns cultural objectives with economic sustainability without compromising the former for the latter. Moderate conversion enhancements, reduced no-shows, and improved WCAG compliance on essential pages can exert considerable macroeconomic impacts on project life cycles. At the same time, diminished integration efforts liberate resources for more valuable pursuits (curation, education, research). The generalizability of archives and libraries is substantial due to the similarity in their semantic and search components; conversely, the impact on funnels is contingent upon the transactional intensity and nature of the services provided.

5 Conclusions and future outcomes

This study presents a cohesive framework for E-Business Information Systems in the context of cultural heritage, demonstrating that the loose coupling between the semantic-cultural domain and the transactional domain, facilitated by an API-first and event-driven integration layer, can yield quantifiable advantages in interoperability, data quality, and operational outcomes. The initial premise is that the persistent implementation of open standards (event-oriented ontologies, controlled vocabularies, interoperable manifests) is not solely a technological adjustment, but represents a deliberate selection of knowledge architecture: identifiers, relationships, and events transform into stable agreements upon which to coordinate services, channels, and measurement. The reference scheme (Fig. 1) serves not as a detailed diagram but as a representation of the conceptual constraints that unify the components—content, transactions, analysis, and compliance—within a continuous improvement cycle.

From a scientific perspective, the primary contribution lies in elucidating three interrelated connections that are frequently addressed in isolation: the semantic continuity between cultural descriptions and usage events; the quantifiability of architectural impacts on observable metrics (conversion rates, no-show instances, membership renewals, p95 latency, mapping coverage); the intentional incorporation of ethical and legal constraints (privacy, accessibility) as process controls rather than retrospective evaluations. The discourse on anticipated outcomes delineated feasible orders of magnitude and replicable evaluation frameworks, elucidating assumptions and potential threats to validity. The image indicates that even modest enhancements in operational metrics and a

decrease in integration efforts can substantially influence economic sustainability and user quality without undermining the cultural mission.

Nonetheless, constraints and margins of uncertainty persist. The efficacy of the workflow is contingent upon the calibre of the initial semantic mapping, adherence to schema versioning, and the implementation of comprehensive observability practices. Moreover, external factors (seasonality, major exhibitions, pricing strategies, climatic conditions) can disrupt the effects assessment. To address these factors, it is imperative to compile a corpus of benchmarks that includes datasets (public, synthetic, and anonymised real cases), contract specifications, and experimental protocols, thereby enabling equitable comparisons among architectural alternatives across various contexts.

Future advancements are progressing along four interrelated trajectories. A more comprehensive formalisation of the graph model, incorporating uncertainties, data quality, and detailed provenance, to enhance causal analysis and result interpretability and secondly, incorporating online optimisation techniques (e.g., dynamic capacity management with fairness and transparency constraints) alongside ethical safeguards and metrics reconciling economic and social goals. Third, the experimentation with inter-institutional federations utilising verifiable credentials and distributed access policies aims to facilitate content and signal sharing while maintaining data control; this approach necessitates the standardisation of domain events and interoperability testing among providers(Gaeta et al., 2025b). Fourth, creating tools for reproducibility (data catalogues and schemas, a schema registry with evolutionary compatibility, notebooks, and packages for KPI calculation) that facilitate peer review and production adoption.

Special consideration must be given to equity and prejudice in recommendation and funnel orchestration systems. In the cultural domain, the visibility and dissemination of content are not impartial: selection and recommendation mechanisms can exacerbate disparities between renowned works and obscure material, between dominant and minority languages, and between central and marginal locations. The path ahead necessitates clear criteria for procedural fairness, regular audits of models, and the engagement of relevant communities in establishing quality metrics—broadening the by-design principle from privacy to fairness.

The roadmap encompasses pilot projects across diverse institutions (museums with fluctuating demand, libraries with robust digital services, archives with enduring mandates) to evaluate the generalizability of the workflow and refine the orchestration mechanisms. The development of an operational playbook, encompassing sample contracts, event taxonomies, WCAG checklists, and DPIA models, is proposed to facilitate organisations with diverse resources in transitioning incrementally from monolithic to composable architectures.

In conclusion, the thesis posits that semantic interoperability, reactive integration, and rigorous evaluation are not merely compatible with the objectives of cultural institutions but rather a natural extension of them within the modern digital ecosystem. The proposal presented herein establishes a methodological and technical framework for designing cultural information systems that are transparent, quantifiable, and accountable. The release of supplementary materials—summary datasets, sample configurations, KPI definitions, and audit guides—is essential for establishing a community of practice that can evolve swiftly, adhering to transparency and user protection principles.

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