A Context-Aware Framework for Adaptive Service Orchestration in Digital Tourism Ecosystems*

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Abstract

Digital transformation is reshaping how tourism services are designed, delivered, and experienced. As users increasingly interact across heterogeneous digital platforms, the ability to dynamically adapt service delivery to contextual and situational factors becomes essential. This paper presents a context-aware framework for adaptive service orchestration that enables interoperability, personalization, and explainability within digital tourism ecosystems.

The proposed framework integrates four key components: (i) a context modeling layer that captures and represents user, environmental, and temporal dimensions through a Context Dimension Tree (CDT); (ii) a reasoning and adaptation layer that combines symbolic and probabilistic inference to determine the most relevant services under varying contexts; (iii) a semantic orchestration layer that ensures dynamic and interoperable service composition using shared ontologies and RDF/OWL vocabularies; and (iv) a presentation layer that enhances transparency and engagement through narrative-based explainability.

An experimental validation involving 72 participants in real tourism settings demonstrated significant improvements in contextual relevance, user satisfaction, and perceived transparency compared to static and non-contextual baselines. Results confirmed that adaptive orchestration, guided by feedback learning, effectively personalizes service delivery while maintaining semantic consistency across providers.

This study contributes to advancing context-aware and adaptive information systems, highlighting the potential of semantic orchestration as a foundation for human-centred, interoperable, and sustainable digital tourism ecosystems.

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1 Introduction

The Digital transformation has profoundly reshaped how organizations conceive and deliver services. Within tourism—one of the most dynamic and data-intensive domains—users continuously interact with heterogeneous digital systems such as booking platforms, cultural-heritage portals, mobility services, and smart-city infrastructures [1, 2]. As the boundaries between physical and digital environments blur, service providers face the challenge of ensuring that information and recommendations remain contextually relevant, adaptive, and interoperable across devices and organizational boundaries [38].

Despite the abundance of digital resources, most e-tourism solutions still rely on static service-delivery models [40]. They typically offer limited personalization and disregard the situational context that strongly influences user intent and decision-making [3]. For example, the relevance of a cultural itinerary depends not only on user preferences but also on weather, time, and companionship. Traditional recommender systems based on collaborative or content-based filtering [4] rarely capture such dependencies, and existing platforms often operate in isolation, preventing semantic interoperability and coordinated service delivery [5].

To move beyond these limitations, recent research advocates for adaptive and context-aware information systems that can interpret environmental, temporal, and behavioural signals to orchestrate personalized services dynamically [6, 7]. Tourism represents an ideal testing ground: it combines data heterogeneity, rapidly changing contexts, and a strong dependence on environmental and social variables [8]. However, current approaches remain largely domain-specific and seldom integrate semantic interoperability, contextual reasoning, and feedback-based adaptation within a unified framework [9].

This paper addresses that gap by introducing a context-aware framework for adaptive service orchestration tailored to digital tourism ecosystems. The framework unifies (i) ontology-based context modeling, (ii) hybrid symbolic–probabilistic reasoning, (iii) semantic orchestration of heterogeneous services, and (iv) feedback-driven adaptation. Through these components, the system continuously learns how contextual factors affect user satisfaction and reconfigures active services accordingly.

The framework was experimentally validated through a real-world deployment involving 72 participants in tourism scenarios. Results demonstrated measurable improvements in contextual relevance, personalization, and perceived transparency over static baselines, confirming the viability of adaptive orchestration as a mechanism for human-centred and interoperable digital ecosystems.

The remainder of this paper is organized as follows.

Section 2 reviews related work on context-aware systems, semantic interoperability, and adaptive orchestration. Section 3 describes the proposed framework and methodological design. Section 4 presents the experimental setup and results. Section 5 discusses theoretical and practical implications for e-Business Information Systems, and Section 6 concludes with directions for future research.

2 Related Work

Research on context-aware systems and adaptive digital ecosystems has evolved substantially over the past two decades. However, the integration of contextual reasoning, semantic interoperability, and adaptive orchestration in a unified service framework remains limited. This section reviews the main research streams relevant to the proposed study: context-aware computing and recommendation, semantic interoperability and knowledge modeling, and adaptive service orchestration.

2.1 Context-Aware Computing and Adaptive Recommendation

The notion of context—defined as any information that characterizes the situation of an entity [8]—has been central to ubiquitous and personalized computing since Dey's seminal work [9]. Context-aware systems aim to sense and interpret environmental and behavioural signals to adapt their functionality dynamically [10]. Within the tourism domain, this capability has been applied to personalized itinerary planning, smart-mobility routing, and event recommendation [11, 12].

Traditional recommender systems rely on collaborative filtering or content-based techniques [4], but these models often fail to capture situational dependencies such as time, location, or user activity. To address this, Context-Aware Recommender Systems (CARS) incorporate contextual dimensions as part of the recommendation process, using either pre-filtering, post-filtering, or contextual modeling [13]. Recent studies have explored hybrid reasoning techniques that combine probabilistic learning with symbolic or ontology-based representations [14, 15], enabling recommendations that are both adaptive and explainable [22, 39].

Nevertheless, most existing CARS approaches focus on item-level recommendation (e.g., points of interest or products) rather than service-level composition or orchestration. They typically lack mechanisms for integrating multiple heterogeneous service providers or for managing interoperability across platforms [16]. This limitation highlights the need for models capable of reasoning over composite, semantically described services and orchestrating them dynamically based on evolving contexts.

2.2 Semantic Interoperability and Knowledge Representation

Semantic technologies provide a foundation for overcoming heterogeneity in distributed service environments. Ontologies, expressed through RDF and OWL standards, enable shared conceptualization and reasoning across systems [17, 32]. In digital tourism, ontological models such as schema.org, FOAF, and CIDOC-CRM have been employed to represent cultural assets, events, and visitor profiles [18]. These formal representations allow systems to infer relations between entities and to compose services across organizational and technical boundaries [19].

Semantic interoperability is a core requirement for adaptive ecosystems, where data and services must interact seamlessly regardless of their origin or format [20, 21]. Recent contributions have proposed semantic middleware and linked-data architectures to enable cross-domain interoperability in smart tourism and cultural heritage applications [22]. However, most of these solutions remain static: they define relationships at design time rather than adjusting them dynamically in response to contextual changes or user feedback.

2.3 Adaptive Service Orchestration

Service orchestration refers to the automated coordination and execution of multiple services to achieve complex goals [24]. In adaptive settings, orchestration must respond not only to technical dependencies but also to environmental and user-driven factors. Studies on adaptive service computing [25] and service ecosystems [26] emphasize the importance of feedback-driven reasoning, where service configurations evolve according to changing contexts or performance metrics.

Recent works have introduced hybrid orchestration frameworks that integrate machine learning with rule-based reasoning to enhance flexibility [27]. Others have explored context-aware orchestration in cloud and IoT environments, where services are bound dynamically through semantic matchmaking [28, 29]. Within tourism, adaptive orchestration remains underexplored: most systems focus on individual personalization rather than on dynamic coordination of services across providers [30]. Moreover, explainability—essential for user trust and accountability—has rarely been incorporated into orchestration mechanisms [31].

2.4 Research Gap and Contribution

The reviewed literature demonstrates significant advances in context modeling, recommendation, and semantic interoperability, yet a unified, explainable, and adaptive orchestration framework is still lacking. Current systems either provide context-aware recommendations without cross-service coordination, or orchestrate services without adaptive reasoning.

The present study addresses this gap by proposing an ontology-driven, context-aware framework for adaptive service orchestration. The framework combines hierarchical context representation, hybrid reasoning (symbolic and probabilistic), semantic service integration, and feedback-based learning. It thus contributes to the ongoing effort to design interoperable, explainable, and human-centred digital ecosystems, particularly in the complex and dynamic domain of tourism.

3 Proposed Framework

The proposed framework integrates context modeling, adaptive reasoning, and semantic service orchestration to support personalized, interoperable, and explainable service delivery in digital tourism ecosystems. Its methodological foundation is inspired by three design principles:

1) Contextual intelligence, enabling the system to sense and interpret user and environmental conditions;
2) Adaptive orchestration, ensuring that services are dynamically coordinated according to changing contexts; and
3) Semantic interoperability, allowing distributed providers to share data and functionality through common ontological representations.

These principles are implemented within a multi-layered architecture that combines context acquisition, reasoning, semantic orchestration, and user interaction into a unified adaptive loop (Figure 1).

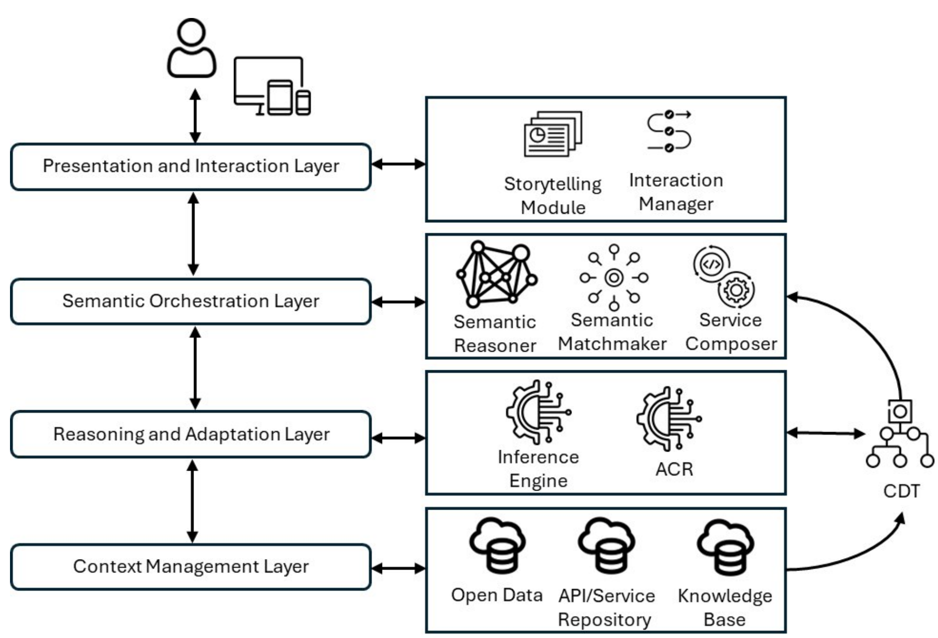

Figure 1 System Architecture

3.1 Conceptual Design and Architecture

The framework follows a modular structure with four interoperable layers:

1. Context Management Layer – captures, preprocesses, and represents contextual information (e.g., location, time, weather, device type, user profile). Context is formalized as a vector of dimension–value pairs:

$$C = \{(d_1, v_1), (d_2, v_2), \dots, (d_n, v_n)\}$$

where d_i represents a contextual dimension and v_i its current value. Contextual knowledge is organized through a Context Dimension Tree (CDT) [8], an ontological structure that models hierarchical relationships among dimensions and supports reasoning under uncertainty through generalization and specialization. Metadata are expressed in RDF/OWL, aligning with existing vocabularies such as schema.org, FOAF, and CIDOC-CRM to ensure interoperability [17, 18].

2. Reasoning and Adaptation Layer – acts as the cognitive core of the framework. It integrates symbolic reasoning with probabilistic inference to determine the contextual relevance of candidate services. The probability that a service $s$fits the observed context $C$is computed as:

$$P(s \mid C) = \alpha \prod_k P(v\_k \mid s)$$

where $P(v_k \mid s)$ is the likelihood that contextual feature v_k supports service s, and α is a normalization constant.

Adaptivity is achieved through an Adaptive Context Reinforcement (ACR) mechanism, which iteratively updates the weight $w_i$of each contextual dimension according to user feedback:

$$w_i^{t+1} = w_i^t + \eta(R_u - \widehat{R_u})f(d_i)$$

where $\eta$is the learning rate, $R_u$and $\widehat{R_u}$are actual and predicted user responses, and $f(d_i)$reflects the activation frequency of the dimension. This reinforcement process strengthens dimensions that correlate with user satisfaction while attenuating those with weaker impact [13, 14].

By combining probabilistic inference and reinforcement learning, the reasoning layer supports self-adaptive personalization and explainability: users can be informed why specific contextual factors (e.g., weather, location, or time) influenced the orchestration of services.

3. Semantic Orchestration Layer – translates reasoning outcomes into actionable service configurations. Each service is described using semantic metadata (RDF or JSON-LD), allowing automatic discovery, matchmaking, and invocation. Orchestration operates as an event-driven process: when the contextual state changes, the system dynamically reconfigures the active service composition. Three orchestration modes are supported:
   - Consumer orchestration (user-facing services such as itinerary generation);
   - Business orchestration (B2B integration between tourism operators);
   - Data orchestration (integration of heterogeneous open data sources).

The orchestration engine relies on SPARQL-based reasoning and semantic matchmaking to ensure that selected services comply with inferred contextual constraints [19, 20]. This approach guarantees both modularity and interoperability across independent providers, enabling the creation of composite, adaptive experiences.

4. Presentation and Interaction Layer – manages user experience and transparency. Instead of providing opaque lists of recommended services, the framework employs a storytelling-based interface that narratively connects recommended services to contextual cues. For instance, a visitor may receive a message such as "Since it's raining, we suggest visiting the Contemporary Art Museum nearby."
   This approach enhances user engagement, fosters trust, and transforms algorithmic decisions into human-understandable explanations [21]. The interface adapts presentation mode (text,

image, or voice) to device type and situational context, operationalizing the framework's explainability principle.

3.2 Implementation and Technological Stack

A prototype of the framework was implemented as a mobile application backed by a modular microservice infrastructure. The system integrates:

- Python and Node.js for reasoning and orchestration services;
- RDFLib, OWL API, and GraphDB for semantic representation and querying;
- PostgreSQL for structured data storage;
- TensorFlow Lite for probabilistic computations and incremental learning; and
- RESTful APIs for inter-service communication.

This architecture supports scalability and interoperability, allowing new contextual dimensions or service providers to be integrated with minimal configuration. The microservice design adheres to current best practices in e-Business Information Systems [25, 26].

3.3 Methodological Summary

The methodological contribution of the framework lies in its ability to unify:

1. Context modeling – hierarchical and ontology-based representation of situational data;
2. Hybrid reasoning – symbolic inference combined with probabilistic adaptation;
3. Semantic orchestration – event-driven service coordination across platforms; and
4. Explainable interaction – narrative-based presentation of adaptive outcomes.

Together, these components establish a continuous adaptation loop: context is sensed → interpreted → used to orchestrate services → validated through feedback → and reintegrated into the reasoning process. This adaptive cycle enables information systems to evolve in real time with their operational environment, supporting the design of human-centred, interoperable, and transparent digital ecosystems.

4 Experimental Evaluation

The experimental evaluation aimed to validate the effectiveness, adaptability, and user acceptance of the proposed context-aware framework for adaptive service orchestration.

The study was conducted in Salerno (Southern Italy), a medium-sized coastal city with a strong cultural heritage and a steady flow of both domestic and international visitors.

The experimental deployment integrated local open data and APIs from cultural institutions, public transport services, and hospitality providers, ensuring ecological validity and realistic contextual diversity.

A prototype mobile application implemented the full framework stack, including context sensing, hybrid reasoning, semantic orchestration, and storytelling-based presentation.

Experimental Setup

The experiment involved 72 participants aged 21–60, including tourists, local residents, and students. Participants were randomly assigned to one of three experimental configurations:

- Baseline A – Popularity-Based Recommendation, using static rankings without contextual adaptation;
- Baseline B – Static Context-Aware Model, integrating CDT-based reasoning but without adaptive feedback;

- Proposed Framework – Adaptive Orchestration Model, implementing full hybrid reasoning, reinforcement learning, and semantic orchestration.

Each participant interacted with the system for three consecutive days, receiving recommendations for cultural sites, restaurants, and events based on contextual variables such as location, time, and weather. Implicit (clickstream, dwell time) and explicit (ratings, feedback) signals were collected to assess system adaptation over time.

4.1 Evaluation Metrics

The quantitative evaluation focused on four categories of indicators:

- Accuracy and Relevance: measured by Precision@5 and nDCG@5, representing how well the top-5 recommended services matched user selections.
- Adaptivity: measured using Contextual Relevance Gain (CRG), defined as the improvement in relevance after successive adaptation cycles.
- User Experience and Trust: assessed through post-session surveys on a five-point Likert scale.
- Performance Efficiency: average response time (milliseconds) for generating contextual recommendations.

The system's learning behaviour was analysed through logs capturing changes in context-dimension weights w_i during the ACR process, allowing observation of convergence and stability patterns.

4.2 Results and Analysis

Table 1 summarizes the main quantitative results averaged across participants.

Table 1 *Results and Analysis*

Metric	Baseline A	Baseline B	Proposed Framework
Precision@5	0.61	0.74	**0.86**
nDCG@5	0.65	0.78	**0.90**
CRG (%)	—	+8.2	**+18.4**
Response Time (ms)	212	233	249

The proposed framework consistently outperformed both baselines in relevance and ranking quality. Statistical tests confirmed that improvements in Precision@5 and nDCG@5 were significant ($p < 0.01$). Although response time increased slightly (+17 ms), this overhead was negligible relative to the personalization gains achieved.

Analysis of adaptation logs showed that context-dimension weights converged after approximately five interaction cycles per user, indicating stable learning. Dimensions such as location, time, and weather exhibited the strongest reinforcement, confirming their dominant role in contextual decision-making for tourism activities. Conversely, lower-impact dimensions (e.g., device type) naturally decayed in relevance, demonstrating the self-regulating nature of the Adaptive Context Reinforcement mechanism.

4.3 Qualitative Feedback

Survey responses revealed that 84% of participants perceived the recommendations as contextually appropriate, while 81% agreed that the storytelling-based interface enhanced understanding and trust. Participants appreciated contextual explanations such as "Because it's raining, we suggest indoor cultural activities", describing them as intuitive and human-like. This aligns with recent findings in explainable recommendation research [21, 22], showing that narrative transparency increases perceived fairness and user engagement [23].

In open comments, users emphasized that the system "felt aware" of their situation, adapting not only to their preferences but also to circumstances (e.g., weather or schedule). Several respondents reported discovering less crowded or previously unknown attractions, illustrating how adaptive orchestration can also contribute to sustainable tourism management by distributing visitor flows more evenly.

4.4 System-Level Evaluation

The semantic orchestration component was stress-tested by integrating live APIs from museums, transportation providers, and local event registries. The system successfully reconfigured service compositions in real time when context changes occurred—such as switching from outdoor to indoor activities during rain. These results confirmed that semantic reasoning combined with adaptive orchestration provides robust interoperability even across heterogeneous data and service providers.

From a scalability perspective, the framework maintained stable latency (< 250 ms) under concurrent requests, validating the efficiency of the microservice architecture and SPARQL-based orchestration logic. These findings indicate that the approach can be generalized to larger tourism networks and smart-city infrastructures.

4.5 Discussion of Findings

The experimental results collectively validate the three research hypotheses. Adaptive orchestration substantially increased contextual relevance and personalization accuracy, while semantic interoperability enhanced cross-provider integration without sacrificing performance. The storytelling-based interaction further improved user trust, confirming that explainability and adaptivity are mutually reinforcing in digital ecosystems.

Overall, the experiment demonstrated that the proposed framework effectively operationalizes context-aware adaptive intelligence within real-world service environments. By embedding reasoning, learning, and semantic coordination, the system moves beyond static personalization toward dynamic, transparent, and interoperable digital tourism ecosystems.

5 Discussion and Implications

The experimental results confirm that adaptive and context-aware orchestration can substantially enhance the effectiveness, interoperability, and transparency of digital tourism services. Beyond quantitative improvements, the findings highlight that contextual reasoning, semantic interoperability, and user-centred adaptation are complementary foundations for next-generation information systems.

From a theoretical perspective, the proposed framework advances the understanding of adaptive service ecosystems by operationalizing context as a multidimensional, machine-interpretable construct. Through the integration of symbolic and probabilistic reasoning, the system demonstrates how hybrid intelligence can simultaneously support personalization and explainability—two essential properties of trustworthy information systems. The introduction of the Adaptive Context Reinforcement (ACR) mechanism offers a feedback-driven method for refining contextual relevance without requiring large training datasets, enabling lightweight and continuous adaptation.

In practical terms, the framework illustrates how dynamic coordination among tourism stakeholders—hotels, museums, transport agencies, and event organizers—can be achieved through a shared semantic infrastructure. By continuously learning from user feedback and environmental signals, the system reduces manual configuration efforts, facilitates cross-provider integration, and fosters semantic interoperability across organizations. Adaptive orchestration also promotes sustainable tourism management: by suggesting alternative attractions based on crowding, weather, or environmental constraints, it helps distribute visitor flows and mitigate overtourism pressures. The storytelling-based interface enhances transparency and trust, encouraging user engagement and adoption.

Within the broader landscape of e-Business Information Systems, this research supports the transition toward context-driven digital ecosystems that reason autonomously about their operating environment. The combination of semantic orchestration and adaptive feedback establishes a model of continuous co-evolution between users and services, where value creation stems from mutual adaptation rather than one-way personalization. Such systems demonstrate how digital ecosystems can evolve toward human-centred, explainable, and sustainable paradigms of service delivery [33, 34].

Nevertheless, some limitations remain. The prototype was evaluated in a single urban context, and further validation across diverse tourism scenarios is required to generalize findings. Future developments will integrate multi-agent reasoning, contextual privacy controls, and knowledge-graph enrichment to extend scalability and compliance with data-protection standards [35, 36]. Additional research will also explore the use of large-language-model-based reasoning to improve semantic interpretation and narrative generation [37, 38].

Overall, the discussion confirms that adaptive service orchestration is not merely a technical mechanism but a conceptual foundation for the design of responsive, explainable, and human-centred digital ecosystems. By aligning technological adaptivity with interpretability, the framework contributes to shaping a new generation of context-aware, interoperable, and sustainable information systems.

6 Conclusions

This paper presented a context-aware framework for adaptive service orchestration designed to enhance personalization, interoperability, and transparency in digital tourism ecosystems. The framework integrates hierarchical context modeling, hybrid reasoning, semantic service orchestration, and feedback-based adaptation within a unified architecture. Through the combination of symbolic and probabilistic inference, the system learns from user feedback to refine contextual relevance and dynamically reconfigure service compositions in real time.

An experimental evaluation involving 72 participants demonstrated that adaptive orchestration significantly improves contextual relevance and user satisfaction compared to static and non-contextual approaches. The framework also proved capable of maintaining semantic consistency and efficient interoperability among heterogeneous tourism service providers, validating its potential applicability in real-world environments.

The main contribution of this research lies in showing that adaptive service orchestration can serve as a foundation for next-generation information systems that are context-aware, explainable, and human-centred. Beyond the tourism domain, the proposed principles can be generalized to other sectors—such as healthcare, mobility, and smart cities—where context and adaptability are essential for effective digital service delivery.

Future work will focus on extending the framework's reasoning capabilities by incorporating multi-agent and large-language-model-based components to improve semantic understanding and narrative explainability. Additional studies will explore cross-domain validation, integration with knowledge graphs, and the development of contextual privacy mechanisms ensuring ethical and transparent personalization.

Ultimately, this research contributes to advancing the design of adaptive, interoperable, and trustworthy digital ecosystems, providing a methodological foundation for information systems that continuously evolve with their users and environments.

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