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Context-Aware Service Design in Digital Museums: Toward Personalized Visitor Experiences

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ABSTRACT

As an emerging service model, contextualized services have drawn significant attention both domestically and internationally, particularly in areas such as context modelling, system frameworks, and context-aware recommendation systems. Meanwhile, museums are evolving into vital platforms for fulfilling growing cultural and experiential demands. To adapt to the digital era, future museums must integrate contextualized services, which go beyond traditional user experience by enhancing the quality and personalization of museum environments and services. This article synthesizes existing research to clarify key concepts and examines the need for contextualized services from the perspectives of users, museums, and knowledge. It outlines the construction of a context-awareness model based on context data collection, computation, modelling, and evaluation. A user-centred service framework is proposed, comprising modules such as context awareness, resource integration, technical infrastructure, and scenario-based service delivery. The study also addresses current challenges in implementing contextualized services and suggests targeted solutions. Ultimately, it proposes strategies for enhancing museum scene construction to deliver deeper, more immersive visitor experiences.

Keywords: *context-awareness, individualized service, recommended service, digitalized museum, scene-based service.*

1 INTRODUCTION

Context—also referred to as circumstances or surrounding information-encompasses any data that helps define the state of an entity, including its location, time, environment, activities, and behavioural patterns. It describes both the characteristics and conditions of physical and virtual entities. By leveraging such contextual information, services and data can be tailored to match a user's real-time situation. This type of personalized provision is known as a context-aware service.

Context-aware services, also known as contextualized services, leverage contextual information—such as who the user is, where they are, when the interaction occurs, and what they are doing—to automatically recognize, interpret, and respond to user needs. These services establish adaptive mechanisms to improve both the accuracy and reliability of system responses, serving as key components in enhancing system performance and user satisfaction (Yang & Shao, 2007).

Given the mobility of users, the context in which they operate constantly changes—across different times, locations, and activities—leading to evolving service demands. In response, significant progress has been made, both domestically and internationally, in developing personalized services based on dynamic context awareness.

However, many modern museums in China still resemble static "relic warehouses," lacking engaging and interactive scene design. Their traditional presentation styles fail to meet the diverse experiential needs of contemporary visitors. Thus, scene reconstruction and experiential enhancement have become pressing priorities for museum modernization.

Drawing on scene theory, this study proposes a new research perspective for constructing immersive, experience-oriented museum environments. Through the lens of scene perception, it explores the interplay between context awareness, contextualized services, and the cultural environment within digital museums. The goal is to advance user-centred strategies such as personalized recommendations and context-driven scene transitions, ultimately enriching the immersive experience for museum visitors.

2 LITERATURES REVIEW

2.1 Research on museums and their scene-building

According to the redefinition by the International Council of Museums (ICOM) in 1989, a museum is a non-profit, permanent institution that serves society by collecting, preserving, researching, and exhibiting tangible and intangible heritage. It operates in the public interest, aiming to contribute to societal development, cultural understanding, and community engagement. As such, museums fulfil educational, research, and service functions (Chen, 2017).

With the growing influence of the tourism industry, museums have increasingly taken on roles related to tourism, leisure, and entertainment. As key components of cultural tourism resources, museums are becoming more integrated with the broader cultural tourism landscape. This growing interdependence between museums and tourism is expected to deepen as both sectors continue to evolve. Domestic scholars have conducted studies on the research and development (R&D) of museum-based tourism products, achieving meaningful progress.

Kong and Sun (2003) identified several challenges facing museum tourism products in China, including underdeveloped hierarchical systems and outdated content. They proposed enhancing the institutional image of museum tourism organizations, standardizing product development, and improving internal coordination among offerings.

Li (2004) further analysed issues such as the imbalance between the supply and demand of museum tourism products, as well as inadequacies in promotional strategies. Li advocated for consumer-centred product development, diversified museum offerings, the incorporation of marketing principles, and improvements in exhibition approaches.

The study of museum audiences dates back to 1916, when Mr. Gilman examined visitor experiences at the Museum of Fine Arts in Boston, marking one of the earliest efforts to understand audience behaviour (Marchetti, 2013). Museologist John H. Falk later conceptualized museum visits as multi-layered experiences, combining personal emotions, historical context, and human-computer interaction (Falk & Dierking, 1992). Wang (2016) analysed audience behaviour in terms of patterns, cognitive models, and emotional responses, emphasizing the importance of affective satisfaction and perceptual engagement in exhibition design.

In the domain of exhibition design, British scholar Kenneth Hudson viewed museums through the lens of media studies, asserting that exhibitions should prioritize human-centred design and flexible communication strategies (Landau & Hudson, 1980). At an academic symposium on curatorial practices, Chen (2019) outlined a project-based framework for exhibition planning and advocated for the development of standardized operating procedures (SOPs) to meet the dynamic demands of curatorship in a changing era.

In examining museum functions, Japanese scholar Aiko Hashimura emphasized the integration of education with recreational experiences, advocating for participatory and appreciable educational models (Cun & Zhang, 2011). Meanwhile, Brüggmann (2016) argued that museum missions have evolved beyond their traditional roles of education, collection, and preservation to include social advocacy and public engagement. Shan (2015), former curator of the Palace Museum in Beijing, analysed the unique societal role of museums and proposed innovative exhibition strategies to enhance public appeal.

2.2 Context-Awareness Recommending System and Context-Awareness Services

In the domain of theoretical research on context-aware services, international studies have predominantly focused on core issues such as context acquisition, context modelling and system architecture development, context-aware applications, and recommendation systems. These studies have produced a wealth of theoretical achievements. A central challenge identified in the field is the accurate capture and representation of dynamic contextual information generated by users. Notably, users' attention patterns often provide a real-time reflection of such dynamic contexts.

Context-aware services have seen broad applications in areas like e-commerce, mobile computing, information retrieval, and personalized recommendation systems. Satoh (2015) emphasized the significant disparity between laboratory-based context-aware service research and its real-world deployment. He identified several common challenges in real-world applications and, drawing from empirical findings in environments such as museums, proposed tailored solutions.

Kim et al. (2010) introduced an innovative personalized recommendation system that improves the satisfaction and precision of advertising by utilizing contextual data—such as user location, time, identity, and demand type. They also developed a prototype system, NAMA, designed to recommend personalized shopping information based on the user's contextual environment (Kwon et al. 2005).

Hong et al. (2009) conceptualized a layered model for context-aware systems, encompassing basic research, networks, middleware, applications, and user interfaces. They proposed using context history via context-aware computation to construct a framework for personalized information services and developed a corresponding prototype system.

Kim et al. (2014) further integrated context-awareness and personalized recommendation into a healthcare service system by combining collaborative filtering with contextual data.

Context-aware recommendation and retrieval systems have also been extensively studied. Adomavicius et al. (2005) detailed a multidimensional recommendation model incorporating contextual variables and proposed a hybrid recommendation algorithm. They validated their approach with a prototype for movie recommendations.

Su et al. (2010) developed a music recommendation system called "uMender," which integrates contextual information, music content, and user ratings. Through a two-level clustering approach, it classifies users by contextual similarity and recommends music aligned with both personal and situational characteristics.

Lee et al. (2006) proposed a hotel recommendation system based on geographic context, employing a decision tree model to rank hotels and provide location-sensitive services for tourists. Similarly, Gavalas et al. (2011) combined personal and contextual data (e.g., location, time, weather, previously visited sites) with collaborative filtering algorithms to deliver dynamic travel recommendations.

Yap et al. (2007) highlighted the importance of context in defining user interest models. Using a Bayesian network approach, they dynamically predicted user preferences and contextual states, enhancing recommendation accuracy in mobile environments.

Madkour et al. (2012) proposed a context-aware retrieval model grounded in fuzzy set theory. The model incorporates both functional (e.g., identity, location, time, activity) and non-functional (e.g., preferences, emotions, cultural background) context information to select and rank services, even under conditions of incomplete or uncertain data.

These studies collectively underscore the critical role of contextual information in improving the accuracy and relevance of personalized information retrieval in mobile and dynamic environments. However, effective implementation requires adapting to specific contextual variables across various application domains.

2.3 Research on the Scenes Construction of Museum Based on Contextual Awareness

Dey (2000) defines context as any information that characterizes the condition or state of an entity. In the era of big data, a user's context reflects their diverse needs across different times, spaces, and behavioural states. As one of the earliest scholars to propose the concept of "context-awareness," Schilit emphasized not only the system's ability to perceive changes in contextual information but also its capacity to respond accordingly (Schilit et al. 1994).

Context-awareness refers to the process of collecting and analysing contextual information through various devices and technologies. It has been widely applied in fields such as advertising, e-commerce, tourism, and information retrieval. In the context of museums, it allows for a more accurate understanding of visitors' needs, enabling the provision of specialized and insightful services tailored to their situational context.

Each scenario represents a unique environment where informational media and the physical space interact. It offers a novel mode of multi-dimensional connection and value exchange. With the proliferation of smart mobile devices, user interaction with their surroundings has become more frequent, placing greater emphasis on service experiences. The book The Coming of a Scenarios Era describes scenarios as being shaped by both tangible elements—such as space, environment, social atmosphere, and user experience—and intangible elements, including cultural ambiance and the configuration of resources (Xie, 2018).

A contextualized service system can only operate effectively when it dynamically adapts to evolving contextual elements through context-switching and resource reallocation. By targeting specific themes or user groups and recognizing users' real-time situational context, the system can autonomously identify user needs. Based on both the context of user requirements and operational tasks, and through resource integration and service orchestration, the system actively delivers services, thus offering users a spectrum of scenario-driven choices (Zeng, 2018).

For museums, contextualized services are vital in responding to contemporary trends. They embody an integrated evolution of space, resources, and service offerings, defining the museum's continued relevance in the digital age. In this user-centric era, context is pervasive and constantly evolving. Therefore, achieving seamless alignment between users' empathetic experiences and contextual conditions should be a core objective of the modern digital museum.

1. DEMAND ANALYSIS OF CONTEXTUALIZED-SERVICES IN DIGITALIZED MUSEUM

3.1 User Dimension

In today's user-driven era, context has become both pervasive and dynamic. When users seek knowledge, they increasingly value not just the content itself, but also the environment and delivery methods of the service. Beyond visual-based information—such as text, images, and videos—users now expect immersive experiences, where knowledge and its associated services are presented through multisensory and scenario-based formats. This shift reflects a growing desire to not only acquire knowledge, but to experience it.

As we move deeper into the age of information overload, users' needs are becoming more refined and personalized. In response, museums must leverage context-aware technologies to understand user behaviour and predict emerging demands. This enables the delivery of more accurate knowledge retrieval and tailored information recommendations.

With the accelerating pace of modern life and learning becoming increasingly fragmented, users often access content in short, on-the-go sessions. Contextualized services can address this challenge by engaging multiple senses to enhance users' perception and absorption of information, thus improving both efficiency and quality. To fulfil the growing user demand for immersive, "being-there" experiences, museums should aim to:

- Deliver contextualized services that are efficient, user-friendly, and purpose-driven, ensuring relevance to users' immediate needs and interests.
- When required, offer immersive, simulated context-based experiences or enable automated, real-time contextual interactions to enhance user engagement.
- For users from educational and scientific research institutions, provide virtual yet realistic contexts such as simulated laboratories, collaborative research environments, and platforms for scientific data sharing—thereby maximizing the museum's advantage in data resources and catering to the demand for knowledge-intensive outputs.
- For primary and secondary school students, design experiential contexts involving hands-on activities, community-based programs, and online science classrooms, addressing their needs for learning, socialization, creativity, and entertainment.
- For the general public, offer contextualized services that include relaxing entertainment spaces and personalized, customized visiting routes to enrich their leisure and cultural experience.

Users increasingly prioritize experiential engagement when acquiring new knowledge. Experience, as a core element of contextualized services, not only enhances the development and user appreciation of such services but also serves as a reference for the creation and continuous refinement of immersive contexts or scenarios.

User experience encompasses a comprehensive perception of the museum's environment, resources, and services. It is reflected in various aspects such as user satisfaction, the effectiveness of scenario construction, and the overall quality of service delivery. Therefore, museums should develop an integrated contextualized service platform that seamlessly connects with user-centred contexts—particularly those evoking empathy and immersion—to ensure a holistic and satisfying service experience.

Museum scenarios should be adaptive, capable of responding dynamically to changes in user needs. By fully leveraging technological infrastructure, service design, and cultural resources, museums can create personalized contextualized services. These services should empower users—whether engaging online or offline—to actively access information while fostering a strong sense of identity and connection. In doing so, the museum can truly realize its mission of being user-centered.

3.2 Museum dimension

According to the Chicago School of Urban Studies, what draws people to a particular place is not primarily local economic factors—as emphasized by classical theories—but rather the culture and lifestyle it offers. In the context of museums, the essence of context theory is reflected in how spatial environments are shaped. Within a given museum space, a scenario typically consists of exhibit arrangements, cultural infrastructure, service offerings, visitor interactions, ongoing activities, and the generation of derivative cultural products (Wu, 2014).

These interconnected elements collectively form the value system of a museum scenario, attracting audiences who share similar cultural preferences and fostering what is often referred to as "visitor stickiness." In other words, the museum becomes a gathering place for diverse forms of cultural participation and consumption. This, in turn, stimulates cultural production and enriches the content and format of cultural experiences, thereby enhancing the museum’s overall vitality and appeal.

As a new conduit for information exchange, context serves not only as an innovative means of information engagement but also bridges the gap between users, museums, and services related to intangible cultural heritage. It facilitates mutual understanding between people and museums, users and services, and users and knowledge. In today’s user-driven era, context has become a vital strategic asset. Without integrating contextualized services into their core functions, museums and libraries risk stagnation and will struggle to achieve sustainable development.

3.3 Dimension of intangible cultural heritage

The European Union (EU) regards the digitalization of cultural heritage as a cornerstone for the sustainable development of both society and economy. Under the Horizon 2020 program, the EU launched the Virtual Multi-Operated Museums (VMOM) project. This initiative, framed within the EU’s broader policy agenda and practice concerning digital cultural heritage, represents a significant action plan combining coordination and support in the field of virtual museums (Ioannides & Davies, 2018). In this project, a team of globally recognized experts proposed a visionary roadmap that integrates advanced policymaking, strategic planning, and the application of mixed reality (MR) technologies in an innovative way. The project’s goal is to promote evidence-based growth and development—particularly in Southern European countries—through the influence of virtual museums.

Traditional knowledge systems are rooted in the collection of lived experiences and the dynamic interaction between humans and their environments. These systems encompass a wide range of practices and understandings, including skills related to hunting and agriculture, midwifery, ethnobotany, traditional medicine, celestial navigation, ethnoastronomy, and climatology. Passed down orally or embedded in stories, folktales, songs, rituals, and customary laws, such knowledge is crucial for the survival of many cultural communities. More importantly, it offers valuable insights into sustainable living, rooted in a worldview of coexistence and interdependence.

However, as the types and carriers of intangible cultural heritage continue to expand, the resulting information overload poses a significant challenge. In response, digital museums must enhance their capacity to curate and deliver cultural heritage through contextualized services. Traditional presentation formats—such as text, images, and video—often fail to sufficiently engage users or deliver an immersive knowledge experience. In contrast, context-driven displays enrich content delivery by presenting knowledge through multi-dimensional, situational scenarios.

Contextualized services, grounded in immersive scenes, help visitors improve memory retention and deepen their understanding. Knowledge becomes more than abstract information—it is embodied in interactive environments. By digitally reconstructing historical contexts, for instance, users can actively participate in a simulated experience, effectively “witnessing” history firsthand.

These scenes serve to bridge the gap between abstract cultural heritage knowledge and the individual learner. Within such environments, knowledge becomes tangible, relatable, and emotionally resonant. Visitors are better able to concentrate, comprehend, and internalize information when engaged in well-designed, scenario-based settings. Digital museums can integrate a diverse array of media—texts, images, audio, video, 3D models, augmented reality (AR), virtual reality (VR), real objects, and even narrative storytelling—to create comprehensive and captivating knowledge environments.

By enabling seamless transitions between multiple scenes and fostering dynamic interaction between users and environments, digital museums can vividly present even the most complex or expansive cultural knowledge systems. This approach not only enhances the learning experience but also revitalizes the way cultural heritage is preserved, shared, and understood in the digital age.

2. CONTEXT-AWARENESS MODEL CONSTRUCTION FOR CONTEXTUALIZED-SERVICES USERS

4.1 Context-data collection

In the context of digital museums, contextualized services are characterized by a user-centred approach, demand-driven orientation, and an emphasis on convenience and efficiency. In response to the requirements of contextualized services and the inherent features of digital museums, this paper proposes an ontology-based context-awareness data model.

In this model, the top-level ontology, denoted as Ci, places the user at the core. The second-level ontology is composed of three primary contextual dimensions: self-context (Xi), physical-context (Yi), and information-context (Zi). Each of these is associated with a label set that defines specific contextual attributes through detailed numerical or categorical descriptors (see Figure 1).

Within the context in which the user is situated, the ontological attributes include but are not limited to: basic user information, behavioural data, psychological state, social context, and interactive feedback. For example:

Basic user information can be retrieved from museum registration data and demographic databases.

Behavioural data—acquired through backend logs or web crawlers—provides insights into user habits and preferences, particularly regarding exhibition browsing patterns.

Psychological states reflect emotional or cognitive responses triggered by specific content or environments. Museums can utilize this information to tailor services according to the user’s current emotional state. These data may be collected through user surveys, online feedback forms, or automated methods such as log analysis, sentiment analysis, and psychological profiling (e.g., the Big Five Personality Traits model).

Social context encompasses the user's interpersonal networks and social needs as they vary across different scenarios. Social data can be harvested via social media platforms, mobile terminals, and web activity. By understanding a user's social environment and preferences, digital museums can offer social context-aware services—enhancing user engagement and community interaction.

Moreover, analysing data from user-to-user interactions allows for the evaluation and comparison of service quality, thus facilitating continuous improvement in service delivery and optimization of the context-awareness model.

The physical scene ontology includes contextual attributes such as time, location, weather, spatial layout, and device usage:

Time refers to the specific period during which a user interacts with the museum. Temporal data can reveal user preferences regarding visit timing, which can be used to schedule personalized services.

Location data helps align services with the user's current or habitual geographic position.

Weather conditions (e.g., temperature, air pressure, lighting) influence the user's physical experience and thus should be considered when adapting service delivery.

Spatial and device attributes allow the museum to optimize its services based on the user's physical environment and the technology in use (e.g., mobile phone, tablet, AR/VR headset). This ensures the delivery of contextually appropriate content through suitable platforms in real-time settings.

The knowledge context ontology includes five key attributes: temporal relevance, character or nature of content, subject matter, domain specificity, and knowledge content itself. These knowledge contexts can be systematically tagged to enable accurate matching between user expectations and knowledge delivery. The more precisely a knowledge context is labelled, the more accurately a contextualized service system can identify and recommend relevant knowledge resources.

In summary, by integrating ontologies of self, physical, and knowledge contexts, this model enables digital museums to deliver intelligent, adaptive, and personalized contextualized services that enhance user engagement, satisfaction, and learning outcomes.

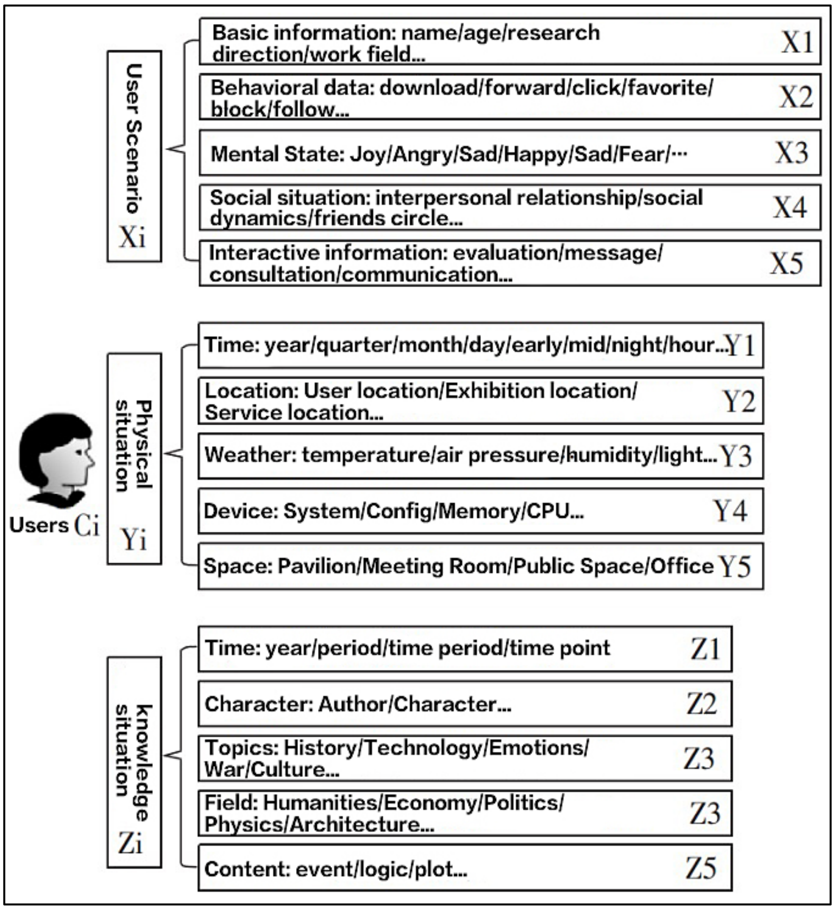

Figure 1 Ontology-based reader context-data model (Source: Author Yunzhen, 2025)

The primary function of a digitalized museum's contextualized service is to deliver scene-based services that are convenient, efficient, and intelligent—ensuring that the right knowledge is presented to the right user through the most suitable context.

4.2 Contextual Computing

After categorizing the labels associated with users' contextual attributes, multiple group context models can be established. This enables the delivery of tailored contextualized services to each group, enhancing the museum system's responsiveness and operational efficiency. While individualized contexts allow for highly precise, personalized services, the effectiveness of such services depends on the completeness and accuracy of the data collected. In cases where individual context data is incomplete or flawed, the constructed context may fail to reflect the user's actual needs.

To address this, new users can be matched with individualized contexts by referencing the contextual preferences of similar user groups, derived from segmentation and profiling. This process typically involves unsupervised learning methods such as K-means or DBSCAN for clustering. Additionally, similarity metrics like Euclidean distance or cosine similarity can be applied to evaluate the closeness between different user groups.

Regarding to the deficiency of user-context label, Bayesian formula$P(Bi|A) = \frac{-P(Bi)\ P(A|Bj)}{P(Bi)\ P(A|Bj)}$can be used to solve this problem. For the purpose of contextualised services, in this formula:

- P(Bi) means the probability of context-Bi,
- P(A|Bj) means the probability of context-A when context-Bj existing, and

・P(Bi|A) means the probability of context-Bi when context-A existing.

Using probability estimation, we can infer the likelihood that a user possesses context B based on their existing characteristics in context A. When data related to context B is missing, this estimation can be used to fill in the missing context labels. Conversely, it can also help validate whether a given context attribute label assigned to a user is appropriate.

Association rules are effective in identifying interdependence and relationships between different objects. Algorithms like Apriori are commonly used to uncover these associations. By analyzing the relationships among multiple contexts, we can construct composite scenes that incorporate multiple elements. This enhances the depth and relevance of contextualized services, increases user engagement, and encourages more proactive participation in the service experience.

Since most user context data is collected in textual form, context attribute labels are typically derived through data mining techniques. In this process, text mining can be applied to extract meaningful labels, where frequency analysis using TF-IDF (Term Frequency–Inverse Document Frequency) helps identify the most significant terms, and LDA (Latent Dirichlet Allocation) is used to extract topic-oriented contexts — referred to as *topic-contexts*.

A topic-context reflects the user's most focused or frequently engaged area of interest and therefore holds greater weight in the process of selecting and prioritizing context labels. While a user’s contextual preferences may shift over time, the topic-context often serves as a stable indicator of their general preferences. Extracting and monitoring the topic-context allows us to detect and respond to dynamic changes in user interest.

To accurately track and respond to evolving preferences, we must first have a comprehensive understanding of the topics that interest the user. With this foundation, even subtle shifts in user preference can be addressed promptly, ensuring that the contextualized services provided remain aligned with the user’s evolving expectations.

4.3 Scenario modelling

Context modeling is established through the process of labeling three primary dimensions: user context, physical context, and knowledge context. Each label is characterized by its concise and semantic-rich format. These short-text semantic units serve as efficient representations of complex contextual data, making them easy for computers to process and humans to understand. This labeling approach enhances both the efficiency of data processing and the system’s ability to recognize and interpret contextual information.

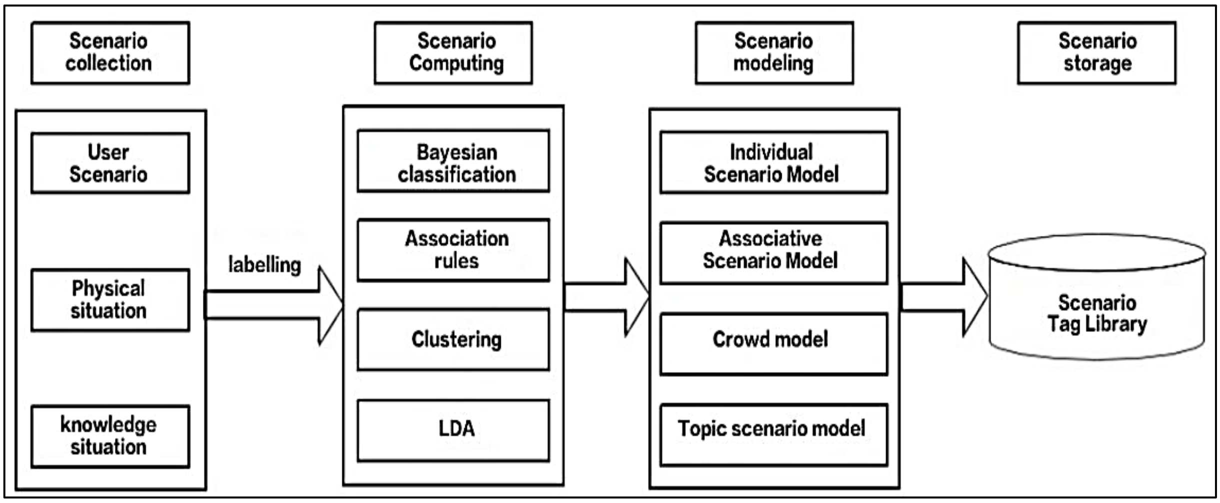

Figure 2 the building process of context-awareness model (Source: Author Yunzhen, 2025)

Once context labeling is completed, various analytical techniques such as Bayesian classification, association rules, clustering algorithms, and Latent Dirichlet Allocation (LDA) can be applied to build different types of context models, including:

- Individual Scenario Model: This model rapidly generates labels based on a user's contextual attributes and is used to identify their unique contextual characteristics or preference patterns.
- Associative Scenario Model: Designed to analyze relationships among multiple context labels, this model supports the simultaneous delivery of services aligned with interconnected contextual needs.
- Group (Crowd) Context Model: By aggregating individual labels, this model forms group-level contexts. It then analyzes these group contexts to identify shared traits and collective demand preferences, which can inform group-specific service strategies.
- Topic Scenario Model: This model focuses on deriving user context within specific thematic or subject-based domains. It helps uncover the underlying contextual factors influencing user preferences, enabling quick identification of dominant interests and tracking how these preferences evolve over time.

After the contextual labels and models have been analyzed and constructed, they can be stored and reused as needed—allowing for efficient application in future contextualized service scenarios (see, Figure 2).

4.4 Model Evaluation

To establish an effective user context-awareness model, it is essential to evaluate the effectiveness of context labels—in other words, to assess the accuracy and reliability of the constructed model. One of the key metrics is the label accuracy rate, which can be assessed using sample surveys,

- the label's accuracy-rate of each ontology is Pi (the ratio of the number of accurate labels to the total number of labels), therefore,
- the average correct rate of sample labels is $\overline{P} = \frac{1}{n}\ Pi$ and
- the variance is $\sigma^2 = \frac{1}{n-1}(Pi - \overline{P})^2$.

Within a given sample group, if the average accuracy rate is high and the variance is low, it indicates a more robust and reliable context-awareness model.

For measuring the effectiveness of conjunctive-contexts model, we can use the lift degree (i.e., $\mathrm{lift}(A, B) = \frac{P(AYB)}{P(A)\,P(B)}$ to make a correlation measuring on those extracted conjunctive-contexts. In this case,

- if context-A and context-B are independent to each other, then P(AUB)=P(A) P(B), i.e., the degree of lifting is 1;
- if the degree of lifting is less than 1, then there is a negative correlation between context-A and context-B. On the contrary,
- if the degree of lifting is more than 1, then there is a positive correlation between context-A and context-B.

In addition to basic statistical metrics, advanced methods such as the Chi-square (χ^2) test and the Kulczynski (Kulc) measure—proposed by the Polish mathematician Kulczynski—can be used to evaluate the correlation strength between context labels and outcomes. These measurements help determine the effectiveness of association rules and co-occurrence between context elements.

When evaluating group-level (crowd) context models, it's also important to assess the accuracy of individual user classification within specific user groups. Each user must be accurately assigned to a relevant context-based group, and the effectiveness of the clustering algorithm should be evaluated accordingly. Common metrics used for this purpose include:

- Accuracy: The proportion of correctly classified users.
- Recall (Sensitivity): The ability to correctly identify all relevant instances within a group.
- Silhouette Coefficient: A measure of how similar an object is to its own cluster compared to other clusters, indicating the validity and separation of clusters.

By applying these quantitative measures, the digital museum can ensure that its context-awareness model is both data-driven and user-aligned, leading to improved precision in delivering contextualized services.

3. DIGITALIZED MUSEUM'S CONTEXTUALIZED-SERVICES SYSTEM BANSED ON CONTEXT-AWARENESS

To enhance the contextualized services of digitalized museums, scene-awareness must be seamlessly integrated into the service process, thereby forming an ecological loop of user ⇌ demand ⇌ scene (see Figure 3). In this system, the scene becomes the lens through which user demands are understood—as user needs shape the scenes they engage with, while those very scenes in turn reflect and represent their contextual states.

Building on this foundation, this paper proposes a service system framework for digital museums, composed of four key modules:

- Context-awareness module – identifies and interprets user context;
- Resource integration module – aggregates and aligns museum resources with contextual cues;
- Middleware module – facilitates data flow and system interoperability;
- Contextualized service module – delivers personalized services based on scene-driven insights.

This framework aims to deliver more responsive, intelligent, and user-centric services by linking context, resources, and interaction in a dynamic and adaptive structure.

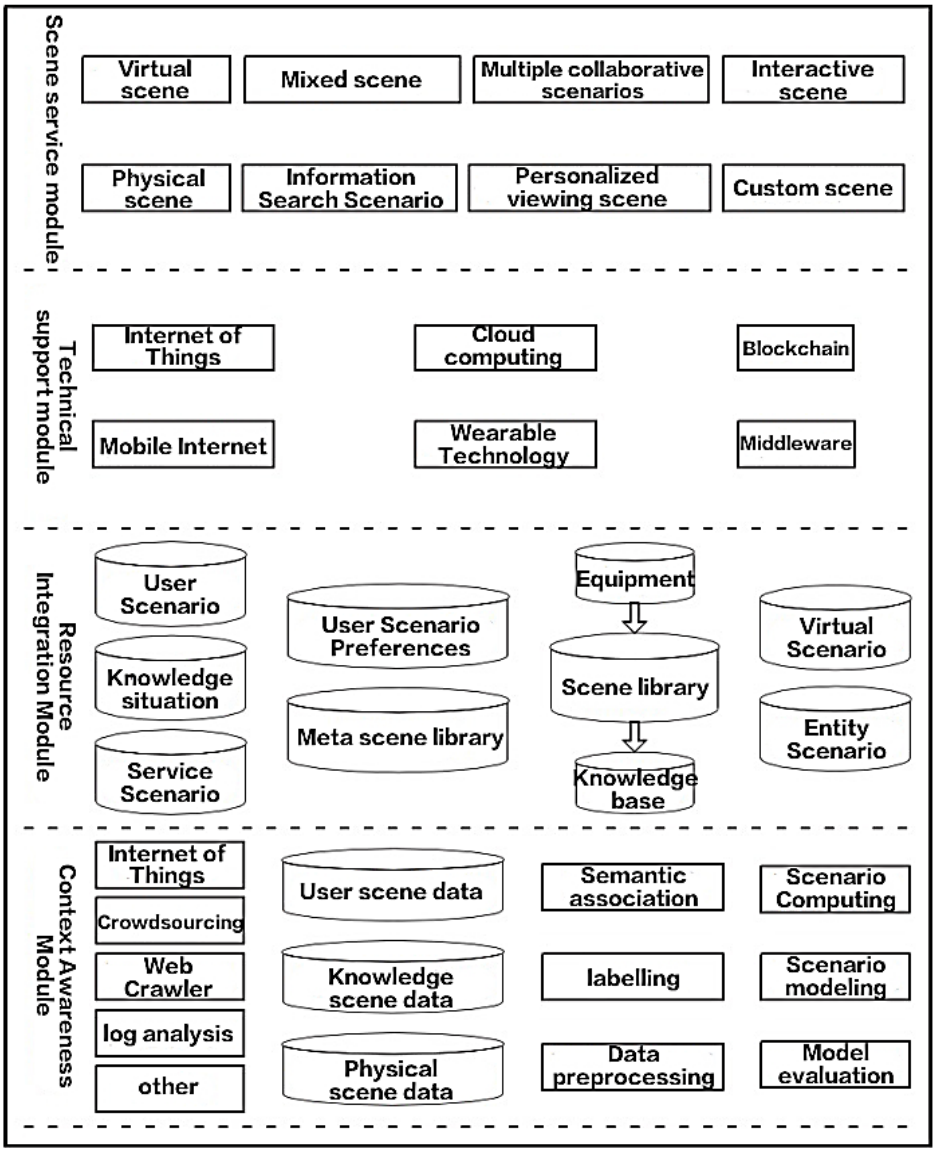

Figure 3 Scenario-based service architecture of Digital Museum based on context awareness (Source: Author Yunzhen, 2025)

5.1 Module of Context-Awareness

To collect context-related data effectively, a range of methods and technologies can be employed, including the Internet of Things (IoT), crowdsourcing, web crawling, and log analysis. Within the IoT domain, core technologies such as sensors, monitors, GPS, and RFID play critical roles. These tools not only gather user context data but also enable the provision of comprehensive, multi-dimensional, and perceptible contextualized services.

For example, sensors detect environmental variables such as temperature, humidity, air pressure, and illumination. Through device middleware, these readings can be used to automatically adjust the scene to enhance user experience. Monitors capture data related to user behavior, spatial movement, environmental conditions, and social interactions. GPS supports real-time location tracking, enabling location-based service delivery tailored to user needs.

Crowdsourcing is particularly effective for collecting and labeling knowledge-context data. It can also capture synchronous elements of scene construction, including design components, cognitive pathways, and service strategies.

Web crawlers gather information on users’ social activity, discussion records, review scores, reading behavior, and more. These insights help identify users’ emotional tendencies, social relationships, and interest preferences, all of which are essential for delivering personalized, context-driven services.

Log collection techniques leverage system backups to extract data on platform performance over time. This approach is useful for tracking user behavior dynamics, data flow patterns, network security events, and system processes, including business logic execution.

Additional context data can be gathered through online questionnaires, interviews, and scenario simulations. Data from diverse sources must be normalized to ensure consistency, reduce noise and redundancy, and improve subsequent analysis and processing.

Since raw data alone does not directly reveal users’ contextual characteristics, it must undergo data transformation and semantic analysis. This includes identifying contextual semantics and applying appropriate labeling processes.

Through the combined use of context computing, context modeling, model evaluation, and data storage, a robust context-awareness system can operate logically and efficiently—ultimately improving the responsiveness and intelligence of digitalized museum services.

5.2 Module for Resources Integrating

Through the resource integration module, a digitalized museum can effectively consolidate its cultural heritage assets, spatial management infrastructure, and user data resources, thereby establishing the foundational conditions necessary for delivering contextualized services.

By leveraging context data—encompassing user context, knowledge context, and physical context, the museum can analyze user scene preferences and distill a meta-scene.

The meta-scene (also referred to as a “scene-of-scenes”) serves not only as a logical framework that defines the structural and content-based foundation of individual scenes but also as a modular unit composed of scene elements. It functions as the core building block for constructing adaptive and interactive scene experiences.

This meta-scene can be dynamically evolved and diversified into multiple scene types, enhancing both its adaptability and scalability. By aligning a user’s contextual demands with the meta-scene structure, the museum can generate personalized scene content tailored to the user’s specific needs and preferences.

Moreover, through the integration of intelligent infrastructure within the digitalized museum—alongside mobile and client-end technologies, the museum can effectively respond to user knowledge demands by delivering virtual or physical scene-based services, thus enabling a seamless and immersive cultural experience.

5.3 Module of Technical Support

The delivery of contextualized services in digital museums relies on a suite of enabling technologies, including the Internet of Things (IoT), cloud computing, blockchain, mobile Internet, wearable technology, and middleware systems.

Through IoT, digital museums can provide services that are comprehensive, three-dimensionally interconnected, and perceptually responsive. By deploying sensors, monitors, RFID tags, and other IoT devices, museums can capture real-time user context, enable facilities, and exhibit to become context-aware and offer more immersive and responsive experiences.

In the era of big data, the computational capacity of mobile devices alone is often insufficient to handle large-scale data processing. To address this, complex data workloads can be offloaded to cloud platforms, where high-concurrency computing tasks are executed on servers. Results are then transmitted back to user devices via cloud channels, significantly enhancing service responsiveness and computational efficiency. In addition, platforms such as Hadoop can be employed for distributed data storage and management, thereby improving both resource acquisition and sharing capabilities.

Blockchain technology — characterized by decentralization, peer-to-peer communication, asymmetric encryption, collaborative maintenance, tamper-resistance, and anonymity—plays a critical role in protecting intellectual property rights and facilitating secure information sharing in digital museums. Through decentralized resource management and immutable data storage, blockchain effectively addresses long-standing challenges related to data security, trust, and copyright protection in the digital preservation and dissemination of cultural heritage.

In the context of the mobile Internet, museums can leverage user-end mobile devices to collect diverse contextual information, such as location, preferences, and behavior. This data provides a foundation for expanding and refining personalized contextualized services.

Wearable technologies further enhance the immersive capabilities of digital museums by supporting the creation of realistic and perceptible virtual scenes. These technologies allow users to engage with digital content in multi-sensory, interactive ways without physically being on-site. As a result, museums not only deliver rich, full-spectrum contextual experiences but also gather more granular user data, enabling precise demand detection and fostering greater user engagement and retention.

Lastly, middleware serves as a bridge software layer that standardizes the interface between application programs and underlying hardware or operating systems. By ensuring compatibility across diverse technical environments, middleware enhances the stability, portability, and scalability of the museum's service software. As long as the middleware-defined standard interfaces remain unchanged, application-level software can continue to function seamlessly, even when hardware platforms or system configurations are updated.

5.4 Module of Scene-Service

The scene-service modules of digital museums encompass a broad spectrum of formats and functions, including virtual scenes, physical scenes, hybrid scenes, information retrieval scenes, personalized reading scenes, multi-element cooperative scenes, interactive scenes, and customized scenes, among others.

Virtual scenes leverage technologies such as virtual reality (VR), augmented reality (AR), smart wearable devices, and smart mobile terminals to deliver immersive digital experiences. These environments enable users to access museum content anytime and anywhere via ubiquitous wireless connectivity, fulfilling their knowledge needs through virtual reconstructions and simulations.

In contrast, a physical scene refers to the tangible, spatial arrangements within the museum's physical infrastructure—featuring curated material exhibits and architectural elements that provide users with authentic, sensory-rich experiences. These physical environments allow users to engage more deeply with cultural content through direct perception and spatial immersion.

A hybrid scene integrates both physical and virtual components to deliver complementary, synergistic experiences. This model maximizes the strengths of both modalities, enhancing user engagement and interpretive depth.

The information retrieval scene module utilizes contextual information about the user's environment and behavior to optimize search results. In situations of information overload, the system can assist users by facilitating intelligent search through multiple input modalities—such as text, voice commands, and image recognition—thereby guiding them toward the most relevant and contextually aligned knowledge resources.

The multi-element cooperative scene supports a dynamic and multidimensional understanding of the user's context. When users are unable to clearly articulate their information needs, this module analyzes contextual cues and submission content to infer the user's intent and expectations. Consequently, the system not only delivers relevant results but also presents them in a multi-dimensional, visualized scene format, improving interpretability and usability.

For example, mobile visual search can utilize contextual data—such as an archaeologist’s geographic location, working schedule, and visual characteristics of a cultural artifact image—to accurately match relevant information resources. This not only enhances search precision but also improves operational efficiency in professional settings.

In accordance with user-specific scene characteristics, digital museums can also offer personalized reading scenes tailored to individual preferences and learning styles. Furthermore, digital museums support synchronous online interactions among users located in distributed environments, enabling collaborative learning, dialogue, and co-exploration. These interactive scenes facilitate various functions such as peer communication, museum-user dialogue, navigation assistance, expert consultation, experience sharing, feedback collection, and assessment.

Finally, customized scene services allow users to autonomously define scene modes based on their subjective intentions or objective requirements. These services enable the dynamic configuration of scene content, structural layout, and thematic focus, thereby delivering targeted, user-centered experiences that align closely with individual goals and preferences.

6 KEY PROBLEMS IN SCENE-BASED CONTEXT-AWARENESS SERVICE BY DIGITALIZED MUSEUM

Context-aware services are characterized by attributes such as intelligence, proactivity, and contextual adaptability. By continuously responding to the dynamic changes in a user's contextual environment, these services can deliver personalized learning resources and adaptive support, effectively enabling mobile and ubiquitous learning experiences. As a result, both domestic and international research communities have made significant progress in this area, and context-aware services are increasingly applied across a variety of domains.

In the specific context of digital museum scene-services and contextualized experiences, a key research focus has emerged around how to leverage user-driven dynamics, multi-dimensional service frameworks, and scene sensitivity to deliver precisely tailored services. This question has drawn growing attention from industry, and the integration of context-aware technologies into digital museum environments has achieved notable advancements in practice.

However, within the museum sector, there still exist critical gaps in both theoretical exploration and practical implementation. Specifically, the mechanisms and operational models of context-aware services remain underdeveloped. Areas such as the design, deployment, and governance of scene-based context-aware service systems in digital museums demand more rigorous, systematic research and strategic development.

Accordingly, there is an urgent need to thoroughly investigate the theoretical foundations of scene-based context-aware information services, particularly as applied to digital museums. Future efforts should prioritize the construction of comprehensive service models and system architectures, the development of robust and adaptive service platforms, and the enhancement of service responsiveness, personalization, and contextual adaptability. These advancements are essential to improving service quality, user satisfaction, and the overall experience of cultural engagement.

Moreover, the implementation of context-aware services in digital museums constitutes a complex systems engineering challenge. Beyond building the appropriate systems and platforms, it is equally important to establish effective operational mechanisms and support infrastructures. A range of additional issues—such as data governance, user privacy, scalability, and semantic interoperability—remain open for further scholarly investigation and practical resolution.

6.1 User’s Experience and User’s Behaviour of Services Accepting

The mobility of users presents not only a central challenge to the implementation of context-aware services but also places users in inherently complex and dynamic environments. As such, key research concerns include how to enhance the richness of users' experiential engagement with information services on mobile devices, and how to foster greater user awareness and acceptance of context-aware services. These issues merit deeper investigation in future studies.

As an emerging service paradigm, context-aware services rely fundamentally on user adoption and continued usage behavior. The degree to which users recognize and accept such services directly affects the operational sustainability and long-term development of the service model. In fact, user engagement serves as a critical benchmark for evaluating the success or failure of context-aware service systems.

In the context of digital museum services, the context-aware service model should not be regarded as static or one-size-fits-all. Instead, museums must continuously adapt and refine their service strategies based on institutional realities and user needs. While efforts to improve physical exhibition environments remain important, equal emphasis should be placed on strengthening virtual scene construction. The integration of virtual and physical scenes can achieve a multi-functional, immersive service experience, enhancing both accessibility and engagement.

Moreover, contextualized services in digital museums should aim to be comprehensive, multilayered, interconnected, and tangibly perceptible to users. Only through such a design can digital museums effectively fulfill their broader missions—not only as providers of cultural knowledge but also as promoters of cultural values, innovative thinking, and contemporary epistemologies. In doing so, digital museums will not only deliver meaningful services but also realize their intrinsic value in the digital era.

6.2 Semantic Gap between the Collection and Acquisition of User’s Cognitive Psychological Data

To effectively deliver contextualized services, digital museums must first identify users’ contextual preferences and service demands based on their scene-related information. However, such scene information often provides only an indirect reflection of users’ actual intentions. In other words, it represents surface-level expressions of user behavior, rather than revealing the full depth of their internal expectations.

Within any user scene, a rich array of contextual semantemes exists—subtle cues that convey meaning about the user’s cognitive state, intent, or focus of attention. Accurately interpreting these semantemes is essential to effectively characterize the scene and anticipate user needs. By leveraging human-computer interactive systems, it becomes possible to systematically identify the discrepancies between the underlying semantemes embedded in the user’s environment and the explicitly expressed service requests. This discrepancy is referred to as the “contextual semanteme gap”.

Different contextual elements are associated with distinct semantemes. Without mining and understanding these semantemes, it is not feasible to gain a true insight into users’ contextualized demands, nor to ensure alignment between scene construction and user expectations.

To bridge the gap between the deep semantemes inherent in context and the surface-level semantics expressed by the user, it is necessary to develop a system of semanteme labels. These labels should encompass a range of core contextual entities, and facilitate the mapping between underlying contextual meanings and users’ articulated needs.

In practice, this process must be iteratively refined—continuously improving semanteme-label systems and minimizing the contextual semanteme gap. Through such refinement, the semantic interpretation of context can more accurately reflect the user’s genuine intent and implicit expectations, thereby enabling more precise and personalized contextualized services.

6.3 Protection to User’s Personal Information

As digitalized museums require the comprehensive collection of user context-data, concerns surrounding user information privacy are inevitably involved. In an open and highly shared environment, the protection of personal information must be given high priority. That is, a digital museum should implement data protection measures throughout the entire process, including data collection, transmission, storage, and application.

Protection in data collection: Firstly, prior to collecting any context-related data, the museum should clearly inform users about what data will be collected and for what purpose and must obtain explicit consent. Secondly, the data collected should be limited to what is necessary, excluding irrelevant information and strictly avoiding violations of user privacy.

Protection in data transmission: During data transfer, encryption technologies should be employed to ensure secure transmission. Additionally, museums should, whenever possible, utilize internal networks or local area networks (LANs) to minimize the risk of interception or unauthorized access.

Protection in data storage: Data should be desensitized (e.g., anonymized or pseudonymized), and access to stored information must be controlled via firewalls and permission settings. Centralized storage should be avoided where possible, and distributed storage should be adopted to enhance security and reduce systemic risk.

Protection in data application: When analyzing and applying user context-data, strict security management should be implemented to ensure proper use, and to prevent internal data breaches, especially those caused by improper staff handling.

In summary, protecting users' personal information and privacy is crucial to building trust and enhancing the public credibility of digital museums. It also reflects a responsible and user-centered attitude, demonstrating the institution's commitment to ethical information practices.

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