USD-Based 3D Archiving Framework for Time-Series Digital Documentation of Natural Heritage

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Abstract

Natural heritage assets, including ancient trees, ecosystems, and geological formations, are dynamic and evolve biologically and environmentally over time. Traditional documentation methods, typically static and fragmented, fail to comprehensively capture these temporal changes. Unlike built heritage, which benefits from standardized models such as Historic Building Information Modeling (HBIM), natural heritage lacks an integrated digital framework capable of representing its inherent variability and continuous transformation.

This study proposes a conceptual time-series documentation framework that unifies spatial geometry and contextual metadata within a single hierarchical model using Universal Scene Description (USD). Leveraging USD's variantSet and in-file metadata capabilities, the framework represents multiple temporal states of natural heritage objects, enabling effective tracking, comparison, and interpretation across time. A flexible metadata schema is designed with a two-layer structure: common core fields (assetInfo) and type-specific extended attributes (customData), tailored to diverse natural heritage categories such as plants, animals, geological features, and scenic sites. Additionally, a dynamic visualization model supports interactive exploration, multi-temporal comparison, and condition-based filtering, facilitating both qualitative and quantitative heritage analysis. By shifting documentation from static capture to dynamic record-keeping, this framework addresses critical gaps in natural heritage preservation and aligns with international heritage charters emphasizing transparency, interpretability, and sustainability. The proposed approach provides a robust, scalable, and extensible foundation for preserving the evolving condition and meaning of natural heritage assets, ultimately fostering informed conservation strategies and sustainable heritage management.

1. Introduction

Natural heritage—including ancient trees, endemic ecosystems, and geological formations—is inherently dynamic and temporally evolving. These elements do not merely exist as static monuments but continually transform in response to seasonal cycles, ecological shifts, and anthropogenic interventions. Documenting natural heritage, therefore, demands more than traditional static capture; it requires a dynamic and temporally responsive framework that reflects changes in condition, context, and meaning over time.

In contrast to built heritage, which benefits from well-established documentation protocols such as Historic Building Information Modeling (HBIM), natural heritage lacks a standardized digital methodology capable of capturing both structural diversity and temporal fluidity. While HBIM integrates geometry, metadata, and chronology into a coherent digital model, its architecture is fundamentally suited to stable, human-constructed assets. Applying such models to natural heritage, with its organic, irregular forms and constantly shifting states, presents critical challenges.

Conventional recording methods—including photographs, maps, textual logs, or separate 3D scans—often treat natural heritage as frozen in time. These fragmented approaches result in the separation of geometry and metadata, complicating long-term monitoring, reducing archival consistency, and limiting interpretive value. Without a unified structure, researchers and managers face difficulties in tracking change, understanding causality, or making evidence-based decisions about conservation.

Global heritage philosophy, as articulated in international charters such as the Nara Document on Authenticity (Nara Document on Authenticity, 1994) (1994), the Ename Charter (Ename Charter, 2007), and the London Charter (The London Charter, 2009), has evolved to emphasize the interpretive and participatory dimensions of heritage. These documents assert that documentation should not only record form but also preserve context, enable transparency, and foster interpretive engagement across time and audiences. In particular, the London Charterunderscores the importance of embedding semantic meaning and interpretive flexibility into digital representations, supporting diverse future readings.

This study responds to these principles by proposing a unified digital structure for time-series documentation of natural heritage. Rather than promoting a specific technology, it introduces a conceptual framework that organizes temporal spatial data and embedded metadata within a single interoperable model. We employ Universal Scene Description (Pavelka et al., 2025; Agbossou, 2023) (USD)—a format developed by Pixar—as the enabling backbone due to its hierarchical scene management, variant set functionalities, and in-file metadata capabilities.

The aim is to shift the focus of documentation from static representation to dynamic recordkeeping, where each time state of a natural heritage asset becomes part of a cohesive and interpretable narrative. This aligns not only with scientific needs for monitoring but also with cultural objectives of ensuring meaning, memory, and continuity across generations. The proposed framework enables richer comparative analyses, predictive modeling, and interactive visualization—positioning natural heritage not merely as passive artifacts but as living records of ecological and cultural processes.

By establishing a structure that accommodates variability, supports temporal layering, and embeds contextual meaning, this study contributes a practical and philosophical advancement to the field of digital heritage. It opens pathways for applying digital

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tools to heritage types that have been historically underrepresented in documentation discourse, addressing the need for methodologies that are as adaptive and dynamic as the subjects they seek to preserve.

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2. Related Works

Digital documentation of heritage has largely concentrated on built environments, where structured data models like HBIM have become standard practice. HBIM enables integrated representations of buildings through parametric geometry, condition histories, and semantic metadata, facilitating maintenance, conservation planning, and historical simulation. These models are especially valuable in contexts where structures are stable, geometry is regular, and interventions are predictable. However, natural heritage—defined by irregular forms, unpredictable change, and biological cycles—lacks a comparable digital framework. In many cases, natural heritage is documented using discrete tools: photogrammetric scans, drone imagery, spreadsheets, and GIS maps, with little to no structural integration. These records are often limited to one-time captures and are rarely linked across time. As a result, multi-temporal comparison, historical trajectory mapping, and cross-referencing of condition changes remain difficult, if not impossible, to perform consistently.

Some research in environmental monitoring and remote sensing has attempted to address temporality in natural systems, such as through vegetation indices or time-lapse satellite imagery. However, these approaches typically operate at a landscape or ecosystem level and do not provide object-centric detail suitable for cultural heritage assets, such as protected trees, mineral formations, or sacred natural sites. Furthermore, they rarely include semantically rich metadata or support interpretive tasks beyond statistical analysis.

Natural heritage documentation also faces challenges in metadata standardization. Unlike built heritage, which often fits into existing ontologies and classification systems, natural heritage exhibits diverse types—plants, animals, landscapes, geological features—each requiring different descriptors. This heterogeneity makes it difficult to develop a one-size-fits-all model and necessitates a flexible structure capable of supporting both shared and custom attributes.

Recent interest in using USD in industrial applications has opened new possibilities for heritage documentation. USD’s core features—such as hierarchical scene organization, variant state definitions, and metadata containers—offer a promising foundation for modeling time-series change. Although originally intended for animation and visual effects, USD is now being explored for scientific visualization and digital twin (Kong et al., 2023) applications due to its scalability and interoperability.

This study builds on that momentum, adapting USD’s capabilities to create a metadata-integrated temporal framework tailored to natural heritage. Unlike existing approaches, it offers a hybrid solution that accommodates both general and type-specific metadata, allows branching of temporal states within a unified structure, and enables scalable visualization for analysis and interpretation. In doing so, it fills a critical gap in heritage documentation practices and sets the stage for further interdisciplinary innovation.

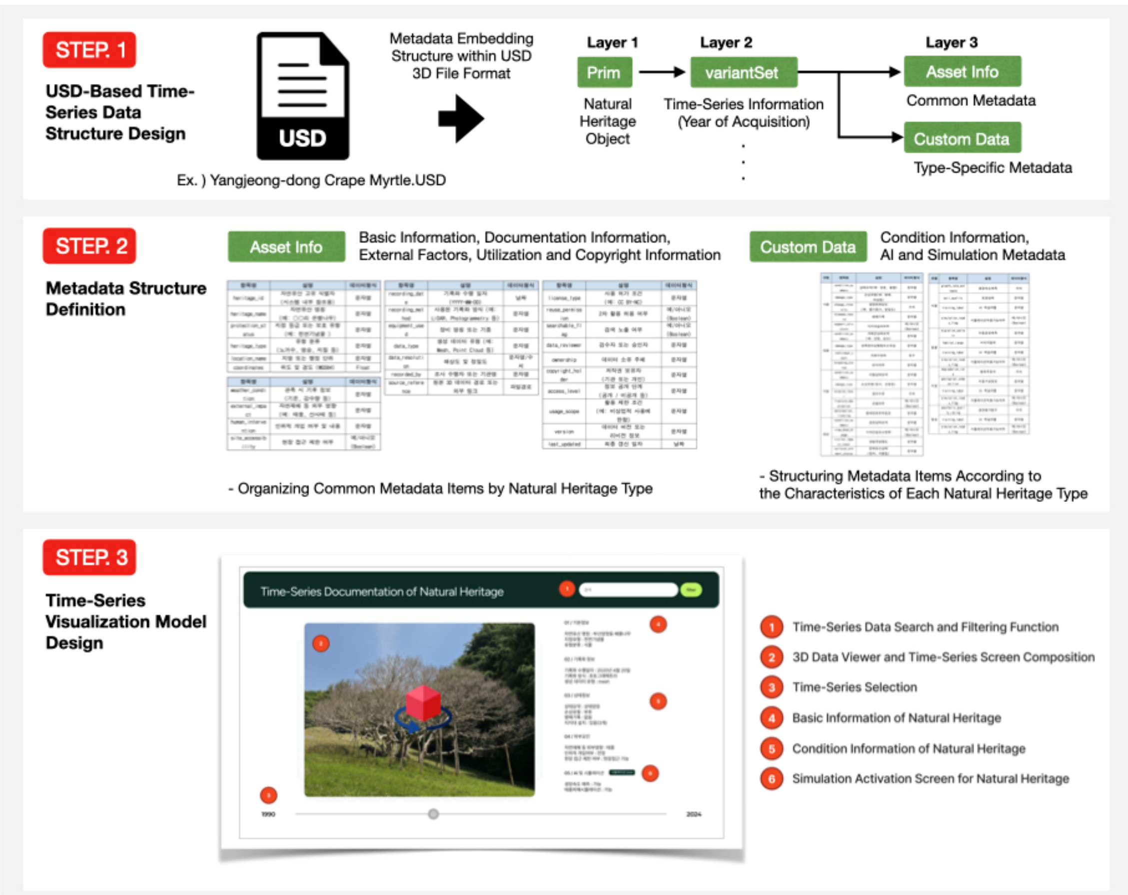

Figure 1 illustrates the overall flow of the proposed framework, composed of three design steps: (1) USD-based hierarchical structuring of natural heritage objects and temporal states, (2) definition of structured metadata across both common and type-specific fields, and (3) design of a dynamic visualization model that integrates time navigation, condition filtering, and metadata display.

3. Methodology

This study proposes a metadata-integrated time-series data framework for documenting the evolving nature of natural heritage. Unlike built heritage, which can often be described using standardized documentation models such as HBIM, natural heritage exhibits significant variability depending on its type—including plants, animals, geological formations, and scenic landscapes. These differences present inherent limitations in applying a uniform metadata schema or digital modeling framework.

To address this challenge, the methodology defines a layered and extensible structure for metadata organization, time-based documentation, and visualization. The approach is based on USD ,which supports variant-based state switching, hierarchical scene graphs, and in-file metadata embedding. The process consists of three major phases:

A. **Time-series data structuring** using USD primitives (Prim, variantSet, customData, assetInfo)
B. **Metadata schema design** tailored by natural heritage type (e.g., plant, animal, geological, scenic)
C. **Visualization model development**, enabling interactive exploration and interpretation of temporal changes

As shown in Figure 1, the overall USD-based data structure enables hierarchical management of time-series records by combining Prim hierarchy, "variantSet" branching, and structured metadata embedding. This foundation allows dynamic visualization and scalable integration of future extensions such as anomaly detection, predictive simulation, and AI-based temporal analysis.

Finally, based on the constructed time-series structure, a visualization interface is designed that enables users to intuitively explore temporal changes, conduct multi-temporal comparisons, and interact with metadata. The visualization model supports year-based transitions through the "variantSet" mechanism, metadata-driven filtering, and comparative analysis across different time points, all integrated within a unified platform environment.
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3.1 USD-Based Time-Series Data Structure Design

The time-series documentation of natural heritage demands a structural recording method that captures not only static data at a single point but also the dynamic transformations and external factors occurring over time. To address this need, this study adopts the USD framework developed by Pixar, designing a data structure capable of temporal comparison and scalable metadata integration.
USD is a format designed for hierarchically organizing complex 3D scenes, based on a structure where each object is defined as a Prim (primitive). A Prim represents a single object or conceptual unit within a scene and can contain a name, attributes, child Prims, and metadata. For example, an ancient tree, a specific geological formation, or a natural landscape element can each be defined as a separate Prim. This structure is particularly advantageous for separating and independently recording multi-temporal states of dynamic subjects like natural heritage.
In this study, each temporal instance of the same natural heritage object is defined as an independent Prim. For instance, instances such as /Heritage/Tree_001_2020, /Heritage/Tree_001_2022, and /Heritage/Tree_001_2024 are separately constructed to organize time-based data, embed metadata, and enable visual comparison and condition-based exploration. This approach allows the precise tracking and interpretation of changes occurring over time at the object level.
Additionally, when the differences between temporal states are relatively minor or when continuous state transitions within a single object are required, the "variantSet" function of USD is utilized complementarily. The "variantSet" functionality enables multiple states to be branched within a single Prim. For example, defining "variantSets" = "Year" under the Prim /Heritage/Tree_001 allows users to switch between states corresponding to different years via the interface. This method facilitates user-friendly visualization, year-to-year comparisons, and ensures structural consistency.
Metadata within USD are embedded inside each Prim using two structures: "assetInfo" and "customData".

- **assetInfo :** contains common identification and management information applicable to all natural heritage types, such as a unique identifier, name, type, designation status, location, recording date, and condition summary.
- customData : accommodates type-specific attributes and additional extended metadata for time-series analysis, AI-based prediction (Yu et al., 2025), and simulation applications. For instance, plant-type objects may include attributes for disease records and support structure installation status, while geological-type objects include erosion levels, fracture observations, and deformation tracking information.

This structure is designed to support future use cases such as time-based visualization, conditional filtering, anomaly detection, and policy simulations. The extensibility of "customData" provides a flexible yet standardized framework for back-end and front-end platform integration and API-based operations.
Although "customData" allows flexible user-defined fields, standardized key names, data types, and value ranges must be pre-defined to ensure system interoperability and automation. Accordingly, this study categorizes metadata into six groups, placing common items within "assetInfo" and type-specific and extended attributes within "customData".

3.2 Metadata Schema Definition for Natural Heritage

Given the diversity of natural heritage types, a unified metadata schema would be too restrictive. This study separates metadata into two layers:

- **assetInfo** : core fields applicable across all types
- **customData** : expandable, type-specific attributes for each category

This separation enables common processing logic (for indexing, querying, sorting) while maintaining the flexibility to support the nuanced needs of different domains.

3.2.1 Basic Information ("assetInfo") The basic information category includes static attributes necessary for the identification and administrative classification of natural heritage. These attributes are common across all types and temporal states of heritage and primarily focus on establishing the fundamental identity of the object rather than describing its changing conditions over time. As shown in Table 1, the key attributes include the unique identifier, heritage name, designation status, type classification, location information, and geographical coordinates. These fields serve as the foundational reference for managing and organizing natural heritage data systematically within the USD structure.

Field Name	Description	Data Type
heritage_id	Unique identifier for natural heritage (for internal system reference)	String
heritage_name	Name of the natural heritage (e.g., Yangjeong-dong Crape Myrtle)	String
protection_status	Designation grade or protection type (e.g., Natural Monument)	String
heritage_type	Classification type (e.g., ancient tree, scenic site, geological feature)	String
location_name	Place name or administrative division	String
coordinates	Latitude and longitude (WGS84)	Float

Table 1. Metadata Structure (Basic Information)

3.2.2 Documentation Information ("assetInfo") The documentation information category records the conditions and environment under which each time-series dataset was created. This information is crucial for evaluating the technical quality of the data and serves as a foundation for post-processing, comparative analysis, and historical tracking of recording methods over time. As presented in Table 2, this category includes the documentation date, method employed (such as LiDAR or photogrammetry (Kim & Lee, 2024)), equipment specifications, data type and resolution, the organization or individual responsible for the recording, and the reference path to the original 3D dataset. Accurate documentation of these attributes ensures the reliability and reproducibility of the time-series records.

Field Name	Description	Data Type
recording_date	Date of documentation (YYYY-MM-DD)	Date
recording_method	Method used for documentation (e.g., LiDAR, photogrammetry)	String
equipment_used	Equipment name or model	String
data_type	Type of generated data (e.g., Mesh, Point Cloud)	String
data_resolution	Resolution or precision	String/Number
recorded_by	Organization or individual conducting the recording	String
source_reference	Path to the original 3D data or external link	URI/File Path

Table 2. Metadata Structure (Documentation Information)

3.2.3 Condition Information ("customData") The condition information category records the physical, biological, or geological status of natural heritage at each time point. Since natural heritage varies greatly depending on its type (e.g., plants, animals, geological features, scenic sites), this category is subdivided accordingly. As presented in Table 3, the fields include condition summaries, damage types, and specific indicators such as growth changes for plants, population dynamics for animals, erosion levels for geological objects, and view obstruction changes for scenic sites. These attributes enable a detailed, type-specific assessment of changes over time.

Type	Field Name	Descriptio n	Data Type
Plant	condition_summary	Condition Summary (e.g., Good, Poor)	String
Plant	damage_type	Damage Type (e.g., Disease, Trauma)	String
Plant	change_intensity	Growth Change Intensity (e.g., Stem Expansion, Leaf Density)	Numeri c
Plant	disease_record	Disease Record	String
Plant	support_structure	Support Structure Installed (Yes/No)	Boolea n
Animal	condition_summary	Population Condition Summary (e.g., Stable, Declining)	String
Animal	damage_type	Observed Abnormal Behavior or Trauma	String
Animal	individual_count	individual Count Change	Integer
Animal	breeding_status	Breeding Status	String
Geologic al	condition_summary	Geological Condition Summary	String
Geologic al	damage_type	Damage Type (e.g.,	String

		Erosion, Fracture)	
Geological	erosion_level	Erosion Level	Numeric
Geological	fracture_observation	Fracture Observation (Yes/No)	Boolean
Geological	deformation_tracking	Deformation Tracking Information	String
Scenic Site	condition_summary	Scenic Condition Summary	String
Scenic Site	view_shed_change	View Obstruction Change (Yes/No)	Boolean
Scenic Site	visitor_impact_level	Visitor Impact Level	String
Scenic Site	cultural_element_status	Cultural Element Status (e.g., Pavilion, Stone Structures)	String

Table 3. Metadata Structure (Condition Information)

3.2.4 External Factors ("assetInfo" + "customData") External factors influencing natural heritage, such as climatic conditions, natural disasters, and human interventions, are recorded in this category. This information is critical for contextualizing observed changes in heritage status. As shown in Table 4, the fields capture weather conditions during observation, the occurrence of external impacts like typhoons or landslides, the presence and description of human interventions, and site accessibility conditions.

Field Name	Description	Data Type
weather_condition	Weather conditions during observation (e.g., temperature, precipitation)	String
external_impact	External impacts such as natural disasters (e.g., typhoon, landslide)	String
human_intervention	Human intervention details	String
site_accessibility	Site accessibility restrictions (Yes/No)	Boolean

Table 4. Metadata Structure (External Factors)

3.2.5 Utilization and Copyright Information ("assetInfo" + "customData") This category defines how the data can be accessed, shared, or reused, ensuring the proper management of intellectual property rights and public availability settings. As shown in Table 5, it includes fields for license type, reuse permission, search visibility, copyright ownership, access level, and version tracking.

Field Name	Description	Data Type
license_type	License condition (e.g., CC BY-NC)	String
reuse_permission	Permission for secondary use	Boolean
searchable_flag	Visibility for search	Boolean
data_reviewer	Reviewer or approver	String
ownership	Data ownership entity	String
copyright_holder	Copyright holder (organization or individual)	String
access_level	Access level (e.g., public / restricted)	String
usage_scope	Usage restriction (e.g., non-commercial use only)	String
version	Data version or revision information	String
last_updated	Last updated date	Date

Table 5. Metadata Structure (Utilization and Copyright Information)

3.2.6 AI and Simulation Metadata ("customData") Designed for future applications such as automated anomaly detection, AI-based prediction (Yu et al., 2025), and simulation models, this category contains type-specific fields aimed at enabling advanced analyses. As presented in Table 6, metadata fields include growth rate estimates for plants, migration patterns for animals, degradation rates for geological sites, and aesthetic quality ratings for scenic sites. This prepares the data structure for integration with machine learning models and predictive simulations.

Type	Field Name	Description	Data Type
Plant	growth_rate_estimate	Growth rate estimation	Numeric
Plant	soil_quality	Soil condition	String
Plant	training_label	AI training label	String
Plant	simulation_ready_flag	Simulation applicability	Boolean
Animal	migration_pattern	Migration path prediction	String
Animal	habitat_range	Habitat range	String
Animal	training_label	AI training label	String
Animal	simulation_ready_flag	Simulation applicability	Boolean
Geology	degradation_rate	Degradation rate	Numeric
Geology	geological_composition	Geological composition information	String

Geology	training_label	AI training label	String
Geology	simulation_ready_flag	Simulation applicability	Boolean
Scenic	aesthetic_quality_rating	Aesthetic quality score	Numeric
Scenic	training_label	AI training label	String
Scenic	simulation_ready_flag	Simulation applicability	Boolean

Table 6. Metadata Structure (AI and Simulation Metadata)

3.3 Time-Series Visualization Model Design

Natural heritage experiences a wide range of transformations over time, including biological growth, physical deterioration, geological changes, and environmental impacts. Capturing and interpreting these complex temporal dynamics requires an advanced visualization framework that integrates both spatial data and rich metadata.
This study proposes a time-series visualization model based on USD (Pavelka et al., 2025; Agbossou, 2023) format. Leveraging USD's hierarchical Prim structures and its variantSet feature, the model facilitates dynamic exploration and comparison of heritage states across multiple temporal snapshots within a unified interface.

The core functionalities of the proposed visualization system are:

- **Timeline-Based Navigation:** Users interact with a timeline interface to select specific recording dates. Upon selection, the corresponding variant within the variantSet is activated, and the associated 3D geometry and metadata load dynamically, enabling smooth temporal traversal.
- **Multi-Temporal Comparison:** The system supports simultaneous visualization of multiple time states, either by switching between variants within a single Prim or rendering multiple Prims side-by-side. This capability enables detailed examination of structural or environmental changes, fostering evidence-based assessments.
- **Condition-Based Filtering:** Users can apply metadata-driven filters, such as condition_summary, weather_condition, or external_impact, to isolate specific states of interest. Filter application updates the timeline and 3D view in real-time, enhancing targeted analysis and decision-making.
- **Interactive Metadata Panels:** Contextual metadata linked to the selected variant—including condition summaries, recording information, protection status, and licensing—are displayed in an interactive panel. This tight integration of spatial and descriptive data enriches interpretive potential.
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As illustrated in Figure 2, the USD structure uses a variantSet named "Year" to switch among temporal states of a heritage object, each embedding metadata in assetInfo and customData fields:

```
def Xform "Heritage_Tree_001" (
    variants = {
        string Year = "2020"
    }
)
{
    variantSet "Year" = {
        "2020" {
            def Mesh "Tree_Mesh" (
                assetInfo = {
                    heritage_name = "Yangjeong-dong Crape Myrtle"
                    protection_status = "Natural Monument"
                    heritage_type = "Plant"
                    recording_date = "2020-04-20"
                }
                customData = {
                    condition_summary = "Good"
                    support_structure = "3"
                }
            )
        }
        "2022" {
            def Mesh "Tree_Mesh" (
                assetInfo = {
                    heritage_name = "Yangjeong-dong Crape Myrtle"
                    protection_status = "Natural Monument"
                    heritage_type = "Plant"
                    recording_date = "2022-07-15"
                }
                customData = {
                    weather_condition = "Post-typhoon"
                    condition_summary = "Poor"
                    support_structure = "5"
                }
            )
        }
    }
}
```

Figure 2. Example of time-series Prim structure using variantSet

The visualization framework facilitates multi-temporal comparison by enabling users to view different temporal states side-by-side within a single interface. For example, 3D models of a heritage tree captured in 2020 and 2024 can be rendered simultaneously, allowing detailed examination of structural degradation, growth patterns, or environmental impacts. This comparison can be achieved through seamless switching between variants within a single Prim or by displaying multiple Prims concurrently. Such capabilities encourage objective, evidence-based assessments of natural heritage conditions, enhancing the rigor of conservation analyses over time.
Beyond simple visualization, condition-based filtering enables users to flexibly explore and isolate data based on key metadata attributes—such as external_impact (e.g., typhoons), condition_summary (e.g., poor health), or weather_condition—supporting targeted analysis and decision-making. For example, when investigating the impact of a typhoon, users can instantly retrieve all records marked with post-storm damage, allowing them to narrow their focus to the most affected periods or regions. This filtering mechanism directly interacts with the timeline and 3D viewer, updating both in real time and thereby streamlining data exploration and informed management decisions.
Complementing these features, interactive metadata panels provide comprehensive contextual information for the currently selected temporal variant. These panels display condition summaries, precise recording dates, legal protection statuses, and licensing details. By embedding this metadata within the visualization environment, users gain a holistic understanding that integrates spatial geometry with historical, environmental, and regulatory contexts—crucial for informed interpretation and stewardship.

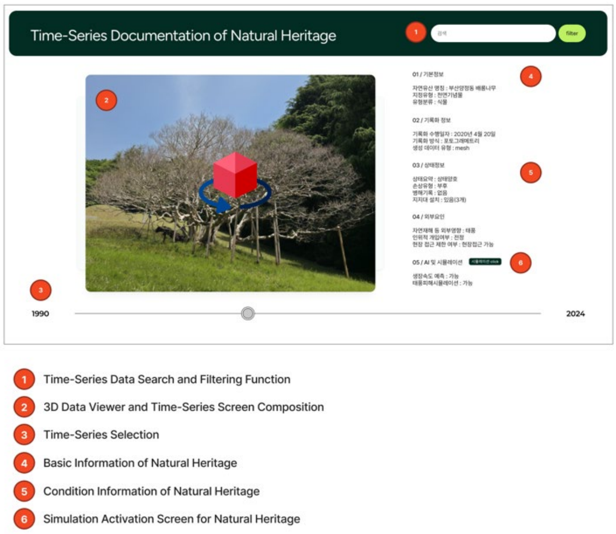

Figure 3. Visualization Model Wireframe

Figure 3 illustrates the wireframe of this visualization model, where timeline navigation, variant selection, filtering operations, and metadata display are cohesively integrated into a unified, user-friendly interface. The system architecture ensures that all modules respond dynamically to user input—so selections or filter changes instantly propagate through the timeline, 3D views, and metadata panels. This tight coupling affords users both panoramic overviews of heritage evolution and granular insights into specific temporal snapshots.

The visualization platform is designed for flexibility and accessibility. It can be implemented using NVIDIA Omniverse USD Composer for high-fidelity desktop visualization, Blender with USD plugins for creative workflows, or web-based viewers built with Three.js and WebAssembly to maximize accessibility without specialized software. Control over variant switching, metadata synchronization, and dynamic filtering is facilitated through Python APIs or JavaScript, enabling seamless integration into existing heritage management pipelines.

By fusing a well-structured metadata schema with the powerful USD time-series architecture, this visualization system provides a robust, scalable, and intuitive environment for tracking natural heritage's dynamic progression. It supports:

- Qualitative evaluations through immersive 3D visual inspection
- Quantitative analyses enabled by metadata-driven condition tracking
- Pattern discovery via condition-based navigation and filtering
- Informed decision-making for conservation strategies grounded in temporal evidence

Ultimately, this framework elevates natural heritage documentation from static records to dynamic, actionable knowledge—ensuring preservation efforts are both scientifically rigorous and culturally meaningful for future generations.

4. Discussion

Natural heritage is not static. Trees grow and decay, habitats shift, and human interventions shape landscapes over time. In this context, documentation is not merely a technical task—it is an act of interpretation. The proposed framework acknowledges that change itself is heritage, and thus must be recorded structurally, not accidentally.

In contrast to traditional practices in cultural heritage, which often prioritize geometric accuracy and original form preservation, natural heritage demands time-aware, condition-aware data structures. The HBIM paradigm, while powerful for architectural assets, assumes material permanence and discrete component logic. Such assumptions do not hold in the organic, continuous, and unpredictable nature of ecological systems.

The proposed USD-based time-series structure addresses this gap by integrating temporal states, spatial geometry, and metadata into a unified schema. Importantly, it aligns with the evolving principles of heritage documentation:

- The Nara Document on Authenticity (Nara Document on Authenticity, 1994) (1994) shifted the focus from material form to contextual meaning.
- The Ename Charter (Ename Charter, 2007) emphasized interpretability and the role of communities in making meaning from heritage.
- The London Charter (The London Charter, 2009) called for transparent, purpose-driven digital documentation that supports future reinterpretation.

Our framework operationalizes these principles in a computational environment. By structuring the digital record to reflect time and context, it enables future interpretation without relying on the memory or judgment of current experts alone. This is particularly valuable in the case of plant-based heritage, where slow transformations may not be visible in the short term but are critical to long-term significance.

Moreover, by integrating metadata directly into the 3D data structure, we eliminate the risk of interpretive detachment—where descriptive records become separated from visual models. This promotes data integrity, eases long-term archival, and improves accessibility for interdisciplinary collaboration (e.g., ecologists, conservators, data scientists).

However, the framework is not without limitations. It assumes regular data acquisition, which may be constrained by logistics or funding. Additionally, while USD is powerful, its adoption within the heritage field is still limited, and tooling for non-technical users remains underdeveloped. These challenges must be addressed through training, interface design, and standards development.

5. Conclusion

This study proposed a USD-based 3D archiving framework designed to structurally document and analyze the time-series characteristics and type-specific attributes of natural heritage. The framework utilizes Pixar's USD format, leveraging its hierarchical structure along with variantSet, assetInfo, and customData functionalities to manage multiple temporal states and diverse metadata within a unified schema.

The metadata structure is organized into six categories, comprising common identification information and type-specific extended attributes. This enables time-based comparison, condition-based filtering, and interpretable visualization within a consistent data model. As a result, the proposed framework provides a transition from static, fragmented documentation to a temporally structured recording system.

In particular, the model offers a generalizable and scalable approach for representing biological, geological, and environmental transformations of natural heritage, which are often difficult to capture using conventional cultural heritage

documentation methods. It serves as a foundational structure adaptable to various types of natural heritage assets.
Future work will involve applying the proposed framework to actual natural heritage sites to build time-series datasets and validate its practical effectiveness. Additional developments will focus on automation of data updates, integration with AI-based anomaly detection and predictive simulations, and the design of user-friendly authoring environments for broader accessibility.
This research provides a technically and structurally validated model that can serve as a new standard for digital documentation of natural heritage. The proposed approach has strong potential for practical application in policy-making, research, education, and conservation management.

References

Agbossou, I., 2023: Urban Landscape Digital Twin Implementation Challenges: OpenUSD Ecosystem's Solutions, *Ecology & Conservation Science*.

Pavelka, K., Pavelka Jr., K., Nováková, J., Beneš, J., 2025: A Reconstruction of the Shrine of the Prophet Nahum: An Analysis of 3D Documentation Methods and Data Transfer Technology for VR/AR, *Applied Sciences*, 15(5), 1234.

Gong, Y., Liu, X., Chen, M., Zhang, T., 2025: A Large-Scale Time Series Data Management Platform for Cultural Heritage Site Risk Monitoring: Architecture Design and Application, *ACM Journal on Computing and Cultural Heritage*.

Niu, W., Zhang, J., Li, Q., 2024: Dynamically Documenting Archaeological Excavations Based on 3D Modeling, *Heritage Science*, 12(1), 34.

Penjor, T., Dorji, K., Wangchuk, S., 2024: HBIM for Heritage Conservation (Penjor et al., 2024; Intrigila et al., 2024): Framework of Challenges, Gaps, and Existing Limitations of HBIM, Digital Applications in Archaeology and Cultural Heritage.

Intrigila, C., Ippolito, A., Mancuso, S., 2024: HBIM for Conservation and Valorization of Structural Heritage: The Stylite Tower at Umm ar-Rasas, *Journal of Cultural Heritage*.

Storeide, M. S. B., Hougen, L., Tveito, H., 2023: Standardization of Digitized Heritage: A Review of Implementations of 3D in Cultural Heritage, *Heritage Science*.

Buragohain, D., Das, A., Boruah, R., 2024: Digitalizing Cultural Heritage through Metaverse Applications, *Heritage Science*.
Piroddi, L., Angeletti, C., Sanna, G., 2025: Imaging Cultural Heritage at Different Scales: Part II, the Meso-Scale (Sites), *Remote Sensing*, 17(3), 4567.

Kim, S., Lee (Lee, 1983), J. H., 2024: A Study on the Digital Restoration of an Ancient City Based on HBIM of Wooden Architectural Heritage, Heritage Science.

Nieto-Julián, J. E., Salazar, S., Pérez, M. A., 2021: Implementation of a TeamWork-HBIM for the Management and Sustainability of Architectural Heritage, *Sustainability*, 13(7), 3500.

Argiolas, R., Floris, F., 2022: Virtual Environments to Communicate Built Cultural Heritage: A HBIM-Based Virtual Tour, *ISPRS Archives*.

Barrile, V., Fotia, A., Manti, P., 2024: Review of Geomatics Solutions for Protecting Cultural Heritage in Response to Climate Change, *Heritage*.

Kong, X., Zhang, Y., Han, J., 2023: Preserving Our Heritage: A Photogrammetry-Based Digital Twin Framework for Monitoring Deteriorations of Historic Structures, *Automation in Construction*, 150, 104849.

Yu, Y., Wang, R., Zhang, L., 2025: How Digital Technologies Have Been Applied for Architectural Heritage Risk Management: A Systemic Literature Review, *Heritage Science*.

Giuliani, F., Conti, A., Galli, M., 2024: A HBIM Pipeline for the Conservation of Large-Scale Architectural Heritage: The City Walls of Pisa, *Heritage Science*.

Smith, J., 2000: Remote sensing to predict volcano outbursts, *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXVII-B1, 456–469.

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-1097-2025