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Article

IDDA: An Immersive Digital Data Asset Framework for Cultural Heritage Preservation with Embedded Local Philosophical Values: Design and Triangulated Evaluation at Pura Taman Ayun, Bali

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Abstract: Cultural heritage sites in the Indonesian Archipelago face continuing physical deterioration and erosion of traditional knowledge, while many immersive digitization initiatives prioritize visual representation over the semantic and cultural contexts that give heritage its meaning. This study developed the Immersive Digital Data Asset (IDDA) framework, which integrates geometric, semantic, and culturally grounded design layers within a web-based heritage platform. Following an adapted Design Science Research Methodology, the framework was instantiated as an immersive virtual tour of Pura Taman Ayun, Bali, using Terrestrial Laser Scanning, unmanned aerial vehicle photogrammetry, semantic information points, and a staged asset-optimization pipeline. Selected principles of Tri Hita Karana were mapped to spatial organization, navigation, user interaction, and site–landscape representation. The evaluation combined black-box functional testing, System Usability Scale assessment, and an internal target-achievement analysis. All seven functional modules met their predefined acceptance criteria. The optimization process reduced the polygon count from approximately 15 million to 500,000 polygons, representing a 96.67% reduction, and decreased the asset size from approximately 2.5 GB to 85 MB. Loading time was reduced from more than 45 seconds to under 5 seconds under the reported testing conditions. A purposively recruited sample of 31 respondents produced a mean System Usability Scale score of 96.29 (SD = 4.12; 95% CI [94.78, 97.80]), indicating high perceived usability within the sampled group. The findings demonstrate the technical feasibility, functional integration, optimization performance, and preliminary usability of a culturally grounded immersive heritage platform. External validation by qualified cultural authorities and evaluation across additional sites and independently recruited user groups remain necessary before claims regarding cultural correctness and broader transferability can be established.

Keywords: culturally grounded design; digital heritage; immersive digital data asset; Pura Taman Ayun; system usability scale; virtual tour

1. Introduction

Cultural heritage in the Indonesian Archipelago encompasses tangible assets, including temples, monuments, and artifacts, as well as intangible traditions such as dance, music, ritual practices, and oral histories. These forms of heritage face continuing threats from physical deterioration, natural hazards, environmental change, and the gradual loss of traditional knowledge associated with social and technological transformation [1]. At the same time, the increasing use of digital media among younger generations has created both challenges and opportunities for cultural transmission. Although conventional documentation and conservation remain essential, they may not independently provide the interactive and contextual experiences needed to support sustained public engagement with cultural heritage [2].

Immersive technologies, particularly virtual reality (VR), augmented reality (AR), and mixed reality (MR), have expanded opportunities to document, visualize, and communicate cultural-heritage sites [1], [3], [4]. Existing studies demonstrate the value of immersive environments for spatial exploration, remote access, reconstruction, and public interpretation. Nevertheless, the literature remains fragmented in its treatment of multidimensional heritage information. Many systems prioritize geometric reconstruction and visual presentation, while semantic information, cultural interpretation, and the relationships between physical space and local knowledge are incorporated less systematically [5], [6]. Consequently, culturally grounded design approaches that connect spatial data, interpretive metadata, and locally situated philosophical principles remain underdeveloped and insufficiently evaluated in implemented heritage platforms. Section 2 examines this gap in relation to immersive heritage visualization, semantic data integration, and culturally informed system design.

This study addresses the identified gap through the Immersive Digital Data Asset (IDDA) framework, a structured architecture for integrating geometric assets, semantic information, and culturally grounded design features within a web-based immersive heritage environment. The framework draws primarily on Tri Hita Karana, a Balinese philosophical principle concerning harmonious relationships among the spiritual, human, and environmental dimensions of life. Within the prototype, selected Tri Hita Karana principles are mapped to spatial organization, navigation, user interaction, and the representation of the relationship between the temple complex and its surrounding landscape. Tri Mandala provides the spatial ordering used to structure movement through areas of differing levels of sacredness. Desa Kala Patra, which emphasizes the contextual relevance of place, time, and circumstance, is treated in the present study as a broader interpretive consideration rather than as a fully implemented adaptive system constraint. This distinction prevents the concepts from being treated as interchangeable and aligns the conceptual claims with the available implementation evidence.

Pura Taman Ayun in Bali was selected as the case site because of its architectural, historical, spiritual, and landscape significance. The temple forms part of the Cultural Landscape of Bali Province, which is inscribed on the UNESCO World Heritage List [insert the renumbered UNESCO reference here]. Its hierarchical spatial organization and relationship with the surrounding environment provide an appropriate setting for examining how selected local philosophical principles may inform immersive heritage-system design. The framework was designed, instantiated, and evaluated using the Design Science Research Methodology (DSRM) [9], [10].

This study makes three contributions. First, it proposes a culturally grounded architecture that maps selected principles of Tri Hita Karana and Tri Mandala to implemented features governing spatial organization, navigation, interaction, and site–landscape representation. The architecture is designed for potential adaptation to other heritage settings, although its transferability has not been empirically established beyond the present case. Second, the study presents an end-to-end acquisition and optimization pipeline that combines terrestrial laser scanning and unmanned aerial vehicle photogrammetry to produce browser-accessible three-dimensional heritage assets, with quantified reductions in polygon count, file size, and loading time. Third, it applies an evaluation protocol combining black-box functional testing, System Usability Scale measurement, and an internal target-achievement analysis based on criteria established before evaluation. Together, these contributions provide evidence of the framework's technical feasibility, functional integration, optimization performance, and perceived usability, while cultural correctness and broader applicability remain subjects for external validation and multi-site research.

2. Related Work

2.1. Immersive Technologies for Cultural Heritage

Immersive technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), have become increasingly prominent in cultural-heritage documentation, interpretation, education, and public engagement. Zhang et al. [1] identified substantial growth in research on immersive cultural-heritage applications, while Cecotti [3] showed that fully immersive environments can support remote exploration and experiential access to heritage objects and sites. Boboc [4] similarly documented the expanding use of AR for visualization, interpretation, reconstruction, and visitor engagement.

Despite these advances, the literature remains dominated by technology-centered concerns such as visualization quality, interaction modalities, hardware configurations, and user experience. Existing applications frequently present three-dimensional models and supplementary historical information, but the relationships among geometric assets, semantic records, interpretive evidence, and locally situated cultural knowledge are not always represented through an integrated system architecture. Consequently, immersive presentation is well established, whereas the systematic integration of physical, semantic, and culturally grounded design layers remains comparatively underdeveloped [1], [3], [4].

2.2. Data Integration, Semantic Modeling, and Digital-Twin Frameworks

Digital-twin and heritage-information research provides useful approaches for integrating heterogeneous data. Hakimi [7], for example, proposed a conceptual digital-twin architecture that combines geometric, sensor, and infrastructure information. Such architectures demonstrate the value of connecting multiple data sources through a unified digital representation. However, frameworks originating in civil infrastructure and asset management are generally oriented toward monitoring, maintenance, and operational decision-making rather than cultural interpretation. Their direct applicability to heritage is therefore limited when historical narratives, ritual significance, social relationships, and local knowledge must be represented alongside physical geometry.

Semantic modeling offers a complementary approach to this integration problem. The CIDOC Conceptual Reference Model (CIDOC CRM) provides a formal ontology for representing cultural-heritage entities, events, actors, places, time spans, and relationships [10]. Its purpose is to support semantic interoperability among heterogeneous museum, archival, archaeological, and heritage-information systems. CIDOC CRM and related semantic approaches can therefore connect digital objects with their provenance, historical context, creators, locations, and documentary evidence. Nevertheless, semantic interoperability alone does not determine how culturally situated values should influence navigation, interaction, spatial organization, or other architectural decisions within an immersive platform.

2.3. Principles for Responsible Heritage Visualization

The London Charter establishes principles for the intellectually and technically rigorous use of computer-based visualization in cultural-heritage research and communication [8]. It emphasizes the need to document research sources, distinguish evidence from interpretation, maintain transparency regarding visualization decisions, support sustainability, and provide appropriate access. The Seville Principles extend these concerns to virtual archaeology and emphasize historical rigor, authenticity, interdisciplinary collaboration, efficiency, transparency, and scientific validation [9]. Together, these frameworks provide an important methodological foundation for developing responsible virtual-heritage applications.

These principles are particularly relevant to the IDDA framework because they require digital representations to make their interpretive foundations visible rather than presenting reconstructions as culturally neutral or unquestionably authoritative. However, the charters primarily establish standards for documentation, evidence, transparency, and visualization quality. They do not prescribe how a specific local philosophical system should be translated into the interaction architecture or spatial logic of an immersive application.

2.4. Culturally Grounded and Community-Informed Digital Heritage

Recent digital-heritage research increasingly recognizes that local communities, cultural practitioners, curators, and knowledge holders should participate in determining how heritage is selected, interpreted, represented, and communicated. Community-based and co-design approaches show that digital heritage should be developed with communities rather than solely for them and should account for authority, ownership, plurality, cultural sensitivity, and situated knowledge [11]. Studies of indigenous and community heritage have similarly demonstrated the value of involving cultural storytellers and community representatives in shaping immersive content, narrative structures, and interaction features [12]. Such work challenges technology-led approaches in which cultural knowledge is added only after the underlying platform has already been designed.

Other studies have developed structured methods for representing traditional practices, object histories, contextual narratives, and intangible knowledge through digital records and interactive systems [13]. These contributions demonstrate a movement from visual reconstruction toward culturally informed and semantically enriched heritage experiences. Nevertheless, most existing studies focus on participatory content production, digital storytelling, co-curation, semantic documentation, or the interpretation of heritage objects. Comparatively limited evidence is available on frameworks that map a local philosophical system directly to the structural organization, navigation rules, interaction logic, and data relationships of an implemented immersive platform. This area should therefore be described as underdeveloped and insufficiently evaluated rather than entirely unexplored.

2.5. Positioning of the Present Study

The IDDA framework is positioned at the intersection of immersive visualization, multi-source geometric acquisition, semantic heritage information, and culturally grounded system design. Rather than treating philosophical values as proof of cultural correctness, the framework maps selected principles of Tri Hita Karana and Tri Mandala to implemented design features. These mappings affect spatial sequencing, navigation, user interaction, and representation of the relationship between the temple complex and its surrounding landscape. Desa Kala Patra is retained as a broader contextual consideration but is not presented as a fully implemented adaptive mechanism in the present prototype.

Table 1 compares the selected studies and standards using criteria appropriate to their respective purposes. Reviews are identified as literature syntheses, standards as methodological or semantic guidance, conceptual frameworks as architectural proposals, and implemented systems as empirical cases. This distinction avoids treating reviews, charters, ontologies, and operational prototypes as directly equivalent forms of evidence.

Table 1. Positioning of IDDA within immersive and culturally grounded digital-heritage research

Source	Study or contribution type	Primary integration scope	Treatment of cultural context	Evaluation or validation
Zhang et al. [1]	Bibliometric review	VR, AR, and MR research trends	Examined at the literature level	Bibliometric analysis; no implemented system
Cecotti [3]	Review of immersive VR	Virtual environments and heritage visualization	Cultural content represented within VR applications	Comparative review and conceptual assessment
Boboc [4]	Review of AR applications	Visual, spatial, and interactive AR components	Contextual information presented through AR	Literature synthesis; no single-site implementation
Hakimi [7]	Conceptual digital-twin framework	Geometric and sensor data	Cultural interpretation not addressed	Conceptual framework outside the heritage domain
London Charter [8]	Professional visualization principles	Evidence, documentation, transparency, sustainability, and access	Requires disclosure of interpretive foundations	Normative and methodological guidance
Seville Principles [9]	Virtual-archaeology principles	Scientific rigor, authenticity, interdisciplinarity, and efficiency	Requires responsible archaeological interpretation	Normative and methodological guidance
CIDOC CRM [10]	Semantic ontology	Cultural entities, events, actors, places, time, and relationships	Supports formal representation of cultural context	International semantic standard
Community and co-design	Participatory digital-	Local knowledge, narratives, values,	Cultural communities contribute to	Qualitative, participatory, or

studies [11], [12]	heritage research	and stakeholder participation	design and interpretation	case-based evaluation
IDDA (this study)	Implemented design-science framework	Geometric assets, semantic information, and culturally grounded feature mapping	Selected Tri Hita Karana and Tri Mandala principles mapped to system features	Black-box testing, SUS assessment, and internal target-achievement analysis at Pura Taman Ayun

As Table 1 indicates, established research and professional standards separately address immersive visualization, multi-source data integration, semantic interoperability, responsible reconstruction, and community participation. IDDA does not claim to replace these approaches. Instead, it combines selected elements within a single implemented design-science artifact and examines whether culturally grounded feature mappings can coexist with a technically optimized web-based heritage environment. The present case provides evidence of technical feasibility, functional operation, and perceived usability; it does not independently establish the cultural correctness of the philosophical interpretation or the framework's transferability to other heritage contexts.

3. Method

3.1. Research Methodology

This study adopted the Design Science Research Methodology (DSRM) developed by Peffers et al. [9]. The original methodology comprises six activities: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication. In the present study, these activities were organized into five reporting stages by combining demonstration and evaluation because both activities were conducted through the deployment and assessment of the same prototype. This adaptation retained the logic of the original DSRM while aligning the methodological presentation with the sequence of activities undertaken in the study. DSRM was selected because it provides a systematic process for designing, implementing, demonstrating, and evaluating information-system artifacts [9], [10].

The study began by identifying limitations in existing immersive cultural-heritage systems, particularly the fragmented integration of geometric assets, semantic information, and culturally grounded design principles. The second stage translated the identified problem into functional, usability, and performance objectives. The third stage involved development of the IDDA architecture, acquisition and processing of site data, optimization of the three-dimensional assets, and implementation of the web-based prototype. During the fourth stage, the artifact was demonstrated through the Pura Taman Ayun virtual-tour application and evaluated through black-box functional testing, the System Usability Scale (SUS), and an internal target-achievement analysis. The final stage involved communicating the framework, implementation process, findings, and limitations.

Only targets documented before the evaluation were used in the target-achievement analysis. These targets were: (1) successful operation of all seven functional modules, (2) a scene-loading time below 5 seconds under the specified testing conditions, and (3) a mean SUS score of at least 68. Polygon-count and file-size reductions are reported as measured optimization outcomes rather than as pre-established targets because the available planning documentation did not define fixed thresholds for these variables.

Table 2. Adapted DSRM stages, activities, and outputs

Stage	**Main activities**	**Output**
1. Problem identification and motivation	Review of literature indexed in IEEE Xplore and Scopus; identification of limitations in geometric, semantic, and culturally grounded heritage-data integration	Problem definition and research motivation
2. Definition of objectives	Specification of system requirements and pre-evaluation criteria: seven functional modules must	IDDA design objectives and evaluation targets

	pass testing, loading time must be below 5 seconds, and the mean SUS score must be at least 68	
3. Design and development	Framework architecture; TLS and UAV data acquisition; photogrammetric processing; semantic-content integration; asset optimization; WebGL prototype development	IDDA framework and virtual-tour prototype
4. Demonstration and evaluation	Deployment at the Pura Taman Ayun case site; black-box testing; SUS survey with 31 purposively recruited respondents; internal target-achievement analysis	Functional, usability, optimization, and target-achievement results
5. Communication	Documentation and interpretation of the framework, procedures, results, limitations, and implications	Present manuscript

3.2. Framework Architecture

The IDDA framework integrates three principal data layers: geometric, semantic, and culturally grounded design layers. The geometric layer contains the spatial and visual representations produced through terrestrial laser scanning and UAV photogrammetry. The semantic layer connects interactive locations and digital assets with descriptive text, audio, historical information, and other contextual records. The culturally grounded design layer maps selected Balinese philosophical principles to implemented spatial and interaction features.

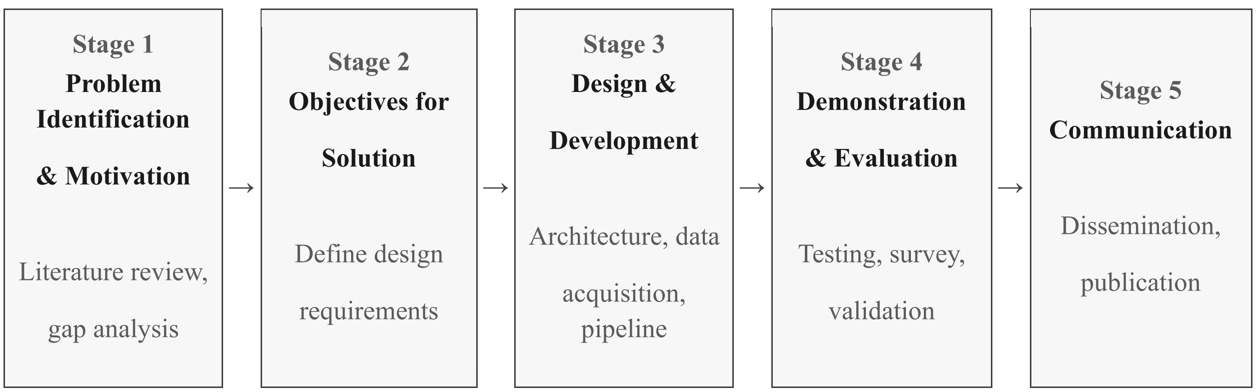

Figure 1. IDDA framework architecture

Tri Hita Karana provides the principal philosophical basis for the current implementation. Its three relational dimensions—Parahyangan, Pawongan, and Palemahan—were used to guide the mapping of system features. Parahyangan informed the hierarchical representation of sacred space, particularly through navigation structured according to Tri Mandala. Pawongan informed the emphasis on accessible interaction and communication of heritage information to users. Palemahan informed the representation of the relationship between the temple complex, its spatial setting, and the surrounding landscape. These mappings are treated as design alignments rather than as proof that the platform provides an authoritative or culturally validated interpretation of the philosophy.

Tri Mandala served as the most directly implemented spatial principle. The prototype organized navigation according to the hierarchical progression of the temple environment, enabling users to move through spatial zones in a sequence reflecting differing levels of sacredness. By contrast, Desa Kala Patra was retained as a broader interpretive principle concerning sensitivity to place, time, and circumstance. The present prototype did not implement automated adaptation of content or interaction according to temporal or situational conditions; therefore, Desa Kala Patra is not claimed as a fully operational system constraint. Tri Pramana was also excluded from the evaluated framework because the study did not implement or externally validate a formal epistemological content-validation procedure based on its three dimensions.

3.3. Data Acquisition and Processing Pipeline

The geometric data were acquired through terrestrial laser scanning (TLS) and unmanned aerial vehicle (UAV) photogrammetry. TLS was used to capture dense point-cloud data for architectural and spatial features at ground level, while UAV imagery provided aerial coverage and broader views of the temple complex. Structure from Motion (SfM) and Multi-View Stereo processing were used to reconstruct the photogrammetric model [13], [14].

The processing pipeline comprised six stages. First, raw TLS and UAV data were collected as the primary inputs. Second, preprocessing was undertaken to remove noise, filter unusable observations, and calibrate the image and point-cloud datasets. Third, the main processing stage included point-cloud registration and SfM/Multi-View Stereo reconstruction. Fourth, the TLS and UAV-derived data were integrated through georeferencing and spatial alignment. Fifth, three-dimensional meshes were generated, UV coordinates were prepared, and textures were projected onto the model surfaces. Finally, the processed assets were validated and exported for integration into the web-based application. Assets that did not satisfy the project’s geometric or visual inspection criteria were returned to an earlier processing stage for correction.

The complete SfM dataset comprised 1,590 aerial images and generated 873,217 tie points in Agisoft Metashape. These values refer to the photogrammetric processing of the Pura Taman Ayun site model rather than to a single isolated object. The resulting high-density model was optimized through polygon decimation, retopology, texture baking, and asset compression. The optimized assets were subsequently integrated into an HTML5/WebGL virtual-tour application accessible through the project website.

For reproducibility, the final manuscript should report the actual TLS instrument and settings, UAV and camera models, flight altitude, forward and side overlap, number and distribution of ground-control points, coordinate reference system, registration error, software versions, mesh-generation settings, decimation ratio, texture resolution, export format, and WebGL framework. These details must be taken from the project’s acquisition and processing records and should not be reconstructed retrospectively from assumptions.

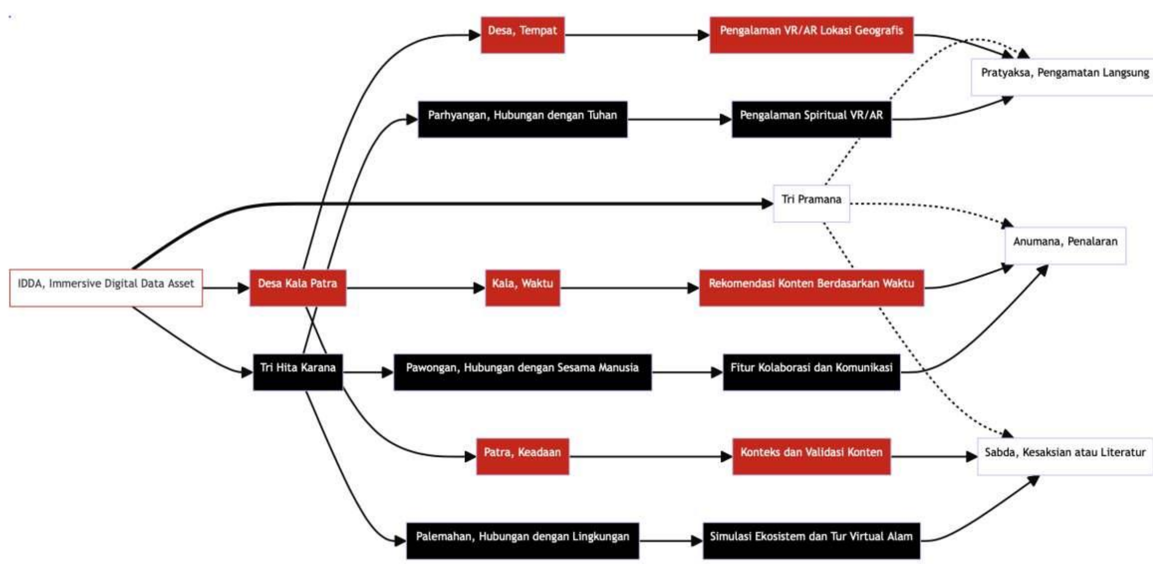

Figure 2. IDDA data acquisition and processing pipeline

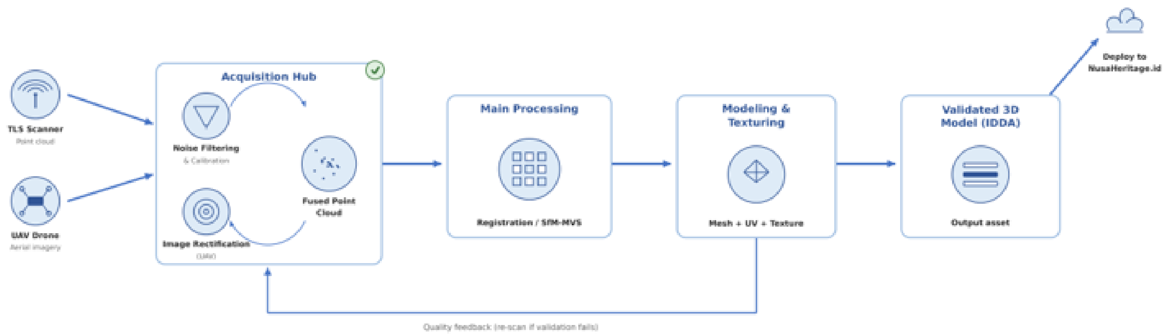

Figure 3. Structure from Motion processing of Pura Taman Ayun in Agisoft Metashape

3.4. Semantic Metadata Architecture

The semantic layer was designed to connect culturally and historically relevant information with specific three-dimensional assets and interaction points in the virtual environment. Each interactive record was associated with a unique identifier and linked to a defined location or object within the three-dimensional scene. The records contained the information required by the implemented interface, including the asset or location title, descriptive text, media type, media location, spatial reference, and the identifier of the corresponding interaction point. Text and audio resources were displayed through pop-up or multimedia components when users activated the relevant hotspot.

The current implementation should be described as an application-specific metadata structure unless the project documentation confirms formal compliance with CIDOC CRM, Dublin Core, or another recognized standard. Conceptual similarity to a heritage ontology does not establish standards compliance. Where mappings to CIDOC CRM are subsequently documented, the manuscript should distinguish between full implementation, partial alignment, and prospective interoperability.

Semantic records were maintained separately from the optimized three-dimensional geometry so that contextual information could be revised without rebuilding the underlying model. Links between metadata records and virtual-tour elements were managed through the unique identifiers assigned to objects and interaction points. This separation supported updates to text, audio, and other contextual resources while preserving the stability of the geometric assets.

Because no external cultural-authority validation procedure was conducted as part of the reported evaluation, the semantic information is described as project-curated content rather than culturally verified content. Accordingly, the functional-testing table evaluates whether the correct record and media are retrieved at the assigned interaction point; it does not evaluate whether the interpretation itself is culturally authoritative. The final manuscript should additionally identify the actual content authors, documentary sources, languages provided, internal checking process, version-control procedure, and persons authorized to update records.

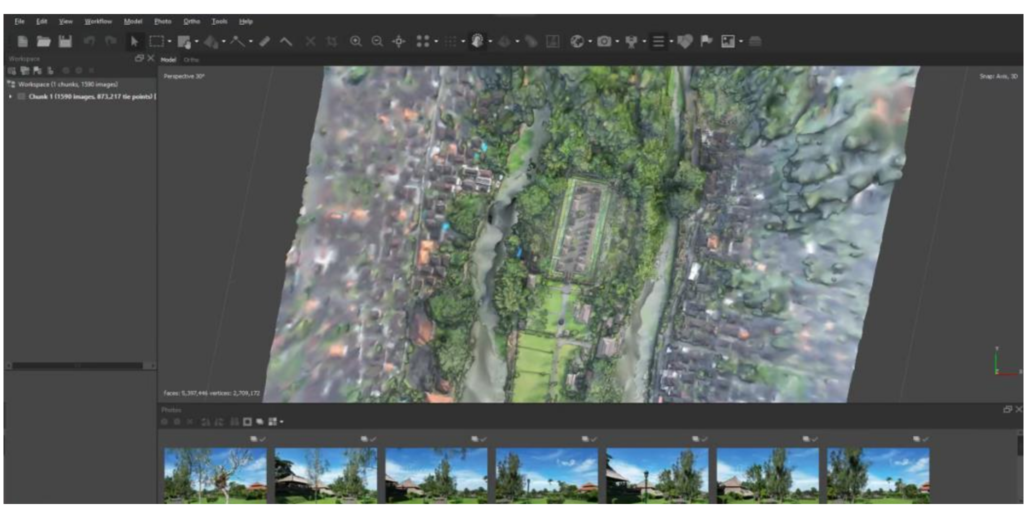

Figure 4. Structure from Motion processing of Pura Taman Ayun in Agisoft Metashape

3.5. Scope of Cultural Validation

The present study did not include a separate validation study involving temple authorities, Balinese Hindu scholars, traditional custodians, or other qualified cultural informants. Consequently, the study does not claim that the philosophical mappings or semantic interpretations were externally validated as culturally correct. The evaluation was limited to whether the designed features were implemented and operated as intended and whether the sampled users perceived the platform as usable.

The relationship between Tri Hita Karana, Tri Mandala, and the implemented features is therefore reported as preliminary design alignment. External cultural validation is identified as a necessary subsequent stage of the framework's development. Such validation should involve qualified cultural authorities, transparent informant-selection criteria, a structured walkthrough of the prototype, assessment of spatial and interpretive appropriateness, documentation of disagreements, and revision of the platform in response to expert feedback.

3.6. Evaluation Design

The evaluation combined three complementary approaches: black-box functional testing, SUS assessment, and internal target-achievement analysis. These methods addressed different aspects of the artifact and were not treated as interchangeable forms of validation. Black-box testing assessed whether the seven functional modules produced the specified observable outputs. The SUS assessed respondents' perceived usability of the implemented application. The target-achievement analysis compared the measured outcomes with the functional, performance, and usability criteria defined before evaluation.

Black-box testing was used to assess technical operation without examining the internal program code [11]. Each module was evaluated against an observable acceptance criterion. A module was classified as passing only when its actual output corresponded to the predefined expected output under the reported device, browser, network, and cache conditions. The final report should identify the testers, number of repetitions, desktop and mobile device models, operating systems, browser versions, network-measurement method, cache condition, and treatment of inconsistent trials.

Perceived usability was assessed using the ten-item SUS questionnaire [12]. SUS was selected because it provides a standardized measure of perceived system usability and has demonstrated strong psychometric performance across technology contexts [15]. Responses were scored using the standard procedure: one point was subtracted from responses to positively worded odd-numbered items, responses to negatively worded even-numbered items were subtracted from five, and the sum of the adjusted item scores was multiplied by 2.5 to produce a score ranging from 0 to 100. The criterion of 68 was used as a descriptive benchmark representing approximately average usability in established SUS research rather than as a universal pass–fail boundary.

Thirty-one respondents were recruited through purposive sampling after using the prototype. Eligibility required respondents to be able to operate a browser-based virtual tour and complete the questionnaire. Participation was voluntary. Because purposive recruitment may have produced a sample with greater interest in digital technology, cultural heritage, or the case site than the general population, the usability results are interpreted as within-sample evidence rather than as population estimates.

The final manuscript must provide a participant-characteristics table derived from the original survey or recruitment records. At minimum, it should report age range or age categories, gender, educational or professional background, prior experience with VR or virtual tours, familiarity with Pura Taman Ayun, and any academic, professional, or personal relationship with the research team. Categories for which no data were collected should be transparently identified as unrecorded rather than reconstructed after the study.

An ethics statement should report the actual institutional approval or exemption status, the consent process, voluntary participation, anonymity or confidentiality protections, data-storage arrangements, and access restrictions. If no formal institutional review was required, the manuscript should state the basis for the exemption and identify the responsible institution.

Table 3. Evaluation dimensions, instruments, and predefined criteria

Dimension	Evaluation focus	Instrument or procedure	Predefined criterion
Functional performance	Observable operation of the seven technical modules	Black-box testing	All seven modules satisfy their specified acceptance criteria
Loading performance	Time required to load the three-dimensional scene	Repeated timing under documented device, browser, network, and cache conditions	Loading time below 5 seconds
Perceived usability	Respondents' assessment of system usability	Ten-item System Usability Scale	Mean SUS score of at least 68
Target achievement	Consistency between planned criteria and measured outcomes	Internal specification comparison	No unmet criterion among the three documented Stage 2 targets

The target-achievement analysis is treated as an internal specification check rather than as independent external validation. Functional success does not establish cultural correctness, and a high SUS score does not demonstrate learning, cultural understanding, long-term engagement, or transferability to other heritage contexts.

4. Results

4.1. Functional validation

Black-box testing was conducted to determine whether the seven implemented modules produced their predefined observable outputs. Testing covered desktop and mobile access using Chrome version 120 or later and Android 12 or later under a nominal 10 Mbps network condition. Each module was evaluated against a functional acceptance criterion rather than against an assessment of cultural correctness. All seven modules satisfied their specified functional criteria, as summarized in Table 4.

Table 4. Black-box functional-testing results

No.	**Module**	**Acceptance criterion**	**Observed result**	**Status**
1	Asset loading	The three-dimensional scene loads within the predefined threshold of less than 5 seconds under the reported test condition	The optimized scene loaded in less than 5 seconds	Pass
2	Tri Mandala navigation	Movement follows the implemented hierarchical spatial sequence	The system enforced sequential transitions between the defined spatial zones	Pass
3	Drone view	The aerial scene displays the site panorama and geographic orientation	The 360-degree aerial view was displayed with north–south orientation	Pass
4	Semantic information system	Activating an interaction point retrieves its linked text and audio record	The assigned pop-up text and audio content were retrieved at the corresponding interaction points	Pass

5	Radar orientation	The position indicator updates in relation to user movement	The radar indicator updated during navigation and remained synchronized with the user position	Pass
6	Multimedia	Assigned audio and video resources play when activated	The linked multimedia resources were activated and played through the interface	Pass
7	Gyroscope input	The camera orientation responds to compatible device movement	The viewing direction changed in response to device tilt on the tested mobile platform	Pass

The results show that the geometric assets, navigation controls, interaction points, multimedia resources, orientation tools, and mobile-input functions operated together within the implemented WebGL environment. These findings establish functional integration of the prototype under the reported test conditions. They do not establish the cultural correctness of the semantic content or philosophical interpretation.

For complete reproducibility, the final manuscript should additionally report the number of repetitions, tester identity or role, desktop and mobile device models, browser builds, cache condition, network-measurement procedure, and any variation observed across trials. These values must be taken from the original testing records.

Figure 5. 3D drone view of Pura Taman Ayun from the virtual tour prototype

4.2. Optimization Performance

The optimization pipeline substantially reduced the computational size of the three-dimensional assets. Table 5 compares the digital model before and after polygon decimation, retopology, texture baking, and asset compression.

Table 5. Optimization impact on digital-asset performance

Parameter	Before optimization	After optimization	Observed change
Polygon count	Approximately 15 million	Approximately 500,000	96.67% reduction
File size	Approximately 2.5 GB	Approximately 85 MB	96.60% reduction

Loading time	More than 45 seconds	Less than 5 seconds	At least approximately 88.9% reduction

The polygon count was reduced by approximately a factor of 30, while the file size was reduced by approximately a factor of 29. Under the reported test condition, loading time decreased from more than 45 seconds to less than 5 seconds. Because the before-and-after values were recorded as boundary values rather than exact means, the loading-time change is reported as an approximate minimum reduction rather than as an exact percentage.

The reductions enabled the optimized site model to be delivered through a browser-based HTML5/WebGL application instead of requiring the original high-density asset to be loaded directly. This result demonstrates improved delivery efficiency under the tested conditions. However, no SSIM, PSNR, or equivalent visual-quality metric was collected; therefore, the study does not claim that visual fidelity was quantitatively preserved after decimation.

4.3. Usability Assessment

The System Usability Scale questionnaire was completed by 31 purposively recruited respondents after they had used the prototype. Standard SUS scoring was applied: one point was subtracted from responses to the positively worded odd-numbered items, responses to the negatively worded even-numbered items were subtracted from five, and the sum of the adjusted scores was multiplied by 2.5 to obtain a total score between 0 and 100. Table 6 summarizes the available total-score statistics.

Table 6. SUS total-score statistics (n = 31)

Statistic	Value
Mean	96.29
Standard deviation	4.12
Standard error	0.74
Minimum	87.50
Maximum	100.00
95% confidence interval for the mean	94.78–97.80

The mean SUS score of 96.29 was substantially above the descriptive benchmark of 68 commonly used to represent approximately average usability in established SUS research [15]. Under the Bangor et al. interpretation, the score corresponds to an excellent adjective rating and the upper grade range. The narrow confidence interval indicates that the respondents' total scores were concentrated near the upper end of the SUS scale.

The result provides strong within-sample evidence of perceived usability. Nevertheless, the exceptionally high mean requires cautious interpretation. The purposive sampling strategy may have produced respondents with greater interest in cultural heritage, digital technology, or the prototype than would be expected in a general user population. The score may also reflect respondent familiarity, a novelty effect, limited task complexity, or a ceiling effect. It should therefore not be interpreted as a population-level usability estimate.

A complete final report should include the mean and standard deviation for all ten SUS items, the total-score median and interquartile range, the number and percentage of respondents obtaining the maximum score, and a score-distribution figure or table. These statistics must be calculated from the original response dataset rather than reconstructed from the reported total-score summary. A participant-characteristics table should also report the available information on age, gender, background, prior VR or virtual-tour experience, familiarity with Pura Taman Ayun, and relationship to the research team.

4.4. Target-Achievement Analysis

The target-achievement analysis compared the observed outcomes with the three quantitative criteria documented during Stage 2 of the adapted DSRM process. Only criteria established before evaluation were included. The analysis is presented as an internal specification check rather than as an independent form of validation.

Table 7. Planned criteria and achieved outcomes

Stage 2 criterion	Planned value	Achieved outcome	Assessment source	Status
Scene-loading time	Less than 5 seconds	Less than 5 seconds under the reported test condition	Table 5	Met
Functional modules passing	7 of 7 modules	7 of 7 modules	Table 4	Met
Mean SUS score	At least 68	96.29	Table 6	Met

All three documented criteria were met. No additional target was added retrospectively for polygon count, file size, visual quality, or cultural correctness because the available manuscript does not establish that fixed thresholds for these outcomes were specified before evaluation. Accordingly, Table 7 verifies consistency between the implemented artifact and its predefined internal requirements but does not substitute for independent technical, cultural, or external-user validation.

4.5. Philosophical Design Alignment

The relationship between Tri Hita Karana and the implemented system was examined through feature mapping. This analysis identifies how selected philosophical principles informed system-design decisions; it does not establish that the interpretation was culturally authoritative or externally validated. Table 8 therefore presents operational design alignment rather than cultural-validity evidence.

Table 8. Mapping of Tri Hita Karana dimensions to implemented design features

Dimension	Design interpretation	Implemented feature	Available evidence
Parahyangan	Representation of hierarchical sacred space	Navigation structured according to the Tri Mandala sequence	The navigation sequence operated as specified in Module 2
Pawongan	Facilitation of user access to and interaction with heritage information	Cross-platform interface, interactive information points, and multimedia presentation	All interaction-related modules passed testing; the sampled users reported high perceived usability
Palemahan	Representation of the relationship between the temple complex and its spatial environment	Aerial site view, geographic orientation, and position radar	The drone-view and orientation modules operated as specified in Modules 3 and 5

Parahyangan received the most direct implementation through the hierarchical Tri Mandala navigation sequence. Pawongan was represented through the platform's support for interaction between users and curated heritage information rather than through usability alone. Palemahan was represented through the spatial and geographic presentation of the temple complex in relation to its surrounding landscape.

These mappings demonstrate that selected philosophical ideas influenced identifiable interface and spatial-design decisions. However, functional operation and high perceived usability do not confirm that the mappings are culturally correct. Because no external validation by temple authorities, Balinese Hindu scholars, or other qualified cultural informants was conducted, the findings are limited to preliminary philosophical design alignment. Desa Kala Patra and Tri Pramana are not included in the evaluated mapping because the current prototype does not provide equivalent implementation evidence for these concepts.

5. Discussion

This study developed and evaluated a web-based immersive heritage framework that combines multi-source geometric acquisition, semantic information, culturally grounded feature mapping, and performance-oriented asset optimization. The findings should be interpreted through three distinct contributions: the operational mapping of selected cultural principles to design features, the integration of heterogeneous heritage data, and the optimization of complex three-dimensional assets for browser-based delivery.

First, the study advances culturally grounded digital-heritage design by linking selected Tri Hita Karana principles to identifiable spatial and interaction features. Previous immersive-heritage research has frequently emphasized visualization, reconstruction, and experiential access [1], [3], [4]. The IDDA prototype extends this work by using Tri Mandala to structure navigation and by relating the dimensions of Tri Hita Karana to user interaction and site–landscape representation. The contribution is not evidence that the framework provides a definitive interpretation of Balinese philosophy. Rather, it demonstrates that selected locally situated principles can be translated into explicit design propositions and implemented within a functioning digital artifact.

This approach complements the London Charter and the Seville Principles, which emphasize transparency, interpretive documentation, scientific rigor, and responsible computer-based visualization [8], [9]. Whereas these principles primarily guide how digital reconstructions and their evidentiary foundations should be documented, the present study explores how local cultural concepts may also influence spatial sequencing, interaction logic, and information organization. The contribution therefore lies in preliminary cultural-design operationalization rather than in validated cultural authority.

Second, the framework integrates terrestrial laser-scanning data, UAV photogrammetry, semantic records, multimedia resources, and interaction points within a single browser-based environment. This integration addresses the fragmentation often observed between three-dimensional reconstruction and contextual interpretation. The functional results indicate that the geometric, semantic, geospatial, multimedia, and mobile-interaction components operated together under the reported test conditions. However, the evaluation confirms technical integration only; it does not determine the historical completeness, cultural authority, or educational effectiveness of the content [16].

Third, the optimization pipeline demonstrates the practical importance of reducing computational complexity for web-based heritage access. The polygon count and file size were reduced by more than 96%, while loading time decreased from more than 45 seconds to less than 5 seconds. These changes made the prototype more suitable for browser delivery and reduced dependence on specialist hardware. Nevertheless, the performance finding is conditional on the devices, browser, network, cache state, and measurement procedures used during testing. Moreover, because no quantitative visual-quality assessment was conducted, the study cannot determine the extent to which geometric or textural fidelity changed during optimization [17].

The high SUS score indicates that the sampled respondents perceived the prototype as highly usable. However, the result should not be treated as conclusive evidence of usability across broader populations. Purposive recruitment may have favored respondents who were technologically confident, culturally interested, familiar with the site, or connected to the research environment. The concentration of scores near the maximum also suggests a possible ceiling effect that could limit the instrument's ability to distinguish among positive user experiences. Independent replication with a larger and more diverse sample, detailed task-based usability metrics, and transparent respondent characteristics would provide a more robust assessment [18].

The present case demonstrates that the IDDA architecture can be implemented at Pura Taman Ayun and evaluated for functional operation, optimization performance, and perceived usability. It does not demonstrate that the same philosophical mapping, metadata structure, navigation logic, or optimization settings will be appropriate for other temples, heritage typologies, or cultural traditions. Accordingly, the framework should be described as designed for potential adaptation rather than as empirically transferable. Adaptation to another site would require renewed consultation, documentation, technical calibration, and cultural validation [19].

In practical terms, the framework may inform museums, heritage organizations, government agencies, and cultural institutions seeking to combine three-dimensional documentation with semantic and culturally contextual information. Its browser-based implementation may broaden access to complex heritage models. However, use in conservation, education, tourism, or public interpretation should be accompanied by transparent content governance, cultural-authority involvement, accessibility testing, and site-specific validation.

6. Limitations

Several limitations define the scope of the findings. First, the framework was instantiated and evaluated at a single heritage site. Its applicability to other heritage locations, building types, cultural systems, and user populations has therefore not been demonstrated. Any broader use would require site-specific adaptation and validation.

Second, the usability assessment relied on a purposively recruited sample of 31 respondents. The limited sample size, possible respondent familiarity with the technology or site, and potential relationship with the research environment may have contributed to the unusually high SUS result. The absence of a fully reported demographic profile also restricts assessment of sample diversity and selection bias.

Third, the study did not include external cultural validation by temple authorities, Balinese Hindu scholars, traditional custodians, or other qualified cultural informants. The mapping of Tri Hita Karana and Tri Mandala should therefore be understood as a preliminary design interpretation rather than as culturally validated representation. Desa Kala Patra and Tri Pramana were not evaluated as operational components because equivalent implementation evidence was unavailable.

Fourth, the black-box testing results depend on the devices, operating systems, browsers, network conditions, cache states, repetitions, and testing procedures used. The current evidence does not establish that the same performance would be obtained under slower networks, older devices, different browsers, or uncached first-time access.

Fifth, the optimization assessment reported polygon count, file size, and loading time but did not measure changes in geometric accuracy, texture quality, SSIM, PSNR, or user-perceived visual fidelity. It is therefore not possible to determine quantitatively whether the optimization process preserved all visually or culturally significant details.

Sixth, the evaluation focused on system functionality and perceived usability. It did not assess cultural understanding, knowledge retention, emotional engagement, learning outcomes, behavioral intention, accessibility for users with disabilities, or long-term use. It also did not compare Tri Mandala-constrained navigation with unrestricted navigation. Consequently, the study cannot determine whether the philosophical feature mapping improves cultural learning or interpretation.

Finally, the target-achievement analysis was based on criteria defined by the research team. It is useful as an internal specification check but does not provide independent validation of technical quality, cultural appropriateness, or generalizability.

7. Conclusion

This study developed and evaluated the Immersive Digital Data Asset framework as a web-based approach to culturally grounded digital-heritage representation at Pura Taman Ayun, Bali. The framework integrated geometric assets, semantic information, multimedia resources, and selected Tri Hita Karana-based design mappings within an immersive virtual-tour environment.

The prototype demonstrated technical feasibility under the reported evaluation conditions. All seven functional modules satisfied their specified acceptance criteria. The optimization pipeline reduced the polygon count from approximately 15 million to 500,000 and the file size from approximately 2.5 GB to 85 MB, while loading time decreased from more than 45 seconds to less than 5 seconds. The 31 purposively recruited respondents reported a mean SUS score of 96.29, indicating high perceived usability within the sampled group.

The study's conceptual contribution is the preliminary operational mapping of selected Tri Hita Karana and Tri Mandala principles to spatial organization, navigation, user interaction, and site–landscape representation. The implemented features were functionally evaluated, but their cultural interpretation was not externally validated. The findings therefore support claims concerning technical integration, optimization performance, functional operation, and within-sample usability, rather than claims of established cultural correctness or broad transferability.

Future research should involve qualified cultural authorities in validating the philosophical and semantic mappings, replicate the usability assessment with independently recruited and demographically diverse participants, test performance across multiple devices and network conditions, assess visual-quality changes after optimization, compare constrained and unrestricted navigation, and evaluate cultural learning and long-term engagement at additional heritage sites.

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Author contributions

Ida Bagus Ary Indra Iswara: conceptualization, methodology, investigation, writing (original draft, review and editing), supervision, project administration, funding acquisition. Ida Bagus Gede Sarasvananda: methodology, investigation, data curation, writing (original draft, review and editing), supervision. Putu Praba Santika: software development, validation, visualization. All authors have read and approved the final version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The virtual tour prototype is accessible at https://nusaheritage.id/.

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