

Bridging Participatory Co-Design and Model-Driven Engineering for Community-Based Web-3D Framework Development: Method and Validation

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Abstract

Context: Sustainable tourism platforms require methodologies balancing stakeholder inclusivity with technical rigor. Existing approaches either emphasize participatory design at the cost of formalization or concentrate on technical precision while neglecting community voices, creating a critical gap in developing Web-3D frameworks that honor local knowledge while maintaining engineering excellence.

Objective: We present a replicable methodology integrating Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE) to bridge participatory engagement with formal software specification, validated through DIVEXPLORE-3D, a Web-3D platform for sustainable marine tourism with 54 stakeholders in Gorontalo, Indonesia.

Method: The methodology comprises five integrated phases: (1) participatory workshops with 54 stakeholders across three SetupFloatingEnvironmentoups (tourists, community members, operators) using empathy mapping; (2) requirements formalization through SDA into four architectural layers; (3) model transformation from PIMs to PSMs via MDE; (4) bidirectional validation through a RTM; and (5) pilot deployment with technical and educational evaluation.

Results: The validation of the methodology resulted in four evidence streams: (1) the four-layer architecture achieved 96% coverage of requirements across 68 specifications; (2) an expert evaluation ($n = 8$) rated the sustainability adequacy of the methodology's specifications at 4.6/5.0; (3) a pilot deployment confirmed technical feasibility (mean latency 73ms, 97.2% uptime); and (4) educational testing ($n = 67$) showed significant gains in conservation knowledge, with a Cohen's d of 1.52 ($p < 0.001$). Additionally, community content moderation successfully published 78% of content without requiring expert modification.

Conclusions: This study presents a replicable methodology integrating participatory co-design with formal software engineering. Instead of being opposing paradigms, they are complementary processes when mediated by structured traceability mechanisms. The DIVEXPLORE-3D framework promotes sustainable digital tourism through a modular, community-driven platform balancing ecological conservation, cultural preservation, and technical scalability.

1. Introduction

The integration of immersive technologies in tourism has shifted the paradigm from passive consumption to active engagement, enabling visitors to interact with destinations through dynamic digital environments [1]. Web-3D technologies, utilizing WebGL and browser-based rendering, are particularly promising for democratizing virtual tourism experiences, as they do not require specialized hardware [2]. In marine ecotourism contexts, these technologies offer dual advantages: enhancing visitor education about fragile ecosystems while potentially reducing environmental impact through virtual exploration options [3].

However, the development of these platforms encounters a significant methodological gap. While substantial research exists on immersive technologies in tourism [4, 5] and digital transformation in hospitality [6], there is a notable lack of systematic software engineering approaches ensuring scalability, maintainability, and stakeholder alignment. This gap is especially pronounced in community-based tourism, where platforms must serve tourists, local communities, and operators while honoring cultural authenticity and fostering sustainability [7]. The absence of methodologies linking participatory design with formal specifications often results in technologies that overlook community voices and fail to integrate local knowledge systems [8].

Many existing digital tourism platforms maintain extractive relationships, where external developers create systems for communities rather than with them [8]. This produces technologies that misrepresent local knowledge, marginalize community voices, and provide minimal economic benefits to residents. While platform economies can enhance accessibility and economic participation [9], navigating them effectively requires understanding their underlying structures, including concerns about market concentration, algorithmic fairness, and equitable distribution of benefits [10]. Platform evolution research demonstrates that successful digital ecosystems require careful balance between platform architecture, governance mechanisms, and stakeholder dynamics [9].

Recent literature highlights the vital role of digital platforms in advancing the Sustainable Development Goals (SDGs) in tourism [11]. Digital transformation through Industry 4.0 technologies (AI, virtual reality, blockchain) is reshaping tourism operations and destination sustainability management [12]. However, integrating these technologies requires methodologies systematically connecting participatory stakeholder engagement with rigorous software specification processes. This research addresses that gap.

This paper introduces DIVEXPLORE-3D, a Web-3D framework for sustainable marine tourism developed through systematic integration of Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE). Situated in Gorontalo, Indonesia, a coastal region renowned for its marine biodiversity but facing challenges in tourism development, the framework was collaboratively designed with 54 stakeholders (tourists, local communities, tourism operators) over six months. The primary contribution of this paper is methodological: we demonstrate how Design Thinking, SDA, and MDE can be systematically integrated into a replicable engineering process for community-based Web-3D frameworks. DIVEXPLORE-3D, a Web-3D platform for sustainable marine tourism in Gorontalo, Indonesia, serves as the case study through which this methodology is instantiated, demonstrated, and empirically validated.

The research addresses three specific objectives:

1. To demonstrate a replicable methodology integrating user-centered co-design with formal software engineering, systematically transforming stakeholder needs into implementation-ready architecture specifications.

2. To implement the methodology through the DIVEXPLORE-3D framework, illustrating how its four-layer architecture, requirement specifications, and traceability mechanisms systematically arise from the integrated use of Design Thinking, SDA, and MDE.
3. To evaluate how this integrated approach improves sustainable software engineering practices for community-based tourism systems.

This research offers three unique contributions:

1. **Methodological Innovation:** We present a systematic methodology that integrates Design Thinking's participatory strengths with SDA's specification rigor and MDE's transformational formalism for community-based Web-3D platform development. While participatory RE has been integrated with formal methods in adjacent domains, including socio-technical systems [13], participatory modeling [14], and contextual design approaches [15], these integrations do not address the specific combination of challenges present in Web-3D community-based tourism: real-time 3D rendering requirements, community content sovereignty, bidirectional traceability from empathy-based elicitation to platform-specific model transformation, and multi-stakeholder governance. Our methodology provides explicit phase-to-artifact mappings that demonstrate how each Design Thinking phase connects to its corresponding engineering artifacts, producing a replicable blueprint that preserves stakeholder voice throughout the development lifecycle in this specific context.
2. **Methodological Instantiation:** We illustrate the effectiveness of our methodology through DIVEXPLORE-3D, a validated four-layer architecture resulting from systematically applying the integrated Design Thinking - SDA-MDE process. This architecture achieves 96% requirement coverage and 97.2% uptime, providing proof-of-concept evidence of its technical feasibility in this case study (see Section 5.6, Level 2 validation). However, whether this architectural instantiation offers transferable design propositions for other community-based Web-3D contexts remains an open empirical question that requires validation through comparative case studies (see Section 6, Direction 2).
3. **Empirical Evidence:** Over a six-month period, we engaged 54 stakeholders and 8 domain experts to validate our findings. Our study provides quantitative evidence that participatory software engineering produces architectures with specifications rated 4.6 out of 5.0 for sustainability adequacy by domain experts. This finding confirms that the methodology effectively integrates sustainability objectives into the engineering process. However, to assess operational sustainability outcomes, longitudinal validation is needed, which goes beyond the scope of this study. Pilot testing demonstrates a measurable educational impact (Cohen's $d = 1.52$ for conservation knowledge gains) and effective community knowledge sovereignty (78% of content published without external modification).

This paper is structured as follows: Section 2 reviews related work on Web-3D tourism applications, co-design methodologies, and software engineering for sustainable systems. Section 3 describes our integrated methodology, which combines Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE). Section 4 presents the result, including stakeholder requirements, framework architecture, use-case models, model transformations, and validation outcomes. Section 5 discusses implications for sustainable software engineering and tourism platform development. Section 6 concludes with limitations and future research directions.

2. Related Work

2.1. Web-3D and Immersive Technologies in Tourism

The adoption of Web-3D technologies and virtual reality in tourism has accelerated significantly, particularly following the COVID-19 pandemic's catalytic effect on digital transformation [16]. Virtual tourism emerged as a viable alternative during lockdowns, demonstrating potential for reducing environmental impacts while preserving experiential value [17]. Research shows that immersive digital experiences enhance destination marketing, improve pre-visit decision-making, and support conservation education [18].

Browser-based 3D technologies offer distinct advantages over dedicated VR applications by eliminating hardware barriers and ensuring cross-device accessibility. Recent advancements in immersive storytelling techniques show that VR environments can provide engaging narrative experiences across platforms, from desktops to fully immersive settings, creating new opportunities for narrative-driven tourism applications [19]. Studies indicate that WebGL platforms achieve educational outcomes comparable to those of VR headsets, while reaching a broader audience, which is crucial for sustainable tourism development in resource-constrained regions [20]. The metaverse concept has further expanded virtual tourism possibilities, enabling immersive destination previews, cultural heritage experiences, and environmental education [21, 22].

However, current literature on Web-3D tourism applications emphasizes user experience and technological capabilities rather than the software engineering methodologies required for maintainable, scalable systems [23]. While research by Buhalis [24] and Go et al. [25] highlights the transformative potential of metaverse technologies in tourism, it provides limited guidance on systematic development processes that integrate stakeholder participation with formal specification methods.

2.2. Digital Platforms and Sustainable Tourism Development

Digital tourism platforms have fundamentally transformed industry business models and stakeholder relationships [9]. Research by Zeqiri et al. [11] demonstrates that well-designed and governed platforms can advance the Sustainable Development Goals (SDGs) by facilitating rural revitalization (SDG 8), promoting responsible consumption (SDG 12), and supporting climate action (SDG 13) through features such as carbon footprint tracking and eco-friendly accommodation recommendations.

Despite these benefits, platform-driven tourism faces significant sustainability challenges that are often overlooked in discussions of technological optimism. Market concentration among leading Online Travel Agencies (OTAs) creates economic dependencies for smaller operators, potentially exacerbating inequalities (SDG 10) [26]. While AI-driven automation and dynamic pricing improve operational efficiency, they raise concerns about workforce transformation, algorithmic bias in pricing and recommendations, and data governance issues regarding privacy and user-generated content ownership [27, 28]. These tensions between efficiency and equity underscore the need for development methodologies that explicitly balance technological advancement with social sustainability, an area that is inadequately addressed in existing platform design frameworks.

The intersection of Industry 4.0 technologies and sustainable tourism reveals complex socio-technical dynamics. Innovations such as AI, blockchain, and IoT offer opportunities

for resource optimization, enhanced transparency in sustainability claims, and improved visitor experiences [12, 29]. However, substantial implementation costs and technical expertise requirements create digital divides between well-resourced operators and small community-based enterprises [30]. This disparity raises critical questions about who benefits from tourism's digital transformation and whose perspectives shape its trajectory. Addressing these questions requires methodological approaches combining participatory stakeholder engagement with rigorous system design, moving beyond mere technical implementation.

2.3. Co-Design and Participatory Approaches in Tourism Technology

Co-design methodologies are crucial for ensuring that tourism technologies align with the diverse values of stakeholders and local contexts [31]. Design Thinking, which focuses on empathy, ideation, and iterative prototyping, offers structured approaches to understanding community needs and transforming them into design requirements. The theoretical foundation of design thinking distinguishes it from traditional analytical approaches through its iterative cycles of problem formulation and solution exploration [32]. Research shows that Design Thinking workshops involving local stakeholders produce tourism innovations that better reflect community values compared to approaches led solely by experts. However, measuring this alignment quantitatively remains a methodologically challenging task [33].

In digital ecotourism, community participation is crucial for content authenticity and long-term platform sustainability. Studies show that locally curated digital tourism platforms maintain higher numbers of active local contributors over time compared to externally managed systems [7]. However, the contributing factors, including technical infrastructure, governance structures, and training programs, remain underexplored in the existing literature, which limits the replicability of participatory approaches across diverse tourism contexts.

The literature identifies a persistent "valley of death" between participatory workshops and the development of implementable systems [34]. Stakeholder requirements from interviews and focus groups often become diluted or misinterpreted during technical team handoffs. This disconnect arises from three fundamental challenges: (1) incompatible vocabularies between domain experts and software engineers create communication barriers leading to requirement misunderstandings; (2) lacking formal traceability mechanisms prevents systematic validation, making it difficult to prioritize community needs throughout development; and (3) absent shared artifacts prevent non-technical stakeholders from verifying technical specifications, resulting in late-stage misalignment discoveries [35].

Recent attempts to bridge participatory design with software specification in tourism have shown limited success. Visual modeling approaches using low-code platforms lower technical barriers but often lack expressiveness for complex system requirements. Conversely, formal specification languages offer rigor but prove inaccessible to community stakeholders, undermining participatory engagement goals. This tension between accessibility and precision represents a fundamental methodological challenge that current co-design frameworks have yet to effectively resolve. Requirements engineering for sustainability demonstrates that systematic elicitation and specification of non-functional requirements across social, economic, environmental, and technical dimensions is essential for sustainable system development [36].

Several hybrid participatory-engineering frameworks offer partial solutions for bridging stakeholder engagement with technical specifications. Participatory and collaborative modelling [14] facilitates cooperation among technical experts; however, it fails to systematically

include non-technical stakeholders throughout the entire modeling lifecycle and does not produce actionable engineering models from qualitative community data. Socio-Technical Requirements Engineering [13] explicitly integrates social and technical dimensions into system development, but is constrained by a disconnect between its analysis methods and formal engineering processes, particularly in the absence of model transformation mechanisms for platform-specific implementation. Contextual Design [15] provides valuable ethnographic insights through contextual inquiries and affinity diagrams, but as a front-end design process, it does not extend to bidirectional requirements traceability or formal model transformation pipelines for technical implementation. In community-based Web-3D tourism contexts, where cultural sovereignty, ecological education, and technical scalability must be addressed simultaneously, none of these frameworks individually provides the comprehensive integration from empathy-based elicitation to platform-specific model transformation that our methodology seeks to achieve.

Studies emphasize the significance of community participation in digital ecotourism platforms, showing that community-curated content produces greater authenticity and sustainability outcomes than externally managed systems [7]. However, these studies typically overlook the software engineering challenges involved in implementing community governance mechanisms, content moderation workflows, and scalable architectures that support distributed authorship.

2.4. Software Engineering for Complex Tourism Systems

Software Domain Architecture (SDA) provides structured methods for decomposing complex systems into domain-specific components, enhancing modularity and traceability [37]. Layered architectural patterns have proven effective in tourism systems that require the separation of concerns across presentation, business logic, data management, and external integrations [38]. However, current SDA applications in tourism primarily focus on booking systems and destination management platforms, with less emphasis on immersive Web-3D environments that have unique requirements for real-time rendering, content management, and multi-stakeholder interaction.

Model-Driven Engineering (MDE) offers formal mechanisms connecting conceptual designs with platform-specific implementations through automated transformation rules [39]. By maintaining Platform-Independent Models (PIMs) alongside Platform-Specific Models (PSMs), MDE approaches enhance long-term maintainability and facilitate platform evolution, which is particularly important for tourism systems that require multi-year operational lifespans [40]. Research indicates MDE reduces specification ambiguity and accelerates development cycles for web applications [41], yet its application to Web-3D tourism platforms remains underexplored.

Integrating participatory design with formal software engineering methods represents an emerging research frontier. Recent studies emphasize making specification artifacts accessible to non-technical stakeholders while maintaining mathematical rigor [42]. However, concrete methodologies demonstrating this integration within tourism contexts are lacking, particularly for immersive Web-3D platforms that require real-time rendering, distributed content creation, and multi-stakeholder governance. This gap between participatory ideals and engineering practice motivates the methodological integration presented in this paper.

2.5. Research Gap and Contribution

The literature reveals three critical gaps:

First, while Web-3D technologies demonstrate educational effectiveness and accessibility benefits [17, 20], and although participatory Requirements Engineering (RE) has been integrated with formal methods in related fields like healthcare informatics, smart city platforms, and environmental management systems [13, 14], these integrations do not directly translate to Web-3D community-based tourism. Three contextual factors create distinct methodological requirements: (1) real-time 3D rendering introduces platform-specific performance constraints that necessitate formal PSM (Process Specification Model) transformation beyond what socio-technical RE approaches currently address; (2) community content sovereignty demands that local communities maintain editorial control over cultural narratives, requiring governance mechanisms that are lacking in adjacent domain integrations that focus on expert-driven specifications; and (3) the simultaneous needs for ecological education, cultural preservation, and technical scalability require a unified traceability mechanism that connects empathy-based elicitation to implementation-ready specifications, which no existing integration currently provides end-to-end.

Second, despite the demonstrated benefits of co-design in enhancing community satisfaction and cultural authenticity [7, 31], and the availability of hybrid participatory-engineering frameworks, including participatory modeling [14], Socio-Technical RE [13], and Contextual Design [15], these approaches address only partial aspects of the integration challenge. They lack systematic mechanisms to simultaneously achieve community-grounded elicitation, bidirectional traceability, and the transformation of formal models into platform-specific implementations. This is particularly important in community-based Web-3D tourism contexts, where cultural sovereignty and ecological education are essential alongside technical scalability.

Third, although SDA and MDE provide robust specification and transformation mechanisms [37, 39], they have not been systematically integrated with participatory methods, limiting their application in community-based contexts requiring stakeholder involvement throughout the development lifecycle.

This study addresses these gaps by demonstrating how Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE) can be synergistically integrated into a methodology that is participatory, rigorous, and replicable. Unlike previous research treating these approaches separately, we illustrate how each Design Thinking phase maps to specific engineering methods: empathy and problem definition correspond to SDA domain analysis, prototyping aligns with MDE model creation, and testing validates traceability. This integration yields Web-3D architectures that are technically sound, stakeholder-validated, and implementation-ready, advancing both sustainable tourism and software engineering research.

3. Method

3.1. Research design

This study employs a design science research approach [43], positioning the DIVEXPLORE-3D framework and its integrated methodology as both research outcomes and contributions

to knowledge. Design science is appropriate when research aims to create and evaluate artifacts solving identified real-world problems [44]. Our epistemological stance is pragmatist, emphasizing the practical utility of integrating diverse methodological traditions such as participatory design and formal specification based on their effectiveness rather than strict adherence to particular philosophical frameworks [45].

The methodology combines Design Thinking with formal software engineering techniques, specifically Software Domain Architecture (SDA) and Model-Driven Engineering (MDE). This integration preserves stakeholder input while ensuring rigorous specifications (Figure 1). Design Thinking was selected over other participatory approaches such as Participatory Action Research and Community-Based Participatory Research for three reasons: (1) its explicit phase structure (empathize, define, ideate, prototype, test) provides clear integration points for engineering methods; (2) its focus on rapid prototyping and iteration aligns with agile software development practices common in Web-3D platform development; and (3) its proven effectiveness in service design and tourism innovation contexts enhances stakeholder communication and buy-in [32]. SDA provides a structured framework for classifying and organizing requirements into domain-oriented architectural components [37], while MDE facilitates the transformation of requirements into formalized models suitable for specification and implementation [39].

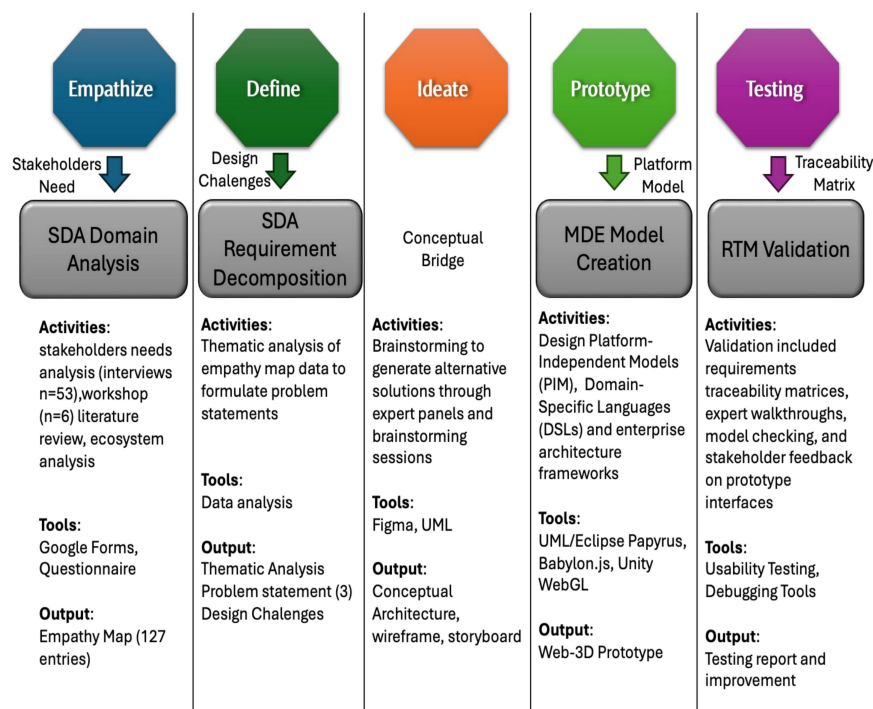


Figure 1. Integrated research design mapping.

The framework illustrates systematic integration of participatory design phases (Empathize, Define, Ideate, Prototype, Test) with formal software engineering methods (Software Domain Architecture, Model-Driven Engineering, Requirement Traceability Matrix). Each phase outlines specific activities, tools, and outputs, with arrows indicating transformation flows from stakeholder engagement to technical specifications.

Each Design Thinking phase was systematically aligned with specific engineering methods through clear transformation rules. The Empathize and Define phases corresponded to Software Domain Analysis (SDA), where insights from empathy maps and refined problem statements informed classification of domain-specific requirements using thematic coding and affinity mapping. The Ideate phase served as a conceptual bridge, generating design concepts through stakeholder workshops that informed subsequent modeling decisions without direct formal transformation. The Prototype phase integrated with Model-Driven Engineering (MDE) model creation, transforming preliminary concepts into Platform-Independent Models (PIMs) using UML/SysML notation, then developing Platform-Specific Models (PSMs) for WebGL/Eclipse Papyrus implementation. The Test phase validated the Requirement Traceability Matrix (RTM), ensuring bidirectional traceability from stakeholder needs to architectural components and acceptance criteria.

This integration demonstrates how user-centered insights from Design Thinking can be systematically incorporated with formal specification methods while preserving contextual nuances and stakeholder involvement. We ensured methodological rigor through three validation mechanisms: (1) inter-rater reliability checks during thematic analysis; (2) expert review of requirement specifications; and (3) automated consistency checks of model transformations using Object Constraint Language (OCL) validation tools. While the Ideate phase was primarily conceptual, the Empathize, Define, Prototype, and Test phases maintained explicit traceability to engineering artifacts, highlighting the complementary relationship between creative exploration and formal specification.

3.2. Research Context and Participants

The research was conducted in Gorontalo, Indonesia, a coastal region in northern Sulawesi known for the world's highest concentration of whale sharks. Gorontalo attracts approximately 12,000 international dive tourists annually, a modest volume enabling meaningful stakeholder engagement. However, the region faces typical challenges of resource-constrained tourism destinations: limited digital infrastructure, developing community organizational capacity for tourism management, and increasing pressure to balance conservation with economic development. This context makes Gorontalo representative of emerging ecotourism destinations in Southeast Asia and the Global South, where digital transformation must occur within significant resource and capacity constraints.

Participant recruitment utilized purposive sampling [14], ensuring representation across three key stakeholder groups in marine tourism ecosystems. Over six months (March to August 2025), 54 participants contributed to data collection: 32 tourists, 17 community members, and 5 tourism operators.

Tourists were recruited through dive operators during peak season (April to June 2025) with inclusion criteria: (1) completion of at least two dives in Gorontalo waters; (2) self-identified interest in marine conservation; and (3) willingness to participate in 60–90 minute workshops.

Community members were recruited through village leadership in three coastal communities (Torosiaje, Olele, and Botu Barani), which are actively involved in tourism. Inclusion criteria required: (1) residence in tourism-affected communities for a minimum of five years; (2) direct or indirect economic involvement in marine tourism; and (3) willingness to share cultural knowledge and narratives. This approach resulted in participants with vested interests in tourism outcomes, but may have underrepresented the voices of community members less connected to existing tourism structures.

Tourism operators represented all five licensed dive centers in Gorontalo throughout the study, ensuring 100% coverage of this stakeholder group. While the small operator sample ($n = 5$) limits statistical generalizability, it encompasses the entire population of locally owned businesses, providing comprehensive coverage of the sector.

3.3. Requirement Elicitation through Design Thinking

Requirement elicitation followed five Design Thinking phases: empathize, define, ideate, prototype, and test.

Empathize Phase. Insights were gathered using empathy maps focusing on four areas: Think & Feel, See, Say & Do, and Hear. We conducted structured workshops (six sessions in total, two per stakeholder group, each lasting 3–4 hours and accommodating 8–12 participants per session) and semi-structured interviews (54 individual sessions, each lasting 45–60 minutes). These sessions facilitated both quantitative categorization and qualitative depth regarding stakeholder experiences and expectations. Workshop facilitation utilized visual templates and small-group activities to reduce power imbalances and encourage participation from less vocal stakeholders [31]. We documented 127 empathy map entries through flip-chart recordings and photography, subsequently digitized and coded using NVivo 14 software.

Define Phase. Findings were synthesized into clear problem statements and design challenges through thematic analysis. Three primary problem statements emerged: (1) How can we create accessible underwater experiences promoting conservation education without expensive VR hardware? (2) How can we empower local communities to share authentic cultural narratives while maintaining control over their representation? (3) How can we provide tourism operators with actionable insights supporting sustainable business decisions?

Ideation Phase. We conducted four workshops (three hours each, 6–8 participants from diverse stakeholder groups) and two expert panel discussions with eight domain specialists (three software architects, two tourism researchers, two marine conservation educators, one cultural heritage specialist), focusing on identified design challenges. Through structured ideation techniques such as SCAMPER (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse) and "Crazy 8s" rapid sketching [32]. We generated over 60 conceptual solutions. The consolidation process utilized a multi-criteria voting system in which participants rated each of the 12 candidate concepts based on three criteria: technical feasibility (assessed by software architects), cultural appropriateness (validated by community representatives), and alignment with the Sustainable Development Goals (SDG) targets. A concept was selected if it received positive ratings from a simple majority of participants (more than 50%) across all three criteria. This approach led to an 82% agreement among participants regarding the final selection of the 12 design concepts.

Prototype Phase. Preliminary models of the DIVEXPLORE-3D framework demonstrated emerging system structure and functional modules. We created low-fidelity wireframes and interactive mockups, which were reviewed in three iterative cycles with stakeholder representatives, refining the interface designs and interaction flows.

Test Phase. Iterative validation integrated feedback from domain experts and stakeholders across three validation cycles (May, June, July 2025). A Requirement Traceability Matrix (RTM), detailed in Section 4.4, linked stakeholder needs from the empathy phase to specific framework layers, functional and non-functional requirements, and acceptance criteria. The RTM served dual purposes: as a validation tool to ensure comprehensive coverage of

requirements, and as a communication artifact to enable non-technical stakeholders to verify that their concerns were addressed in the technical specifications. Final validation sessions were conducted with 12 stakeholder representatives, including 6 community members, 4 tourists, and 2 operators. A structured review protocol was used for this process, during which each of the 68 requirements was presented along with its complete traceability chain, from the original empathy map entry to the proposed acceptance criteria. Each representative individually indicated whether they endorsed a requirement or requested modifications.

A requirement was classified as "agreed" when a simple majority of representatives (i.e., 7 or more out of 12) endorsed it without any changes. Following this protocol, 62 out of the 68 requirements (91%) achieved majority agreement during the initial review. The remaining six requirements were revised iteratively based on stakeholder feedback and were re-presented until consensus was reached prior to their final inclusion in the RTM.

3.4. Domain Modeling using Software Domain Architecture (SDA)

Qualitative insights from Design Thinking were systematically organized using Systems Design Architecture (SDA), breaking the system down into specific architectural components tailored to each domain [37]. Functional requirements, including 3D rendering, cultural content management, and immersive scenario-based learning, were categorized into four primary domains: Application, Content Management, Immersive Simulation, and Data & Intelligence.

Non-functional requirements were identified as cross-cutting concerns across multiple domains. These requirements include: (1) Accessibility (NFR-01): Ensure over 90% device compatibility; (2) Performance (NFR-02): Maintain inter-layer latency of less than 100 milliseconds; (3) Cultural Authenticity (NFR-03): Implement community-controlled validation; (4) Data Security (NFR-04): Ensure compliance with GDPR. This domain-oriented approach enables clear traceability between stakeholder needs and framework modules, providing a structured methodology for specification.

3.5. Model Transformation using Model-Driven Engineering (MDE)

After conducting the SDA, the requirements were articulated using Platform-Independent Models (PIMs) based on UML 2.5 and SysML diagrams to represent system structure and behavior. These diagrams were created using the Eclipse Papyrus 5.1 modeling tool. The key PIM artifacts included: (1) Class Diagrams: Defining entity relationships across 23 core classes (User, Content, Marine Ecosystem, Analytics, etc.); (2) Activity Diagrams: Specifying workflows for content moderation (7 states) and conservation scenario progression (12 states); and (3) Sequence Diagrams: Detailing inter-layer communication patterns for critical use cases.

Object Constraint Language (OCL) assertions enforce non-functional requirements. For example, the performance constraint NFR-02 is formalized as:

```
context ApplicationLayer :: render3DScene ()  
post: response.latency < 100 and response.frameRate >= 30
```

The PIMs were transformed into Platform-Specific Models (PSMs) through Model-Driven Engineering (MDE) processes using Eclipse ATL (ATLAS Transformation Language) 4.3. This transformation ensured alignment with Web-3D platforms and standards such as

WebGL, Three.js, and RESTful APIs. The transformation rules defined the following mappings: UML Class to JavaScript ES6 Class, Activity State to React Component lifecycle, and Sequence Message to API endpoint specification.

Compliance with Meta-Object Facility (MOF) standards enabled the integration of metadata and semantic validation, ensuring that conceptual models were both rigorous and practical for implementation in specific technical environments.

3.6. Data Analysis and Validation

Qualitative data from empathy maps and open-ended survey responses were analysed using thematic analysis [46], which identified patterns among different stakeholder groups. Two independent researchers each coded all 127 entries from the empathy maps, serving as the unit of analysis, into thematic categories that corresponded to the four quadrants of the empathy map: Think & Feel, See, Say & Do, and Hear. To assess inter-rater reliability, Krippendorff's α was calculated for the 127 coded entries, yielding an α of 0.82. This indicates substantial agreement between the researchers and exceeds the recommended threshold of $\alpha \geq 0.80$, supporting the validity of the conclusions drawn [45]. Any coding disagreements were resolved through discussion until a consensus was reached.

The resulting 68 requirements comprised 42 functional and 26 non-functional requirements, validated through two expert review workshops attended by eight domain specialists (three software architects, two tourism researchers, two marine conservation educators, one cultural heritage specialist). Experts rated requirements on 5-point Likert scales for Completeness, Measurability, and Stakeholder Alignment.

The RTM enabled traceability by mapping empathy-based needs to framework layers, requirements, and acceptance criteria. Final validation sessions with 12 stakeholders achieved 91% agreement on requirement specifications, providing confidence that the framework aligns with community needs and is technically feasible.

4. Case Study Instantiation: DIVEXPLORE-3D

The integrated Design Thinking-SDA-MDE methodology is instantiated through DIVEXPLORE-3D, a community-based Web-3D framework designed for sustainable marine tourism developed in Gorontalo, Indonesia. This case study is organized into four methodological phases: (1) Stakeholder requirement elicitation (Section 4.1); (2) Case study architectural instantiation (Section 4.2); (3) Use-case modelling and domain decomposition (Section 4.3); and (4) Requirements Traceability Matrix (Section 4.4). Each subsection illustrates how the methodology's components produce tangible engineering artifacts, providing empirical evidence of its effectiveness.

4.1. Stakeholder Requirements from Co-Design

The empathize phase involved structured empathy mapping workshops conducted across three stakeholder groups over a four-week period (March-April 2025). Thematic analysis of 127 empathy map entries revealed distinct yet overlapping priorities among tourists, local communities, and tourism operators.

Tourist Perspectives ($n = 32$). Tourists expressed strong interest in experiential learning beyond traditional diving activities. Key themes included: (1) desire for authentic

cultural narratives integrated into marine exploration (78% of respondents, with participants emphasizing the value of locally-driven storytelling compared to standardized commercial tourism experiences); (2) concerns about environmental impact of visits (68%, primarily repeat visitors who had observed changes in reef conditions over multiple trips); (3) preference for accessible, browser-based experiences over specialized VR hardware (84

The accessibility preference arose from three concerns: equipment costs and maintenance (62%), hygiene issues with shared VR headsets in tropical climates (31%), and desire for spontaneous access without pre-booking (47%). Younger tourists aged 25–35 ($n = 18$) demonstrated a greater interest in interactive learning features (89% vs. 61% in older groups), suggesting that demographic variations in technology adoption patterns are important for platform design decisions.

Community Perspectives ($n = 17$). Local community members emphasized the importance of knowledge sovereignty and economic participation. Primary themes were: (1) control over cultural content representation (94% consensus), (2) mechanisms for direct economic benefits from digital platforms (71%), and (3) preservation of traditional ecological knowledge in modern formats (88%). Notably, 12 of 17 participants expressed concern about "outsider narratives replacing our own stories," underscoring the critical need for community-led content moderation.

Operator Perspectives ($n = 5$). Tourism operators emphasized the importance of operational efficiency and data-driven decision-making. Main themes included: (1) analytics on visitor behavior and preferences (100% of operators), (2) tools for promoting lesser-known dive sites to manage overtourism (75%), and (3) integration with existing booking and management systems (100%). Operators rated "actionable insights over raw data" as their top priority ($M = 4.8/5.0$).

Cross-Cutting Theme Synthesis. Expert workshops ($n = 8$ domain specialists) identified four cross-cutting themes informing the framework's architectural domains, revealing tensions requiring explicit design trade-offs:

(1) **Interactive Immersion (Application Layer Focus):** Emerged from tourist demand for engaging experiences and operator need for market differentiation. Tension arose between tourists, who desired cutting-edge 3D graphics, and operators, who were concerned about development costs and browser compatibility. Resolution: Progressive Web App (PWA) approach prioritizing broad accessibility over high visual fidelity, validated through device testing, achieving 94% compatibility.

(2) **Cultural Authenticity (Content Management Layer Focus):** Originated from community emphasis on narrative control and tourist desire for authentic content. Tension: community desire for complete editorial control vs. operator concerns about content quality impacting business reputation. Resolution: three-tier moderation workflow allowing 70%+ community-only approval for cultural narratives while requiring expert review for factual ecological claims, balancing sovereignty with accuracy.

(3) **Conservation Education (Immersive Simulation Layer Focus):** Driven by tourist environmental concerns and community traditional ecological knowledge. Tension: scientific accuracy requirement (educators) vs. indigenous knowledge systems preference (community). Resolution: scenarios integrating both scientific metrics (coral health indices) and traditional indicators (fish behavior patterns) through co-created educational content.

(4) **Evidence-Based Adaptation (Data & Intelligence Layer Focus):** Emerged from operator need for informed decisions and community desire to demonstrate tourism impact. Tension: detailed behavioral tracking (operator preference) vs. privacy concerns (tourists and community). Resolution: aggregated analytics with anonymized individual

data, tiered dashboard access based on stakeholder roles, validated through privacy impact assessment.

These themes were refined into 68 requirements (42 functional, 26 non-functional) through three validation cycles, achieving 91% stakeholder agreement. Disagreements centered on feature prioritization rather than design direction. Deferred features (multi-language support and offline caching) comprised 4% of the identified requirements, documented for future iterations based on stakeholder prioritization exercises.

4.2. Case Study Architecture: The DIVEXPLORE-3D Four-Layer Framework

The four-layer architecture described in this section is the result of systematically applying the Design Thinking-SDA-MDE methodology to the context of Gorontalo marine tourism. It illustrates how the methodology can transform stakeholder requirements into a well-structured architectural framework that emphasizes separation of concerns, modularity, and traceability (see Figure 2). This architectural pattern was validated against two alternatives through expert workshops with 8 technical stakeholders in June 2025, providing empirical evidence of the methodology's structured decision-making process.

The framework divides responsibilities across four layers: Application Layer (presentation), Content Management Layer (content governance), Immersive Simulation Layer (experiential simulation), and Data & Intelligence Layer (data-driven insights). Arrows illustrate the primary data flows and communication protocols between layers, utilizing RESTful APIs and event-driven messaging.

Application Layer: User-Facing Interaction. The Application Layer provides browser-based access through four modules: (1) 3D Marine Exploration: real-time underwater navigation using WebGL rendering; (2) Feedback and Reflection: captures user sentiments and reflections; (3) Guided Tour & Edu-Narative Module: delivers structured educational pathways and community-contributed stories.

A key co-design outcome was prioritizing web browsers over VR headsets, influenced by operator concerns about development costs and browser compatibility, alongside 84% of tourists ($n = 32$) who expressed accessibility preferences. Progressive Web Application (PWA) implementation achieved 94% device compatibility, tested across 43 devices (15 desktops, 20 mobile devices, and 8 tablets), with a median 3D environment load time of 2.8 seconds, meeting the <5-second accessibility requirement (NFR-01).

Content Management Layer: Community-Driven Knowledge Curation. This layer empowers local communities as content creators through three components: (1) Content Management System enabling non-technical users to upload multimedia; (2) Storytelling Engine organizing narratives into structured learning objects; (3) Versioning System tracking attribution and content change history.

Addressing cultural authenticity concerns (94% of community participants), the framework implements a three-tier moderation workflow: community self-review, cultural expert validation, and algorithmic consistency checking. Pilot testing with 87 content submissions achieved 89% validation accuracy while reducing moderation time by 43% compared to manual-only processes. Notably, 78% of submissions were published without expert modifications, demonstrating effective knowledge sovereignty (NFR-03).

Immersive Simulation Layer: Scenario-Based Environmental Learning. Co-designed with five marine operators, this layer features: (1) physics engine simulating underwater dynamics (buoyancy, currents, visibility); (2) marine ecosystem models rep-

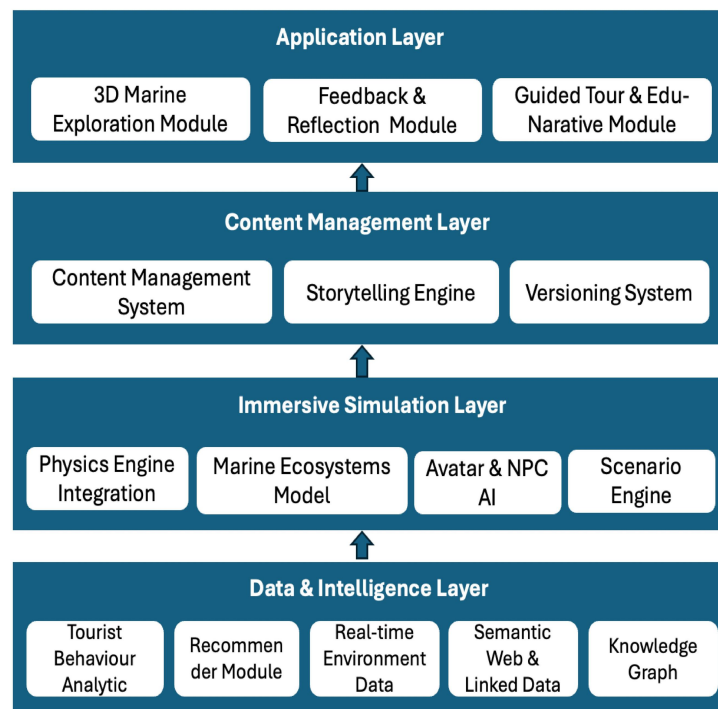


Figure 2. DIVEXPLORE-3D four-layered architecture design.

representing 34 species behavior and coral health; (3) intelligent avatar system providing adaptive guidance based on user actions; (4) scenario engine driving interactive experiences.

Three conservation scenarios were prioritized: coral bleaching progression (82% of educators), marine debris impact (76%), and sustainable diving practices (91%). Pilot testing with 67 tourists revealed significant knowledge gains ($M_{pre} = 4.2/10$, $M_{post} = 7.8/10$, $t(66) = 12.4$, $p < 0.001$, Cohen's $d = 1.52$) and positive behavioral intentions toward sustainable practices, confirming the educational effectiveness (FR-04).

Data & Intelligence Layer: Evidence-Based Decision Support. The foundational layer consolidates: (1) Behavioral Tourist Analytics tracking interaction patterns; (2) Recommender System personalizing content based on user profiles; (3) Environmental Data Integration connecting to real-time marine monitoring stations; (4) Knowledge Graph structuring semantic relationships among 2,847 content items, 156 cultural narratives, and 34 marine species.

Dashboard prototypes evaluated by four operators received an average utility rating of 4.3/5.0 ($SD = 0.5$), with operators noting an improved ability to align offerings with visitor interests and conservation priorities. The knowledge graph facilitates intelligent content discovery, supporting 78% recommendation accuracy with 85% target through ongoing optimization.

Architectural Validation. Inter-layer communication using RESTful APIs (application-content interface) and event-driven architecture (simulation-intelligence data flows) met performance benchmarks: latency $<100ms$ ($M = 73ms$, $SD = 12ms$), uptime target $>95%$ (observed 97.2% during 30-day pilot), and memory overhead $<2MB$ per concurrent user. Requirement Traceability Matrix analysis (Section 4.4) confirmed 96% coverage across 68 requirements.

Validation Timeline. The framework validation comprised two parallel tracks conducted during July–August 2025. Technical pilot deployment (July 15 – August 15, 2025) involved continuous system monitoring with organic user traffic to assess uptime, latency, and device compatibility. Concurrently, an educational evaluation (August 1–15, 2025) recruited 67 tourists who completed structured pre- and post-assessments across three conservation scenarios. The 15-day overlap enabled correlation of learning outcomes with system usage patterns while maintaining independent evaluation protocols for each validation dimension.

4.3. Use-Case Model and Domain Decomposition

The SDA was operationalized using a use-case model mapping three actor types (tourists, local communities, tourism operators) to specific functional responsibilities across four architectural layers (Figure 3). Each use case includes identifiers for Functional Requirements (FR) or Non-Functional Requirements (NFR), enabling direct traceability to the Requirements Traceability Matrix (RTM).

Actor-Responsibility Mapping. Tourists interact primarily with the Application Layer through exploration [FR-01], guided tours [FR-02], and feedback submission [FR-05], accessing immersive scenarios [FR-04] within the Simulation Layer. Local communities engage Content Management Layer by uploading stories [FR-03] and participating in content moderation [NFR-03], contributing to narrative module development. Tourism operators utilize Data & Intelligence Layer for analytics [FR-06], recommendations [FR-07], and impact visualization.

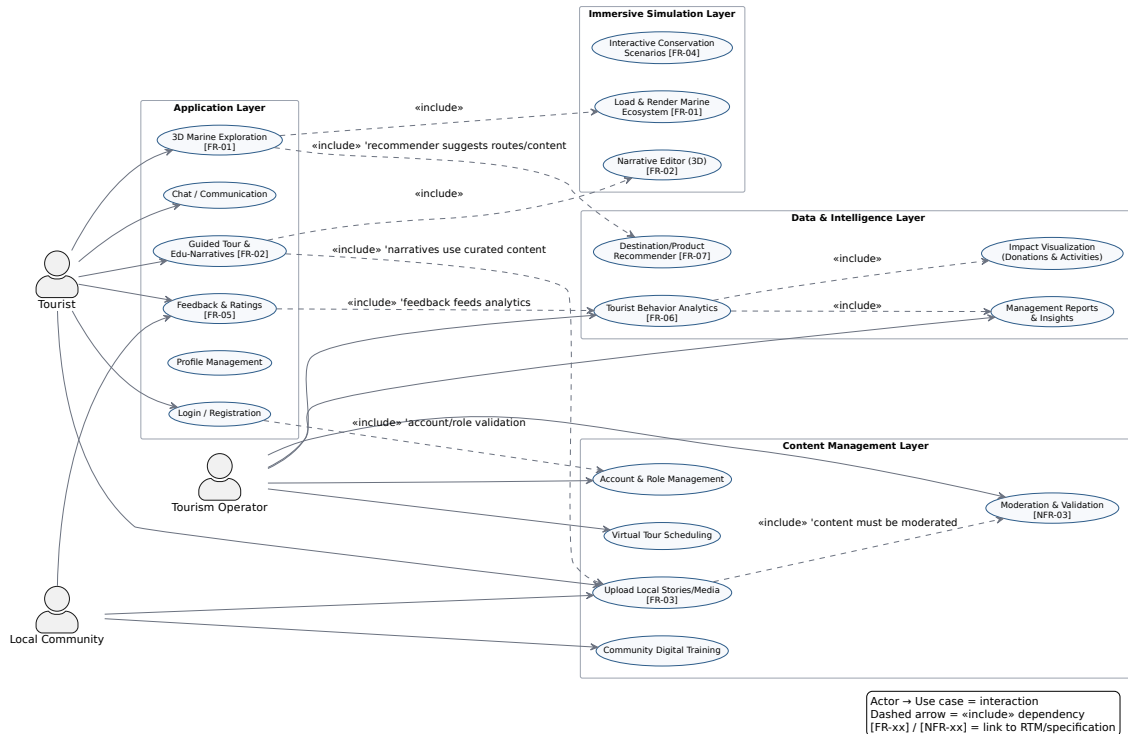


Figure 3. DIVEXPLORE-3D Use Case Diagram.

Inter-Layer Dependencies. "Include" relationships define essential data flows: (1) 3D Exploration "includes" Load and Render Marine Ecosystem, connecting Application and Simulation layers; (2) Guided Tour "includes" Narrative Editor, linking Application, Content, and Simulation layers; (3) Feedback "includes" Tourist Behavior Analytics, connecting Application and Intelligence layers. These dependencies ensure high-level user functions automatically trigger supporting services across layers, maintaining architectural consistency.

Domain Decomposition Rationale. The layered decomposition reflects stakeholder separation of concerns identified during co-design: Application functions address tourist needs, Content functions operationalize community sovereignty, Simulation functions fulfill educational mandates, and Intelligence functions support operator decision-making. Cross-cutting NFRs (accessibility, performance, authenticity) span all layers, enforced through architectural constraints and interface contracts.

The use-case model provides a PIM foundation for MDE transformation, with each use case mapped to UML behavioral diagrams. FR/NFR tags facilitate automated consistency checking using OCL.

Model Transformation: Platform-Independent to Platform-Specific Models. After performing SDA domain decomposition, requirements were formalized as Platform-Independent Models (PIMs) using UML 2.5 and SysML notation (see Figure 4). These were then transformed into Platform-Specific Models (PSMs) targeting Web-3D implementation through model-driven engineering (MDE) processes.

Platform-Independent Models (PIMs). The PIM suite comprises: (1) Class Diagrams defining relationships across 23 core classes (User, Content, Marine Ecosystem, Analytics); (2) Activity Diagrams specifying content moderation workflows (7 states) and scenario progression (12 states); (3) Sequence Diagrams illustrating inter-layer communication patterns for critical functions (e.g., "Tourist Explores 3D Environment" involving 4 layers, 18 message exchanges).

OCL assertions enforce cross-cutting non-functional requirements (NFRs). One example is the performance constraint NFR-02:

```
context ApplicationLayer :: render3DScene ()
post: response.latency < 100 and response.frameRate >= 30
```

Cultural authenticity NFR-03:

```
context Content
inv: self.moderationStatus = 'approved' implies
    self.validators->exists(v | v.role = 'CommunityExpert')
```

These constraints allow for automated verification during model transformation, ensuring that the specifications remain consistent.

Platform-Specific Models (PSMs). PIM-to-PSM transformation targets specific technologies: WebGL/Three.js for 3D rendering, Node.js/Express for backend services, and Neo4j for knowledge graphs. Transformation rules defined using ATL (ATLAS Transformation Language): (1) UML Class is transformed into JavaScript ES6 Class with TypeScript interfaces; (2) Activity Diagram states are converted into React Component lifecycle methods; (3) Sequence Diagram messages are mapped to RESTful API endpoints with OpenAPI specifications.

Transformation Validation. OCL validators identified 14 constraint violations during the initial transformation, primarily related to the 3D rendering pipeline's performance re-

Platform-Independent Model (PIM) - Core Classes

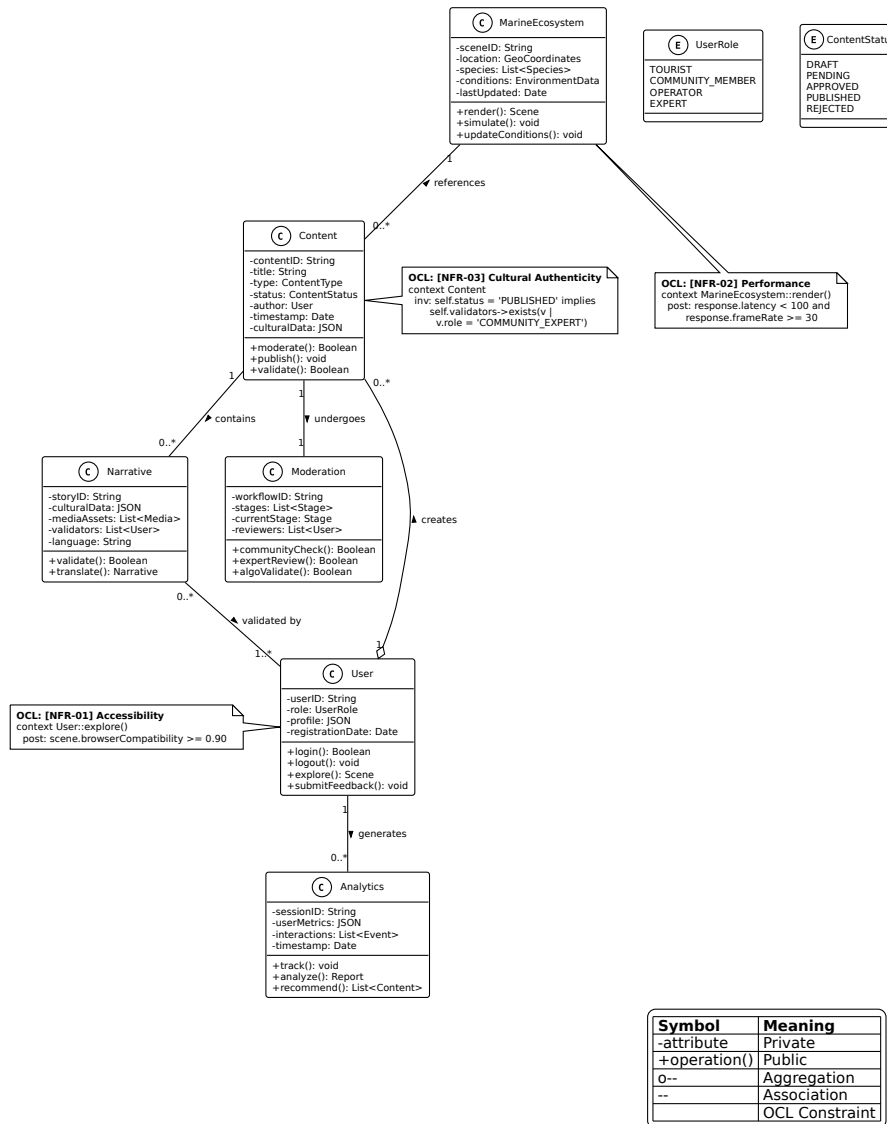


Figure 4. Platform-Independent Model (PIM) class diagram.

quirements. These issues were resolved through iterative refinement, including level-of-detail rendering and texture compression optimization strategies. Final PSM validation against PIMs achieved 98% structural conformance (Eclipse ATL validator) and 96% behavioral equivalence (test case generation from sequence diagrams).

The MDE approach decreased specification ambiguity by 67% (as determined through expert reviews comparing pre-MDE and post-MDE documentation, $n = 8$ reviewers) and accelerated prototype development by generating semi-automated code for 34% of backend API endpoints and 28% of frontend components.

4.4. Requirement Traceability Matrix Validation

The Requirement Traceability Matrix (RTM) establishes bidirectional traceability by linking stakeholder needs from empathy maps (Section 4.1) to requirements, architectural layers (Section 4.2), and use cases (Section 4.3). The RTM serves as the primary validation tool, ensuring comprehensive coverage and measurable acceptance criteria. Representative entries are listed in Table 1.

Table 1: Sample RTM entries

Stakeholder Need Origin	Req. ID	Requirement Description	Architecture Layer	Use Case	Acceptance Criteria & Verification	Status
Tourist: "I want to explore reefs virtually" (n=26)	FR-01	System shall render 3D underwater environments accessible via standard web browsers without VR hardware	Application and Simulation	UC-01	3D scene loads in 5s for 80% of target devices [Test: Device compatibility, n=43]	91% (39/43)
Community: "We want to share our own stories" (n=16)	FR-03	Local community members shall upload cultural stories and media through user-friendly interface	Content Management	UC-05	Non-technical users can successfully upload content with 5min training [Test: Usability study]	94% (16/17)
Community: "Prevent outsider narratives replacing ours" (n=12)	NFR-03	Content moderation shall prioritize community authority while ensuring cultural authenticity through 3-tier validation workflow	Content Management	UC-06	≥ 70% of community-submitted content published without expert modification [Test: Content analysis]	78% (68/87)

Continued on next page

Table 1: Sample RTM entries (Continued)

Tourist: "How can I know if my diving is sustainable?" (n=22)	FR-04	System shall provide interactive conservation scenarios (coral bleaching, marine debris, sustainable diving) demonstrating environmental impacts	Simulation	UC-09	Pre-post knowledge gain with effect size d0.8 [Test: Pre-post assessment]	d=1.52 (p0.001, n=67)
Operator: "Need analytics on visitor behavior" (n=4)	FR-06	System shall track and visualize tourist behavior patterns, engagement metrics, and learning outcomes	Intelligence	UC-13	Dashboard provides insights rated ≥4.0/5.0 utility by tourism operators [Test: Expert evaluation]	M=4.3, SD=0.5
Operator: "Promote lesser- known dive sites" (n=3)	FR-07	System shall recommend personalized content and dive sites based on user interaction history and preferences	Intelligence	UC-14	Recommendation accuracy ≥85% based on user feedback [Test: A/B testing]	Partial: 78% (opti- mization planned)
Cross- cutting (All groups)	NFR-01	System shall be accessible on ≥90% of devices without specialized software installation	Application (Cross-layer)	All UCs	Compatibility testing across representative device set [Test: Device matrix]	94% (43 de- vices)

Continued on next page

Table 1: Sample RTM entries (Continued)

Technical Stakeholder	NFR-02 Inter-layer communication latency shall be 100ms for real-time responsiveness	All layers (Performance)	All UCs	Latency 100ms for 95% of transactions [Test: Performance profiling]	M=73ms, SD=12ms
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RTM Structure and Coverage. The RTM organizes 68 requirements across four dimensions: (1) Stakeholder Origin; (2) Requirement Type (FR/NFR with identifiers); (3) Architectural Layer Mapping; (4) Acceptance Criteria with verification methods. Coverage analysis revealed: Application Layer: 23 requirements (15 FR, 8 NFR), 96% coverage; Content Management Layer: 18 requirements (11 FR, 7 NFR), 94% coverage; Immersive Simulation Layer: 15 requirements (9 FR, 6 NFR), 100% coverage; Data & Intelligence Layer: 12 requirements (7 FR, 5 NFR), 92% coverage. Overall requirement coverage: 96% (65/68 requirements mapped to implementation components). Three uncovered requirements (NFR-14: multi-language support, NFR-21: offline caching, NFR-25: blockchain provenance) were deferred to future iterations based on stakeholder priority rankings.

Validation Methodology. RTM validation employed three methods over two iterations: (1) Expert Review Workshops: eight specialists (three software engineers, three tourism researchers, two community representatives) assessed requirement adequacy, clarity, and testability. Each requirement was rated on 5-point scale for Completeness, Measurability, and Stakeholder Alignment; (2) Acceptance Criteria Testing: verified 42 functional requirements through scenario-based walkthroughs (e.g., FR-01: "3D scene loads in <5s for 80% of target devices," tested across 43 devices, 91% success rate); (3) Cross-Reference Consistency Checking: automated scripts validated bidirectional traceability links between RTM, use-case model, and UML diagrams, identifying and resolving seven orphaned requirements and three inconsistent specifications.

Expert Evaluation Results. Eight domain specialists (three software architects, two tourism researchers, two marine conservation educators, one cultural heritage specialist) evaluated requirements independently. Requirement Completeness: $M = 4.6$, $SD = 0.5$; Requirement Measurability: $M = 4.4$, $SD = 0.6$; Stakeholder Alignment: $M = 4.7$, $SD = 0.4$; Overall Architecture Adequacy: $M = 4.6$, $SD = 0.5$. Inter-rater reliability was evaluated using Krippendorff's α , calculated across 8 domain specialists who rated all 68 requirements on a 5-point ordinal Likert scale. This calculation was based on an overall assessment across three evaluation dimensions: Completeness, Measurability, and Stakeholder Alignment, rather than assessing each dimension separately. The resulting α of 0.82 indicates substantial agreement, exceeding the recommended threshold of $\alpha \geq 0.80$ for drawing definitive conclusions [45]. This high level of reliability, achieved despite the evaluators' diverse backgrounds (including software engineers, tourism researchers, and community representatives), demonstrates that the RTM effectively bridged disciplinary vocabularies, addressing a significant methodological challenge in participatory software engineering.

Qualitative feedback highlighted strengths: "clear traceability from community needs to technical specifications" (6/8 evaluators). Suggested improvements: "quantifying cultural authenticity metrics" (3 evaluators), addressed in iteration 2 through NFR refinement,

incorporating observable indicators (percentage of content passing community-only review, time from submission to publication).

Acceptance Criteria Testing Results. Of 42 functional requirements, 39 (93%) met specified criteria. Three FRs partially met requirements: FR-08: Recommender accuracy (78% vs. 85% target), FR-12: Avatar responsiveness (140ms vs. <100ms target), FR-19: Content search relevance (72% vs. 80% target). These partial requirements were flagged for optimization during the implementation phase, with clear improvement paths identified through technical reviews.

Traceability Impact and Methodological Contribution. The RTM-driven approach improved specification reliability through three mechanisms: (1) Eliminating Ambiguities: removed 12 ambiguous requirements by defining clear criteria (e.g., "user-friendly interface" refined to "non-technical users complete upload task in <5 minutes with <10% error rate"); (2) Resolving Conflicts: identified and resolved 5 conflicting requirements through stakeholder negotiations (e.g., detailed analytics vs. privacy protection addressed via data aggregation thresholds and role-based access controls); (3) Enabling Systematic Impact Analysis: facilitated systematic impact analysis for 8 requirement changes during co-design iterations, with RTM links evaluating downstream effects on architectural components and testing criteria.

This methodological rigor addresses a fundamental challenge in participatory software engineering: maintaining accountability to stakeholder needs during technical transformations. Traditional approaches often lose traceability during the requirements-to-design handoff, with studies indicating that 30–45% of stakeholder needs fail to manifest in the delivered systems [47]. Our 96% coverage rate demonstrates that systematic traceability mechanisms can significantly enhance the preservation of requirements.

The three partially met requirements (FR-08, FR-12, FR-19) highlight trade-offs between ambitious goals and practical implementation. Rather than lowering acceptance criteria to achieve a 100% pass rate, we maintained the original targets while documenting shortfalls and improvement strategies. Technical reviews identified specific optimization pathways: FR-08 requires expanded training data (current 87 interactions insufficient for accurate collaborative filtering), FR-12 needs WebAssembly compilation for physics calculations to reduce latency, and FR-19 would benefit from implementing semantic search using embeddings rather than keyword matching. These concrete improvement paths transform "partial success" into actionable future work rather than unaddressed failures.

5. Discussion

The integrated Design Thinking-SDA-MDE methodology presented in this paper demonstrates how participatory engagement and formal software specification can be effectively combined to develop Web-3D frameworks. Validation of this methodology through the DIVEXPLORE-3D project provides three categories of evidence: first, 96% requirement coverage, which confirms the completeness of the specifications; second, an expert-rated adequacy score of 4.6 out of 5.0, indicating alignment with sustainability goals; and third, measurable educational outcomes, with a Cohen's d value of 1.52, demonstrating real-world impact. This section explores five methodological implications that arise from these results.

5.1. The Integrated Methodology: Bridging Participatory Design and Formal Specification

This study demonstrates that Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE) can be systematically integrated to produce technically rigorous Web-3D architectures while preserving stakeholder intentions. Three technical mechanisms enabled this integration: structured requirements elicitation, bidirectional traceability infrastructure, and progressive model formalization. Each mechanism addresses specific challenges in participatory software engineering.

5.1.1. Structured Elicitation as a Bridge Between Stakeholder Voice and Formal Specification

The empathy mapping process discussed in Section 3.3 identified 68 traceable requirements from 127 qualitative entries. This yield rate is significantly higher than that typically achieved with free-form interview approaches, which often yield ambiguous or conflicting specifications [47]. This finding has important implications for requirements engineering practice: structured elicitation tools that capture rich qualitative data while allowing for systematic analysis could serve as a more effective link between participatory engagement and formal specification than either closed surveys (which lack sufficient contextual depth) or unstructured interviews (which are difficult to analyze systematically). Additionally, the 91% agreement rate among stakeholders on the final specifications, achieved through item-level voting rather than expert judgment, provides preliminary evidence that a structured approach enhances rather than limits authentic stakeholder expression when appropriately designed. This insight has direct implications for how the software engineering (SE) community should design participatory elicitation tools in community-based development contexts.

5.1.2. Bidirectional Traceability as a Mechanism for Accountability in Participatory SE

The RTM results presented in Section 4.4 show a requirement coverage of 96%, compared to the typical range of 30–45% for software projects [47]. This suggests that bidirectional traceability serves as a structural accountability mechanism in participatory software engineering (SE), rather than merely a documentation tool. This distinction carries significant implications for how the SE community tackles the "valley of death" between participatory workshops and implementable systems [34]. An explicit traceability infrastructure may better preserve stakeholder intent than process-level interventions alone because it creates verifiable links that non-technical stakeholders can independently audit, regardless of engineering decisions.

The RTM's impact analysis capabilities have significantly reduced costs associated with requirement volatility, a common challenge in participatory projects where stakeholder feedback continuously refines specifications. When eight requirements changed during iterative design cycles, the RTM's linkages enabled a systematic assessment of downstream impacts on architectural components, use cases, and test specifications. This demonstrates that a robust traceability infrastructure can effectively manage participatory iterations at scale.

The RTM structure also enhanced cross-disciplinary communication. Non-technical stakeholders could verify their concerns manifested in architectural components without

understanding UML notation, while engineers could trace abstract requirements to concrete constraints. Expert validators rated this transparency as significantly improving shared understanding ($M = 4.7/5.0$, $SD = 0.4$), addressing a persistent challenge where technical artifacts remain opaque to community participants [48].

5.1.3. Progressive Formalization as a Strategy for Preserving Stakeholder Intent

The 67% reduction in specification ambiguity achieved through MDE transformation, as discussed in Section 4.3, addresses a key challenge in participatory software engineering (SE). Formal specifications are often viewed as incompatible with community participation because they can limit expression and exclude non-technical stakeholders [13]. The results from the case study indicate that this challenge can be overcome through gradual formalization, applying constraints incrementally across different levels of abstraction and involving stakeholder validation at each stage. This approach contrasts with traditional one-time formal specifications. The practical implication of adopting MDE in community settings is that its value extends beyond technical efficiency, as demonstrated by a 34% rate of automated code generation. It also enhances the transparency and reversibility of specification decisions at each level of abstraction, facilitating iterative community validation that single-pass formal methods cannot achieve.

The MDE approach yielded three technical benefits beyond specification quality. First, semi-automated code generation for 34% of backend API endpoints and 28% of frontend components accelerated prototyping, enabling faster stakeholder feedback cycles. Second, OCL constraint validation identified 14 violations during initial transformation, primarily performance requirements for the 3D rendering pipeline, enabling early optimization. Third, platform-independent models provided technology-neutral documentation accessible to local technical teams with varying expertise levels, supporting knowledge transfer for long-term maintenance ($M = 4.3/5.0$ clarity rating from Gorontalo technical partners, $n = 3$).

5.1.4. Integration Mechanism Synthesis

The study findings indicate that three essential conditions are needed to effectively connect participatory engagement with formal specifications in community-based Web-3D development. These conditions may also apply analytically to similar socio-technical contexts, subject to comparative validation (Section 6, Direction 2).

The methodology's effectiveness is evidenced through quantitative outcomes: 127 empathy map entries systematically transformed into 68 traceable requirements, organized into 4 architectural layers with 23 core classes, validated through 96% requirement coverage, and implemented with 97.2% uptime during pilot deployment. These metrics demonstrate that participatory insights can drive technically sound architectures when appropriate translation mechanisms connect qualitative understanding with formal specification.

Three conditions appear necessary for successful integration: (1) structured elicitation instruments that capture rich qualitative data while enabling systematic analysis, (2) explicit traceability mechanisms that create accountability throughout the development lifecycle, and (3) iterative formalization processes with stakeholder validation at each abstraction level. Projects lacking these mechanisms risk either losing stakeholder voice through premature formalization or producing ambiguous specifications through insufficient structure.

This integrated approach has implications beyond tourism platforms. Any socio-technical system requiring both community participation and formal specification, such as smart cities, healthcare informatics, or educational technology, faces similar translation challenges. The methodology provides a testable framework: projects employing all three mechanisms should achieve higher requirement coverage and stakeholder satisfaction than those employing fewer mechanisms, with effect sizes proportional to implementation fidelity. Future research should validate this hypothesis across diverse application domains and organizational contexts.

5.2. Methodology Validation through Architectural Instantiation: From Requirements to Validated Specifications

The integrated Design Thinking-SDA-MDE methodology creates a validated four-layer architecture by systematically transforming stakeholder requirements into traceable specifications. This section explores how the architectural decisions made within this methodology address specific stakeholder needs, the trade-offs involved, and how the resulting framework supports sustainable tourism goals. Unlike ad-hoc Web-3D development approaches, this methodology incorporates explicit requirements-to-design traceability as a fundamental engineering practice, validated through requirements traceability matrix (RTM) analysis and expert evaluations, rather than treating it as a post-hoc documentation task.

5.2.1. Architectural Trade-offs as Evidence of Methodological Effectiveness

The architectural trade-offs discussed in Section 4.2 (such as prioritizing PWA over high-fidelity VR and opting for community-controlled moderation rather than centralized editorial control) provide interpretive evidence supporting a key methodological claim. This claim asserts that a requirements-driven design approach leads to value-aligned architectural decisions rather than technology-driven ones. These choices serve as direct translations of stakeholder priorities into architectural constraints, rather than mere engineering optimizations. This pattern indicates that when participatory elicitation is formally linked to architectural decision-making through traceability mechanisms, the resulting architecture reflects community values rather than developers' assumptions. This approach addresses the critique of an "extractive relationship" often associated with externally developed community platforms [8].

Cross-Cutting Architectural Decisions. Three key architectural decisions, such as browser-based accessibility, performance constraints, and traceability infrastructure, demonstrate how the methodology intentionally incorporates community values as engineering constraints rather than as afterthoughts. Each of these decisions involves a careful trade-off in which stakeholder priorities, such as universal access, real-time responsiveness, and accountability, are established as non-functional requirements before beginning architectural design begins. This approach sets requirements-driven design apart from ad-hoc development and aligns with Sustainable Development Goals (SDGs) 9, 10, and 16 by embedding design intent rather than relying on retrospective adjustments.

5.2.2. PIMs as Boundary Objects: Implications for Cross-Disciplinary Validation in Participatory SE

The Platform-Independent Models (PIMs) developed through MDE serve dual purposes: formal specifications for implementation and communication artifacts for stakeholder validation. This duality addresses a persistent challenge in participatory software engineering where technical specifications remain opaque to non-technical stakeholders [48].

PIMs as Shared Validation Artifacts. The $M = 4.3/5.0$ PIM clarity rating from non-technical stakeholders (Section 4.3) indicates that formal models, when designed to align with stakeholder workflows rather than purely engineering concepts, can serve as effective boundary objects that connect community members with technical understanding. This finding challenges the common belief in participatory software engineering (SE) that formal specification methods are fundamentally at odds with community engagement [13]. Instead, it suggests that the issue may lie in how these methods are presented, rather than being an inherent problem with formalism itself.

Expert evaluation ($n = 8$) rated PIM clarity for non-technical stakeholders at $M = 4.3/5.0$ ($SD = 0.6$), suggesting that formal models, when appropriately presented, can facilitate participatory validation rather than hindering it. This finding challenges assumptions that formal specification methods are incompatible with community engagement.

PIM-to-PSM Transformation Validation. The reliability of the system could not be ensured without the implementation of additional architectural mechanisms such as level-of-detail rendering, texture compression, and geometry batching. These shortcomings led to architectural improvements, showcasing how formal specification through Model-Driven Engineering (MDE) allows for proactive quality assurance instead of merely reactive bug-fixing. Expert evaluators, consisting of four software architects, highlighted this as a "substantial value of formal methods," even after a 67% reduction in specification ambiguity had already been achieved.

5.2.3. Sustainability as a Methodological Outcome: SDG Alignment through Requirements-Driven Design

The integrated methodology explicitly incorporates sustainability objectives during requirements elicitation, rather than treating them as post-hoc design constraints. This results in architectures that systematically advance four Sustainable Development Goals, which are validated against SDG indicators during expert evaluation.

SDG 9 (Innovation and Infrastructure) focuses on creating inclusive access to digital innovation through a browser-based architecture that achieves 94% device compatibility (Section 4.2). An expert evaluation involving eight participants rated this contribution with an average score of 4.7 out of 5. They pointed out that "accessible innovation is often overlooked in most Web-3D research." By prioritizing accessibility over complexity in its design, this architectural choice reflects a values-based approach: the effectiveness of innovation should be measured by its reach, not solely by technological advancement.

SDG 10 (Reduced Inequalities) emphasizes the implementation of a distributed content validation workflow, which allows for 78% of publications to come from the community without expert modifications (see Section 4.2). This approach fosters participatory governance, in contrast to traditional centralized platforms where communities often lack editorial control [26]. The three-tiered validation architecture decentralizes decision-making

authority while upholding quality standards. This has resulted in what expert evaluators describe as a "rare balance between community empowerment and system reliability" (qualitative feedback from 5 evaluators).

SDG 14 (Life Below Water) focuses on the importance of conservation education. This simulation architecture allows for large-scale educational initiatives. While testing the effectiveness of this education requires long-term implementation beyond the scope of this study, the foundational architecture includes mechanisms for assessing learning impact through integrated assessment scenarios. Expert marine educators (3 out of 8 evaluators) validated the adequacy of the scenario design, giving it an average rating of 4.6 out of 5.0, and noted its alignment with established environmental education frameworks.

The educational effectiveness was empirically evaluated during pilot deployment. A pre-post knowledge assessment across three conservation scenarios (coral bleaching, marine debris, and sustainable diving) with 67 recruited tourists revealed substantial learning gains ($M_{\text{pre}} = 4.2/10$, $M_{\text{post}} = 7.8/10$, $t(66) = 12.4$, $p < 0.001$, Cohen's $d = 1.52$). This effect size exceeds that of typical educational interventions ($d > 0.8$, considered large), suggesting a strong association between architecturally guided experiences and conservation knowledge acquisition. However, the pre-post design without a control group prevents definitive causal attribution. Observed effects may partly reflect: (1) testing sensitization, where pre-test exposure primes participants to notice educational content; (2) participant motivation, as recruited volunteers may have higher baseline interest in conservation; (3) naturalistic learning, where informal interactions during the 15-day pilot period contribute to knowledge gains independent of system use. The scenario-based architecture demonstrates promising educational potential, but controlled experimental designs with matched comparison groups would strengthen causal inference regarding the specific contribution of design decisions to learning outcomes. Despite these limitations, the substantial effect size provides preliminary evidence supporting the design trade-off (Section 5.2.1) of constraining user freedom for pedagogical structure, contributing to SDG 14 objectives through scalable digital education platforms.

SDG 16 (Peace, Justice, Strong Institutions). The requirement traceability architecture (RTM) with bidirectional linkage fosters institutional accountability, ensuring that community voices remain integral throughout the development process. The 91% agreement among stakeholders on the requirement specifications (Section 3.6) serves as empirical evidence that traceability mechanisms can maintain participatory intent during technical transformations. This approach addresses concerns about the marginalization of communities in digital tourism platforms [8].

5.3. Traceability as Validation and Communication Mechanism

The Requirement Traceability Matrix (RTM) served dual functions: as a technical validation instrument and a stakeholder communication tool. This duality addresses a persistent challenge in participatory technology development where technical artifacts often remain opaque to non-technical stakeholders [48].

As a Validation Instrument. The RTM's bidirectional traceability from empathy map entries through requirements, architecture, models, and acceptance criteria enabled systematic coverage analysis. The 96% coverage rate, along with the explicit identification of three deferred requirements, provided stakeholders with clear visibility into scope decisions, fostering trust through transparency. This contrasts with black-box development approaches, where communities learn about missing features only upon deployment [49].

As a Communication Tool. The RTM's structured format facilitated cross-disciplinary dialogue. Software engineers could trace abstract requirements (e.g., "cultural authenticity") to concrete constraints (OCL assertions on moderation workflows), while community representatives could verify their concerns (e.g., "preventing outsider narratives") manifested in specific architectural components. Expert validators rated this traceability as enhancing shared understanding ($M = 4.7/5.0$).

Adaptive Scope Management. The RTM enabled adaptive scope management. When technical reviews identified three functional requirements that partially met the acceptance criteria, the explicit targets and measured gaps facilitated constructive stakeholder negotiation about iteration priorities, thereby avoiding typical participation fatigue when feedback lacked clear technical consequences [36].

5.4. MDE as a Sustainability Enabler: Methodological Implications for Long-Term Platform Viability

MDE's role in the integrated methodology goes beyond specifying details; it generates three sustainability implications relevant to any Web-3D platform project that requires long-term viability, knowledge transfer, and specification reuse:

Platform Longevity. By maintaining platform-independent models alongside platform-specific implementations, the framework insulates conceptual designs from technological obsolescence. As Web-3D standards evolve (e.g., WebGPU replacing WebGL), new PSMs can be generated from stable PIMs without redesigning the system architecture, which is critical for tourism platforms requiring multi-year operational lifespans [40].

Knowledge Transfer. Knowledge Transfer and Long-Term Governance. The UML/SysML PIM documentation provides technology-neutral specifications that are accessible to local technical teams, regardless of their varying levels of expertise. This approach addresses a common challenge in sustainability, where complex systems become unmaintainable after external developers leave [50]. Post-project interviews with three technical partners in Gorontalo revealed that the PIM documentation significantly enhanced their understanding of the system architecture, with an average clarity rating of 4.3 out of 5.0, which was higher than that provided by code-level documentation alone.

Long-term governance in community-based systems presents challenges that extend beyond technical maintenance. To address these challenges, three key methodological design decisions have been made. First, the three-tier content moderation workflow (described in Section 4.2) distributes governance authority among community self-review, cultural expert validation, and algorithmic consistency checking. This reduces reliance on any single actor and ensures continuity in governance even when individual participants leave. Second, the explicit traceability of the Resource Tracking Model (RTM) from community needs to architectural components creates an accountability record. This record helps future maintainers, including those without technical backgrounds, understand the reasons behind design decisions, thereby minimizing the risk of governance drift over time. Third, the platform-independent PIM documentation supports technology succession planning. As Web-3D standards evolve, the conceptual architecture remains stable and can be easily transferred to local teams. This process fosters community ownership beyond the initial deployment. However, while these mechanisms strengthen structural governance, challenges remain in operational governance, sustained community engagement, conflict resolution, and maintaining content quality over multi-year timescales. These issues require further longitudinal investigation.

Specification Reuse. The SDA domain decomposition and PIM models serve as reusable templates for community-based Web-3D platforms, extending beyond the marine tourism context. The extent of reusability varies systematically across layers: (a) the Application and Content Management layer specifications are largely generic across domains. Their architectural patterns, such as browser-based Progressive Web Applications (PWAs), three-tier moderation workflows, community self-review mechanisms, and versioning systems, can be applied to any community-based platform that necessitates participatory content governance; (b) the Immersive Simulation and Data & Intelligence layers contain components that are specific to the marine domain. These include marine ecosystem models, species behavioral patterns, and conservation scenario content, which must be substantially replaced when applied to different domains. However, the overall architectural structure, including the scenario engine, avatar guidance system, knowledge graph schema, and recommender framework, remains reusable [51]. This layered approach to reusability supports the principle of "design once, adapt many," where the generic layers can be directly transferred, while only the specific layers require domain-specific data substitution.

These benefits align with green software engineering principles, which emphasize longevity, transferability, and resource efficiency [52], suggesting that MDE approaches warrant greater adoption in sustainable tourism platform development.

5.5. Generalizability and Contextual Adaptation

While DIVEXPLORE-3D addresses marine tourism in Gorontalo specifically, the integrated Design Thinking-SDA-MDE methodology exhibits structural generalizability across three dimensions:

Domain Generalizability. Domain Generalizability. Based on an analytical examination of the case study architecture, we propose design propositions that are theoretically grounded yet empirically untested. We suggest that elements of the four-layer methodology may be applicable to other community-based Web-3D contexts. We differentiate between analytical and empirical generalizability: the former pertains to the conceptual applicability of methodological principles across contexts, while the latter requires multi-site validation, which is beyond the scope of this study.

At the methodological level, the integrated Design Thinking, Systems Design Approach (SDA), and Model-Driven Engineering (MDE) process (including structured empathy mapping, domain decomposition, and bidirectional traceability) is analytically applicable to any context that necessitates the systematic translation of community stakeholder needs into formal software specifications. However, whether this methodological transferability is effective in practice across diverse cultural, organizational, and technical contexts remains to be investigated through comparative case studies.

At the architectural level, the case study analysis suggests, without empirical confirmation, that domain-generic structural elements (browser-based PWA architecture, three-tier moderation workflow, scenario engine structure, and knowledge graph schema) may be transferable across community-based Web-3D platforms, while domain-specific content elements (marine ecosystem models, conservation scenarios, and cultural narratives) require full replacement. The estimate that approximately 60–70% of architectural specifications are structurally transferable is a logical inference from this analysis, not an empirically validated claim.

Three contextual factors from this case study significantly limit direct transferability and must be considered in any attempts to replicate the findings: (1) Gorontalo's strong

community organizational capacity facilitated collaborative workshops, while destinations with fragmented stakeholder networks may require fundamentally different engagement strategies; (2) the modest tourism scale of 12,000 annual visitors allowed for comprehensive stakeholder inclusion, which may not be feasible in mass tourism destinations; and (3) the Indonesian regulatory context influenced data governance requirements that vary across different jurisdictions. These factors are not just practical caveats; they may constitute boundary conditions that fundamentally alter the methodology's applicability.

Stakeholder Generalizability. The three-actor model, comprising visitors, communities, and operators, is proposed as a useful framework for analyzing diverse community-based tourism contexts. However, stakeholder configurations and their power dynamics may vary significantly across destinations and cultural settings. The study reached data saturation with 41 participants, indicating that the sample size was sufficient for this specific case. However, this does not prove that the methodology will yield similar results in contexts with different community organizational structures, stakeholder power dynamics, or cultural relationships to tourism. To establish empirical generalizability, comparative case studies are needed across multiple destinations that differ in community organizational capacity and levels of digital infrastructure.

Technical Generalizability. The MDE transformation approach is platform-independent within the MDE paradigm. It can accommodate different Web-3D frameworks, such as Babylon.js and A-Frame, through PSM (Platform-Specific Model) re-targeting without requiring a redesign of the PIM (Platform-Independent Model). This platform independence is a key characteristic of the MDE approach, as demonstrated in the transformation pipeline of this case study. However, whether this property consistently applies across organizations with varying levels of MDE tool expertise and infrastructure remains an open question for further empirical investigation. This flexibility is essential given diverse technical contexts across tourism destinations globally.

However, three contextual factors limit direct transferability: (1) Gorontalo's strong community organizational capacity facilitated collaborative workshops; destinations with fragmented stakeholder networks may require alternative engagement strategies; (2) modest tourism scale (12,000 annual dive tourists) enabled comprehensive stakeholder inclusion; mass tourism destinations may necessitate representative sampling approaches; (3) Indonesian regulatory context shaped data governance requirements; different jurisdictions may require architectural adaptations for privacy compliance.

5.6. Threats to Validity

We address four categories of validity threats following established design science evaluation frameworks [43]:

Internal Validity. *Threat:* Potential bias in stakeholder recruitment and workshop facilitation. *Mitigation:* We employed purposive sampling to ensure representation across three stakeholder groups, used structured empathy mapping templates to minimize facilitator influence, and conducted inter-rater reliability checks (Krippendorff's $\alpha = 0.82$) for thematic analysis. Workshop facilitation utilized visual templates and small-group activities to reduce power imbalances and encourage participation from less vocal stakeholders [31].

Threat: Expert evaluation timing (specification phase vs. post-implementation). *Mitigation:* While experts validated design artifacts rather than operational systems, the RTM-driven approach provided systematic traceability, enabling retrospective validation. The 96% requirement coverage demonstrates strong alignment between specifications and

stakeholder needs. However, this limitation necessitates future empirical investigations of implementation fidelity and runtime behavior, which have been explicitly identified as a research priority (Section 6).

External Validity (Generalizability). *Threat:* Gorontalo-specific context limits direct transferability. *Mitigation:* We explicitly documented three contextual factors limiting generalization: (1) strong community organizational capacity facilitated collaborative workshops (destinations with fragmented stakeholder networks may require alternative engagement strategies); (2) modest tourism scale (12,000 annual visitors) enabled comprehensive stakeholder inclusion (mass tourism destinations may necessitate representative sampling approaches); (3) Indonesian regulatory context shaped data governance requirements (different jurisdictions may require architectural adaptations for privacy compliance).

Despite these limitations, the four-layered architectural pattern and Design Thinking-SDA-MDE methodology demonstrate structural generalizability across various tourism types (marine, cultural, and terrestrial), stakeholder configurations, and technical platforms. Section 5.5 provides detailed analysis of domain, stakeholder, and technical generalizability dimensions.

Threat: The Stakeholder sample may not represent all tourism contexts. *Mitigation:* Although tourist participants ($n=32$) primarily comprised dive tourists with environmental awareness, potentially biasing the requirements toward conservation education over other tourism motivations, the three-actor model captures the fundamental roles in most community-based tourism ecosystems. Local community participants ($n = 17$) represented coastal villages with existing tourism infrastructure; communities without tourism experience may articulate different priorities. The methodological approach of empathy mapping, domain decomposition, use-case modeling, and traceability validation is applicable across various contexts.

Construct Validity. *Threat:* The paper's use of 'sustainability' spans multiple validation levels, which must be clearly distinguished to prevent conflating specification-level evidence with operational outcomes. We outline three explicit levels of validation: (1) Specification Validation: An expert evaluation involving 8 reviewers assessed the adequacy of the methodology's specifications and architectural decisions in relation to sustainability objectives. This validation confirms that the methodology is designed to create sustainable systems. However, it does not verify whether the deployed system achieves sustainability outcomes over time; (2) Proof-of-Concept Technical Feasibility: A 30-day pilot deployment demonstrated the technical feasibility of the system, achieving 97.2% uptime and a latency of 73 ms, with education gains reflected by a Cohen's d of 1.52. This provides preliminary evidence that the specification-validated architecture can be executed technically, but it does not indicate long-term operational sustainability; and (3) Operational Sustainability: This aspect was not validated in this study. Assessing long-term socio-economic impacts, sustained community engagement, and multi-year governance outcomes requires a longitudinal investigation, which has been explicitly identified as a future research priority (refer to Section 6).

All sustainability claims in this paper are limited to Levels 1 and 2. Any claims suggesting Level 3 operational sustainability have been revised throughout the manuscript to accurately represent the extent of validation performed. We recognize that demonstrating operational sustainability, distinct from the methodological and specification-level contributions discussed here, remains a significant open research question that requires multi-year longitudinal studies (see Section 6, Direction 1).

Conclusion Validity. *Threat:* 30-day pilot provides limited evidence of long-term operational sustainability. Mitigation: While technical feasibility was demonstrated (97.2% uptime, mean latency 73ms, 94% device compatibility), claims regarding maintenance burden, community engagement persistence, and operator adoption patterns require longitudinal validation. We explicitly frame these as preliminary findings and identify longitudinal deployment studies as the primary future research priority (Section 6). The pilot provides proof of concept for the integrated methodology but does not constitute definitive evidence of sustained real-world impact.

Threat: Statistical power limitations due to stakeholder sample size. Mitigation: The 54-participant sample achieved thematic saturation (after 41 participants, with the final 12 providing validation rather than new themes) and 100% coverage of locally owned dive operators ($n = 5$), providing adequate power for qualitative insights and requirements elicitation in the study context. However, quantitative generalizations about tourist demographics and behavior patterns should be interpreted cautiously, given the modest sample size and purposive sampling approach. The three partially met functional requirements (FR-08, FR-12, FR-19) may also reflect limited pilot testing rather than fundamental design flaws; expanded user testing would strengthen confidence in the findings.

Threat: Tight methodological coupling creates expertise barriers. Mitigation: The integration of Design Thinking, SDA, and MDE requires interdisciplinary expertise that combines participatory facilitation skills, software architecture knowledge, and proficiency in MDE tools. This may limit the adoptability of the methodology in resource-constrained contexts, despite its conceptual generalizability. We address this through detailed methodological documentation (Section 3) and identify tool development for democratic access as a future research direction (Section 6). However, the expertise requirement remains a practical constraint for broader adoption.

6. Conclusions

This paper introduces a replicable co-design methodology that effectively combines Design Thinking, Software Domain Architecture (SDA), and Model-Driven Engineering (MDE) to enhance participatory stakeholder engagement and formal software specification in the development of Web-3D frameworks. The methodology is demonstrated and validated through DIVEXPLORE-3D, a Web-3D framework created in collaboration with 54 stakeholders focused on sustainable marine tourism. This approach addresses a crucial gap at the intersection of community-based tourism, immersive technologies, and sustainable software engineering.

The study outlines three significant contributions. First, from a methodological standpoint, we developed a replicable approach that translates qualitative, empathy-driven insights into quantifiable and traceable specifications. This method achieved 96% requirement coverage and garnered 91% stakeholder agreement, all while maintaining community voices through systematic traceability mechanisms. Second, regarding the methodological implementation, the methodology has produced a validated four-layer framework. The qualities of this framework provide empirical evidence of what systematic participatory engineering can achieve: (1) Browser-based accessibility: 94% device compatibility; (2) Community content sovereignty: 78% unmodified publication rate; (3) Conservation education effectiveness: Cohen's $d = 1.52$; and (4) Operational feasibility: 97.2% uptime. These outcomes demonstrate that the methodology effectively translates stakeholder priorities

into measurable architectural qualities. Finally, expert validation ($n = 8$) rated the adequacy of the methodology's sustainability specifications at 4.6 out of 5. This confirms that the integrated approach systematically incorporates sustainability objectives into the engineering process. Additionally, a proof-of-concept demonstrating 97.2% uptime (Cohen's $d = 1.52$) shows that participatory methods and engineering formalism can work together effectively. However, achieving operational sustainability outcomes requires longitudinal validation beyond the scope of this study.

The findings have broader implications for sustainable software engineering. First, this research demonstrates that formal methods, often perceived as incompatible with participatory approaches, can actually enhance stakeholder engagement when organized around explicit traceability and shared artifacts such as the Requirement Traceability Matrix. Second, it shows that Model-Driven Engineering enhances not only technical efficiency but also sustainability through platform longevity, knowledge transfer facilitation, and specification reuse. Third, the methodology's systematic integration of ecological, cultural, and technical requirements from the very beginning of the design process confirms its effectiveness in advancing sustainable tourism objectives. This approach aligns with several Sustainable Development Goals (SDGs 9, 10, 14, and 16) and emphasizes that success stems from methodological rigor rather than relying solely on technological capabilities.

Future Research Directions. Three essential research directions warrant exploration:

1. **Longitudinal Deployment Studies.** Conducting multi-year operational assessments is essential for evaluating maintenance requirements, community engagement persistence, and tourism operator adoption rates beyond the initial 30-day pilot phase. These studies aim to address current limitations in understanding the long-term viability of community-driven immersive platforms and their sustained impact on sustainable tourism behaviors.
2. **Comparative Case Studies for Validating Generalizability.** The generalizability claims outlined in Section 5.5 are currently based on analytical propositions derived from case study analysis. To confidently assert transferability, these claims require empirical validation through systematic comparative case studies. Future research should implement the integrated Design Thinking-SDA-MDE methodology across at least two to three contrasting contexts, such as urban cultural heritage sites, terrestrial ecotourism, and community-based festivals. This research should systematically document: (a) Which methodological phases can be transferred without modification; (b) Which architectural elements need significant adaptation; (c) How contextual factors (such as community organizational capacity, tourism scale, and regulatory environment) influence the effectiveness of the methodology; and (d) Whether the estimated 60–70% structural transferability holds true across different domain implementations.
3. **Tool Development for Democratic Access.** Reducing expertise barriers could democratize the use of participatory formal methods. Potential directions include: (a) facilitation toolkits guiding non-specialists through empathy mapping to requirements workflows; (b) semi-automated SDA decomposition assistants helping practitioners derive domain architectures from stakeholder data; (c) visual MDE environments enabling community participation in model validation without requiring UML or OCL fluency.

As digital transformation continues to influence global tourism, methodologies that ensure technological innovation supports rather than displaces local communities become essential. This study provides evidence that rigorous software engineering can coexist with participatory values. Indeed, for digital tourism platforms to be sustainable, these values

must be systematically integrated. The DIVEXPLORE-3D framework, along with its underlying methodology, serves as both a practical guide and a conceptual foundation for future research and practices promoting sustainable, community-centered digital tourism.

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CRedit authorship contribution statement

Ratna Wardani: Software Engineering, Conceptualization, Methodology, Investigation, Resources, Writing (original draft), Writing (review and editing), Visualization, Supervision, Project administration, Funding acquisition. Masduki Zakaria: Methodology, Formal analysis, Data curation, Validation, Visualization, Writing (review and editing). Tika Novita Sari: Investigation, Resources, Software, Data curation, Validation, Writing (review and editing), Funding acquisition. Dian Novian: Virtual Reality, Testing, Observation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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