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Article

Immersive Ocean: A Virtual Twin for Participatory Decision Support in Maritime Spatial Planning

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Abstract

Current Digital Twins of the Ocean rely predominantly on two-dimensional geoportal interfaces that constrain the spatial comprehension of complex marine environments. This paper presents Immersive Ocean, a Virtual Twin platform developed under the EU-ILIAD Digital Twins of the Ocean initiative that procedurally transforms standardised European geospatial data (EMODnet, Copernicus Marine Service) into interactive three-dimensional maritime environments via Unreal Engine 5 (Epic Games, Cary, NC, USA). The platform supports both desktop and immersive virtual reality modes, enabling users to visualise and manipulate spatial scenarios involving offshore wind farms, shipping corridors, aquaculture installations, and species distributions. System performance testing confirmed stable rendering across PC and VR configurations (61 FPS and 42 FPS, respectively). A user evaluation with 31 participants across three hardware configurations revealed that core geovisualisation capabilities—ease of use, immersion, and procedural generation utility—remained robust, regardless of hardware, whilst feedback responsiveness ($H = 5.99$, $p = 0.04995$) and perceived realism ($H = 6.31$, $p = 0.04258$) were significantly affected. These findings inform deployment strategies for immersive geospatial tools: minimum specification systems preserve functional access, whilst recommended hardware enhances the perceptual fidelity critical for spatial decision support. This evaluation establishes usability among digitally proficient users; efficacy with domain stakeholders in authentic planning contexts remains for future work.

Keywords: 3D geovisualisation; procedural generation; Digital Twins of the Ocean; maritime spatial planning; virtual reality; geospatial decision support

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1. Introduction

Three-dimensional geovisualisation has become increasingly important for spatial decision-support applications, yet most geospatial platforms for marine environments remain constrained to two-dimensional map-based interfaces [1,2]. Digital Twins of the Ocean (DTOs) are emerging as integrative frameworks for marine data and model visualisation, but current implementations rely predominantly on static data pipelines and pre-configured 2D representations that limit interactive spatial exploration [3–5]. This restricts users' ability to comprehend the vertical and temporal complexity of marine environments—such as interactions between subsea infrastructure, pelagic species distributions, and surface-level shipping traffic—which are central to maritime spatial planning (MSP) decision making [6,7].

A critical limitation of current Digital Twin of the Ocean (DTO) implementations is their inability to support immersive, interactive stakeholder engagement—most rely on static 2D interfaces that restrict spatial reasoning and participatory planning in maritime spatial planning (MSP) contexts [8–11]. These platforms serve a wide array of purposes, including scientific data and model integration, scenario-based planning and decision support, and facilitating stakeholder communication and learning processes—all central to maritime spatial planning and ocean governance [12–14]. Despite notable progress in DTO development, many current implementations remain reliant on static data pipelines and pre-configured simulation models, which inherently limit interactivity and adaptability across use cases [3,4,15–23]. While these systems excel in aggregating and visualising real-time observations, they often fall short in enabling proactive engagement, scenario exploration, or multi-user interaction [5,24–26]. For MSP applications, this results in reduced stakeholder agency, limited capacity for "what if?" scenario planning, and challenges in supporting participatory decision-making workflows [27,28]. Moreover, current DTOs frequently lack robust representation of vertical and temporal complexity in marine ecosystems—such as the spatial and temporal interactions between offshore wind farm construction, shipping, fishing pressure, and seabird behaviour [9,29–32]. This restricts user ability to adaptively test or refine spatial strategies in realistic planning environments, reducing their value as participatory decision-support tools [2].

To address these gaps, the ILIAD DTO project (https://ocean-twin.eu/—The Iliad Project, ILIAD Digital Twins of the Ocean Marketplace) developed *Immersive Ocean*—a novel Virtual Twin platform that reconceptualises traditional DTOs by embedding immersive technologies, procedural generation methods, and spatial interactivity into a unified 3D interface. In contrast to conventional DTOs, *Immersive Ocean* employs procedural generation techniques adapted from the gaming industry to dynamically construct 3D marine environments from 2D geospatial data and real-time conditions. This enables stakeholders to engage with and manipulate virtual marine scenarios in real time, supporting spatial reasoning and participatory planning in both desktop and immersive VR configurations.

This paper presents the *Immersive Ocean* platform, describing its structural components, technical implementation, and interaction design principles. It further reports on preliminary performance validation and user testing conducted across hardware setups and modalities (PC and VR). Through these evaluations, the paper demonstrates the platform's high usability, immersive potential, and relevance for real-world MSP contexts. The study contributes to the growing body of work on immersive geovisualisation by demonstrating that procedurally generated 3D environments from standardised geospatial data can deliver effective spatial decision support across varied hardware configurations. The findings inform deployment strategies for immersive geo-information systems, addressing the gap between advanced 3D geovisualisation capabilities and institutional resource constraints.

2. Immersive Ocean Virtual Twin

Although the adoption of DTOs in MSP is expanding [12], key technical and usability barriers hinder their full potential and stakeholder inclusivity. Most MSP-related digital tools rely on conventional GIS-based 2D or static 3D interfaces rather than immersive modalities such as virtual or augmented reality [1,33,34], falling short in delivering intuitive engagement with marine environments and deeper spatial understanding among stakeholders [5].

A critical consideration is accessibility across diverse institutional settings. Many educational institutions, government agencies, and planning organisations, particularly in resource-constrained contexts, lack access to high-performance VR equipment [1]. This raises an important question: does hardware configuration meaningfully affect user experience and system usability? Understanding whether immersive DTOs can deliver effective decision support on minimum specification hardware is essential for assessing practical deployability in real-world MSP workflows.

The *Immersive Ocean* platform (https://ocean-twin.eu/marketplace/product/proceduralocean—Immersive Ocean, Iliad marketplace; https://cradle.buas.nl/project/immersive-ocean/—Immersive Ocean project, CRADLE, Breda University of Applied Sciences; https://www.mspchallenge.info/immersive-ocean.html—MSP Immersive Ocean, Immersive Twin for maritime spatial planning) was developed to address these limitations by combining procedural 3D environment generation, real-time environmental responsiveness, and an accessible VR-capable interface. It translates 2D geospatial datasets and live environmental data into explorable 3D maritime scenes, enabling stakeholders to engage with dynamic planning scenarios and facilitating collaborative analysis and experience-based decision making. The platform thus serves as a hybrid between analytical decision-support tools and experiential planning environments.

Technical Approach and Procedural Generation

The platform's central technical contribution is a procedural pipeline that converts standardised 2D geospatial inputs into navigable 3D maritime scenes at runtime, without manual scene authoring. This subsection summarises that pipeline; full architectural detail, including the structural diagram and the complete Procedural Rule Pack catalogue, is provided in the Supplementary Materials S1.

Input data are supplied as standardised geospatial formats (GeoJSON, Shapefile, GeoTIFF, WFS/WMS) and JSON scenario configurations; the latter are exportable directly from the MSP Challenge simulation platform. A central Data Parser reads these inputs into a shared Data Pool that synchronises datasets across the rendering modules, with fallback logic where individual data points are unavailable. Coordinate referencing uses EPSG codes, with ETRS89/LAEA Europe (EPSG:3035) as the default projection for European waters [35].

The transformation from 2D vector and raster data to 3D geometry proceeds in two stages. First, an Environmental Base layer constructs the terrain and water volume: bathymetric raster grids (GeoTIFF) are sampled to displace a seafloor mesh, establishing the vertical datum against which all other features are positioned, while the ocean surface and atmospheric conditions are generated above it. Second, a set of modular Procedural Rule Packs (PRPs) instantiates thematic features onto this base. Each PRP encapsulates a single logic domain—for example, the Wind Turbines Pack, Shipping Pack, Benthos Pack, or North Sea Fish Pack—and defines how its features are placed, scaled, oriented, and made interactive. Two-dimensional vector inputs are interpreted accordingly: polygon boundaries (for example, a designated wind farm area) define the footprint within which point features are instantiated; polyline features (for example, shipping corridors or subsea cable routes) are extruded and routed in 3D following the input geometry; and point or density datasets (for example, species distributions) are rendered as 3D models and spatial heatmaps positioned by their geographic coordinates and seabed depth.

Placement, scaling, and texturing are governed by the rules encoded in each PRP rather than by manual editing. Feature footprints, counts, and spacing are derived from the geometry of the input layer—a wind farm polygon is populated with turbine instances at a configured spacing, each anchored to the sampled seabed elevation and scaled to its real-world dimensions—while textures and 3D asset selection are assigned per feature class. This rule-based approach is what allows the platform to scale across geographies and datasets rather than requiring a bespoke model for each site.

The generation process is deterministic: a given input dataset and scenario configuration always produce the same 3D environment, with no stochastic variation in feature placement. This is a deliberate design choice for a decision-support context, ensuring that the spatial relationships presented to stakeholders are a faithful and reproducible representation of the source data rather than a procedurally varied interpretation. Dynamic behaviour at runtime—turbine rotation responding to wind speed, weather-driven visibility changes, vessel movement along routed paths—is similarly rule-driven and data-linked, reflecting environmental parameters rather than introducing randomness into the spatial layout.

The platform supports both desktop and immersive VR modes and draws from pan-European data services (EMODnet, Copernicus Marine Service). This combination distinguishes Immersive Ocean from existing Digital Twins of the Ocean. Where current DTO implementations rely predominantly on 2D geoportal interfaces or pre-authored static 3D scenes, Immersive Ocean generates interactive 3D environments procedurally and deterministically from standardised data at runtime and exposes them through both desktop and immersive VR modalities. It is therefore not a visual upgrade of an existing pipeline but a distinct geovisualisation approach: a runtime transformation layer that sits between standardised geospatial infrastructures and stakeholder-facing immersive interaction.

Although the evaluation scenarios presented here focus on the North Sea, Immersive Ocean's architecture supports geographic transferability. The platform ingests standardised geospatial formats and draws from pan-European data services, enabling deployment across maritime jurisdictions covered by these infrastructures. Current geographic coverage extends to the North Sea, Baltic Sea, and Eastern Mediterranean through the MSP Challenge platform, with additional regions accommodated through EPSG code configuration.

This study evaluates user experience and system usability across three hardware configurations—PC with minimum specifications, PC with recommended specifications, and VR with recommended specifications—to determine whether hardware limitations compromise the platform's effectiveness as a participatory planning tool. The findings inform deployment strategies for institutions with varying resource availability.

3. Materials and Methods

To assess the innovations introduced by *Immersive Ocean*, which build upon and surpass current limitations in Digital Twins of the Ocean (DTO), this study employs a Design Science Research (DSR) paradigm [36]. Specifically, it applies the FEDS (Framework for Evaluation in Design Science) approach [37], targeting the evaluation of two core dimensions: system performance and user experience. The platform itself, including its procedural generation pipeline, is described in Section Technical Approach and Procedural Generation; this section addresses how that platform was evaluated.

Performance evaluation is conducted to determine whether the platform consistently supports interactive, real-time 3D maritime environments on both PC and VR systems. Given the demands of rendering live geospatial and environmental datasets, coupled with procedurally generated 3D content, it is essential to confirm that the platform achieves performance benchmarks such as stable frame rates, responsive rendering, and efficient hardware utilisation. These technical indicators are fundamental to ensuring fluid, uninterrupted interaction—an essential requirement for maintaining stakeholder trust and engagement quality in participatory MSP workshops.

Parallel to the technical validation, a preliminary user experience assessment is carried out to evaluate usability, interactivity, and immersive qualities. This component seeks to establish the platform's viability as a stakeholder-oriented participatory decision-support tool. The testing procedure combines structured play sessions, verbal protocol analysis, and post-session group discussions involving digitally literate early-career professionals. Feedback is collected through both qualitative insights and quantitative metrics, focusing on key experiential dimensions such as navigational intuitiveness, plausibility of simulated scenarios, clarity of interactions, and overall system accessibility.

The following section presents the performance testing results, which confirm that *Immersive Ocean* delivers a stable, interactive experience under varied hardware configurations in both PC and VR environments.

4. System Performance Testing

To verify operational robustness under realistic usage conditions, performance testing assessed the platform's ability to render complex, interactive maritime environments in real time across PC and VR configurations. Tests were conducted on a high-performance workstation (Intel Core Ultra 9—Intel Corporation, Santa Clara, CA, USA; NVIDIA RTX 4080—NVIDIA Corporation, Santa Clara, CA, USA; 32 GB RAM) running Windows 11—Microsoft Corporation, Redmond, WA, USA. Detailed hardware specifications and profiling methodology are provided in the Supplementary Materials S2.

4.1. Testing Protocol, Data Collection and Metrics

A standardised protocol was applied ten times for each platform variant (PC and VR). The test scenario "NL P.A. Wind Park + Fish Farm" was selected for its density and complexity. Each iteration comprised baseline resource measurement followed by a structured interaction sequence encompassing environmental manipulation, infrastructure visualisation, and camera navigation. Internal profiling used Unreal Engine diagnostic tools; external metrics were captured via hardware monitoring software.

4.2. Performance Results

Table 1 summarises performance during scenario execution. Frame rates were consistently high: 61 FPS (PC) and 42 FPS (VR) with minimal deviation. GPU utilisation was high but stable (~97% PC, ~70% VR). No performance bottlenecks or rendering instability were observed.

Table 1. Performance metrics during scenario execution ($\bar{x}$ is the average mean, and σ standard deviation).

Metrics	PC ($\bar{x} \pm \sigma$)	VR ($\bar{x} \pm \sigma$)
Average FPS	61 ± 7	42 ± 11
GPU Load (%)	97 ± 1	70 ± 7
Memory RAM (MB)	$17{,}984 \pm 1069$	$21{,}234 \pm 449$

4.3. Discussion of Test Results

The performance assessment confirms that Immersive Ocean delivers stable runtime behaviour in both configurations. The procedural generation engine transformed 2D geospatial data into interactive 3D scenarios without lag or degradation. These findings support the platform's technical maturity for real-world MSP deployment: minimum specification systems enable basic functionality, whilst recommended hardware enhances the interactive feedback and visual realism critical for high-stakes planning workshops. Extended baseline metrics and diagnostic analyses are available in the Supplementary Materials S2.

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5. User Experience Testing

To evaluate the platform's effectiveness as a participatory decision-support tool for MSP, user testing sessions assessed usability, feedback quality, immersion, and perceived realism across three hardware configurations (PC minimum specification, PC recommended, VR recommended). Metrics covered ease of use, feedback mechanisms, immersion, procedural generation, and realism, evaluated via Likert-scale questionnaires and semi-structured group discussions with 31 participants familiar with immersive technologies.

5.1. Research Design

5.1.1. Protocol

The user study comprised three testing configurations: (1) the PC version on minimum specification hardware, (2) the PC version on recommended hardware, and (3) the VR version on recommended specifications. The evaluation followed a structured five-phase protocol: introduction and informed consent, pre-questionnaire capturing demographic and technological proficiency, 30 min gameplay session with think-aloud protocol, post-questionnaire rating five dimensions on 5-point Likert scales, and semi-structured group discussion. Detailed task prompts are provided in the Supplementary Materials S3.

Participants engaged with structured tasks covering environmental exploration, aquaculture and wind turbine inspection, shipping lane visualisation, and marine life heatmap interaction, progressing from guided interaction to free exploration.

5.1.2. Participants and Location

The testing sample included 31 participants aged 18–30, fluent in immersive technologies but with no prior MSP experience. Of these, 20 tested the PC version (11 minimum specification, 9 recommended) and 11 evaluated the VR version on the recommended hardware. The sessions were conducted in controlled laboratory settings at Breda University of Applied Sciences.

5.1.3. Questionnaire Design

The post-test questionnaire assessed five dimensions: ease of use and intuitiveness (adapted from SUS; [38,39]), perceived control and interactivity (adapted from GEQ and ARI Questionnaire; [40,41]), feedback mechanisms (informed by TAM perceived usefulness; [42]), realism (adapted from [43]), and dynamic procedural generation (custom items). All items used a 5-point Likert scale from strongly disagree (-2) to strongly agree (+2).

5.1.4. Method and Data Collection

Data collection employed a combination of qualitative and quantitative methods, including audio recordings of real-time user interactions (think-aloud), demographic and proficiency pre-questionnaires, usability-focused post-questionnaires using a Likert scale, and semi-structured focus group discussions to gain deeper insights into user experiences and perceptions.

5.1.5. Data Analysis

Quantitative responses were analysed using descriptive statistics (mean, standard deviation, median) and non-parametric inferential tests. Kruskal–Wallis H tests [44]—appropriate for ordinal Likert data and small samples—compared responses across configurations (PC-MIN, PC-REC, VR-REC) for each item ($\alpha = 0.05$). Where significant omnibus effects were detected, post hoc Mann–Whitney U tests [45] assessed pairwise differences. Uncorrected p-values are reported given the exploratory nature and modest sample sizes, acknowledging increased Type I error risk [46].

Qualitative responses were transcribed and coded thematically in Atlas.ti (https://atlasti.com/—Atlas.ti Scientific Software Development GmbH, Berlin, Germany) using a structured scheme aligned with evaluation metrics: usability, feedback mechanisms, immersion, procedural generation, realism, overall satisfaction. Manual content analysis identified emergent sub-themes and recurring patterns.

5.2. User Experience Results

5.2.1. Post-Questionnaire Feedback

Table 2 presents comparative user experience ratings across the three hardware configurations. Responses for the PC version are split by hardware configuration—minimum (PC-MIN) and recommended (PC-REC)—alongside VR with recommended specifications (VR-REC).

Table 2. Comparative user experience ratings across hardware configurations (PC-MIN is PC with minimum hardware setup; PC-REC is pc with recommended hardware setup; VR-REC is VR headset coupled with PC running recommended hardware setup). values show mean ± standard deviation (median) for each questionnaire item on a 5-point Likert scale (−2 to +2). NOTE: Likert scale: −2 = strongly disagree, −1 = disagree, 0 = neutral, 1 = agree, 2 = strongly agree. * Significant hardware configuration effect detected (Kruskal–Wallis, $p < 0.05$).

Evaluation Dimension	Question	Item	PC-MIN ($n = 11$)	PC-REC ($n = 9$)	VR-REC ($n = 11$)
Ease of Use and Intuitiveness	Q1	"The platform was easy to use."	1.09 ± 0.70 (1)	1.44 ± 0.53 (1)	1.09 ± 0.70 (1)
	Q2	"I felt confident navigating the platform without needing much help."	0.82 ± 0.60 (1)	0.89 ± 0.93 (1)	0.45 ± 1.13 (1)
Feedback Mechanisms (Accuracy and Helpfulness)	Q3 *	"The platform responded well and provided useful information when I interacted with it (e.g., clicking, navigating, or using features)."	0.36 ± 1.12 (0)	1.56 ± 1.01 (2)	0.82 ± 0.87 (1)
	Q4	"The information provided by the platform helped me understand maritime spatial planning concepts."	0.64 ± 1.03 (1)	1.33 ± 0.50 (1)	1.45 ± 1.04 (2)
Immersion (perceived control and interactivity)	Q5	"I felt in control of my actions while interacting with the platform."	1.00 ± 1.18 (1)	1.67 ± 0.71 (2)	1.27 ± 1.01 (2)
	Q6	"The platform encouraged me to actively explore and interact with the environment."	0.73 ± 1.19 (1)	1.56 ± 0.73 (2)	1.55 ± 0.93 (2)
Dynamic Procedural Generation	Q7	"The 3D environment and its customization were useful for understanding maritime spatial planning."	1.09 ± 1.04 (1)	1.56 ± 0.53 (2)	1.36 ± 0.81 (2)
Realism	Q8 *	"The 3D environment felt realistic and closely resembled real-world conditions."	0.36 ± 1.36 (0)	1.78 ± 0.44 (2)	1.45 ± 1.04 (2)
Overall Satisfaction	Q9	"Overall, I am satisfied with the platform as a tool for maritime spatial planning."	0.73 ± 0.79 (1)	1.33 ± 0.87 (2)	2.00 ± 1.10 (2)

Table 3 summarises the omnibus test results, revealing significant hardware effects for two dimensions: feedback mechanisms (Q3) and realism (Q8). Raw questionnaire response frequencies per hardware configuration can be found in Appendix A, Table A1.

Table 3. Kruskal–Wallis h test results comparing user experience ratings across hardware configurations (PC-MIN, PC-REC, VR-REC). Significance level: $\alpha = 0.05$. N = 31 total (PC-MIN: $n = 11$, PC-REC: $n = 9$, VR-REC: $n = 11$). * Denotes a statistically significant hardware configuration effect ($p < 0.05$). Yes/No in the final column indicates whether the omnibus Kruskal–Wallis test reached significance at $\alpha = 0.05$.

Question	Dimension	H Statistic	df	*p*-Value	Significant at $p < 0.05$?
Q1	Ease of Use and Intuitiveness	1.3807	2	0.50141	No
Q2	Ease of Use and Intuitiveness	0.7698	2	0.68052	No
Q3 *	Feedback Mechanisms (Accuracy and Helpfulness)	5.9936	2	0.04995	Yes
Q4	Feedback Mechanisms (Accuracy and Helpfulness)	4.8239	2	0.08964	No
Q5	Immersion (perceived control and interactivity)	1.7694	2	0.41283	No
Q6	Immersion (perceived control and interactivity)	3.391	2	0.18351	No
Q7	Dynamic Procedural Generation	0.7334	2	0.69302	No
Q8 *	Realism	6.3129	2	0.04258	Yes
Q9	Overall Satisfaction	2.8653	2	0.23867	No

Ease of use and intuitiveness: Participants rated ease of use positively across all configurations, with mean ratings ranging from 1.09 to 1.44 for Q1 (platform ease of use) and 0.45 to 0.89 for Q2 (navigation confidence). Kruskal–Wallis tests revealed no significant hardware configuration effects for either ease of use item (Q1: H = 1.38, $p = 0.501$; Q2: H = 0.77, $p = 0.681$), indicating that the platform's basic usability remained consistent across hardware setups.

Feedback mechanisms (accuracy and helpfulness): Hardware configuration significantly affected perceived feedback responsiveness (Q3: H = 5.99, $p = 0.04995$). PC-REC participants rated feedback mechanisms substantially higher (M = 1.56, SD = 1.01, Mdn = 2) than PC-MIN participants (M = 0.36, SD = 1.12, Mdn = 0), representing a difference of over one full scale point. Post hoc Mann–Whitney U tests indicated this PC-MIN vs. PC-REC difference approached significance (U = 20, $p = 0.028$), though it did not reach the Bonferroni-corrected threshold ($\alpha = 0.0167$). VR-REC performance (M = 0.82, SD = 0.87, Mdn = 1) fell between the two PC configurations. For Q4 (information helpfulness for understanding MSP), a similar pattern emerged with higher ratings for recommended hardware, though the omnibus effect did not reach significance (H = 4.82, $p = 0.090$).

Immersion (perceived control and interactivity): Participants generally reported positive levels of perceived control and interactivity across all configurations. While PC-REC showed numerically higher ratings for both control (Q5: M = 1.67) and exploration encouragement (Q6: M = 1.56) compared to PC-MIN (Q5: M = 1.00; Q6: M = 0.73), these differences did not reach statistical significance (Q5: H = 1.77, $p = 0.413$; Q6: H = 3.39, $p = 0.184$). VR-REC ratings aligned closely with PC-REC for both immersion items.

Dynamic procedural generation: Ratings for the utility of procedurally generated 3D environments (Q7) were consistently positive across all configurations (means ranging from 1.09 to 1.56), with no significant hardware effect detected (H = 0.73, $p = 0.693$). This suggests that the platform's core capability for generating useful 3D maritime environments remained robust regardless of hardware specification or modality (PC vs. VR).

Realism: Hardware configuration significantly influenced perceived environmental realism (Q8: H = 6.31, $p = 0.04258$). The pattern mirrored feedback mechanisms: PC-REC participants rated realism markedly higher (M = 1.78, SD = 0.44, Mdn = 2) than PC-MIN participants (M = 0.36, SD = 1.36, Mdn = 0), representing a 1.42-point difference on the 5-point scale. Post hoc Mann–Whitney U comparison between PC-MIN and PC-REC approached significance (U = 18.5, $p = 0.020$), though it did not meet the Bonferroni-corrected threshold. VR-REC ratings (M = 1.45, SD = 1.04, Mdn = 2) closely matched PC-REC performance, suggesting that both VR technology and high-specification PC hardware contribute to enhanced perceptual realism.

Overall satisfaction: Although VR-REC achieved the highest overall satisfaction ratings (M = 2.00, SD = 1.10, Mdn = 2), with PC-REC (M = 1.33, SD = 0.87, Mdn = 2) and PC-MIN (M = 0.73, SD = 0.79, Mdn = 1) following in descending order, the omnibus test did not reveal a significant hardware effect (H = 2.87, $p = 0.239$). This may reflect the influence of multiple factors beyond hardware performance on overall user satisfaction.

The quantitative results demonstrate that hardware configuration significantly affects two critical dimensions of user experience: feedback responsiveness and perceived realism. In both cases, the effect was driven primarily by substantial differences between minimum and recommended PC hardware specifications, with recommended-specification hardware (both PC-REC and VR-REC) consistently outperforming minimum specification setups. Notably, core platform capabilities—ease of use, immersion, and procedural generation utility—remained robust across hardware configurations, suggesting that while minimum specification deployment is viable, recommended hardware enhances the quality of interactive feedback and visual realism that support effective MSP decision making.

5.2.2. Talk-Aloud Protocol and Group Discussions

Qualitative data from 31 participants were analysed thematically across six categories: ease of use and intuitiveness, accuracy and helpfulness of feedback mechanisms, immersion (perceived control and interactivity), procedural generation, realism, and overall satisfaction.

Ease of use: Participants found the interface well-structured and visually coherent. Navigation via mouse and keyboard (PC) or motion controllers (VR) enabled fluid exploration, with most users operating independently after brief orientation. The minimalist layout and contextual sidebar facilitated selective layer visualisation. Suggestions included an optional onboarding tutorial and improved visibility for secondary functions (e.g., mouse wheel speed adjustment).

Feedback mechanisms: Dynamic parameter adjustments—wind speed, visibility, noise levels—produced immediate visual and auditory responses that participants considered effective for reinforcing cause-effect relationships. Notable examples included turbine rotation responding to wind sliders, real-time sound heatmap updates, and layer toggling. Occasional ambiguity arose (e.g., turbines stopping at high wind speeds interpreted as malfunction), suggesting contextual tooltips for first-time users.

Immersion: Participants consistently praised the platform's immersive qualities, reporting high presence and control. Users frequently deviated from structured tasks to explore freely, indicating strong intrinsic engagement. Responsiveness, particularly when visual feedback was immediate and spatially coherent, fostered confidence in interactive decision making. Suggestions included spatial orientation aids (mini-map, compass) for open-sea and underwater navigation.

Procedural generation: The system was strongly endorsed for translating abstract 2D datasets into navigable 3D environments—valuable where timely visualisation of proposed developments is constrained. Participants valued visualising overlapping sectors (energy infrastructure, ecological habitats) for multi-stakeholder discussions. Interest in selective layer re-generation and manual override reflected the platform's utility for iterative planning.

Realism: The platform offered credible oceanic environment representation. Visual elements—marine surface dynamics, underwater cable layouts, atmospheric transitions—were considered believable, whilst subtle design choices (turbine noise levels, lighting shifts, species clustering) enhanced interpretability. Refinement opportunities were noted

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for underwater environments, where greater terrain variety, vegetation, and animated marine behaviours could better align with professional expectations.

Overall satisfaction: Participants expressed high satisfaction, describing the tool as engaging and professionally relevant—well-suited for stakeholder engagement, collaborative planning, and communication of spatial trade-offs. The platform was identified as a valuable MSP toolkit addition, whether as pre-visualisation sandbox, stakeholder dialogue environment, or exploratory participatory decision-support tool. Recommended usability improvements did not detract from overall perception of technical robustness and end-user alignment.

5.3. Discussion

The user testing process uncovered both strengths and areas for refinement in the Immersive Ocean platform. Participants consistently praised the tool's potential for real-world MSP applications, particularly its immersive qualities, procedural scenario generation, and capacity to make complex spatial data accessible. The think-aloud protocol and group discussions revealed that users, especially those unfamiliar with simulation environments, were able to grasp key functionalities with minimal instruction, supporting the platform's suitability for stakeholder engagement and potential professional planning workflows.

Despite overall positive feedback, several areas for improvement were identified. Both PC and VR versions faced challenges related to navigation, with underwater orientation described as disorienting due to limited spatial references. Users recommended incorporating navigational aids such as mini-maps, compasses, and consistent transition effects between environments. Additionally, the user interface (UI) presented inconsistencies, with menus sometimes behaving unpredictably and data visualisations requiring clearer legends and advanced layer management features. Movement controls, especially vertical navigation, were widely described as unintuitive, with several participants recommending adoption of standard gaming conventions. Others highlighted challenges in adjusting movement speed, especially underwater, where the default pace was too rapid for fine control. These insights suggest a need for adaptive or context-aware movement logic and clearer onboarding guidance.

A second dimension of the findings concerns the influence of hardware configuration on user experience. While all participants were able to complete core tasks, qualitative differences emerged between those using minimum hardware specifications and those operating on recommended setups. Participants using recommended hardware generally reported smoother performance, faster rendering of data layers, and fewer delays in interaction feedback. This led to more natural exploration and stronger perceived immersion. By contrast, users on lower-end systems experienced occasional input lag, delayed environmental loading, and reduced visual fidelity, which cumulatively impacted task efficiency and overall satisfaction.

Quantitative analysis provides empirical support for the qualitative observations regarding hardware-dependent user experience differences. Statistical testing confirmed significant hardware effects for feedback responsiveness (Q3: $H = 5.99$, $p = 0.04995$) and perceived realism (Q8: $H = 6.31$, $p = 0.04258$), the two dimensions most dependent on real-time system performance and graphical fidelity. The magnitude of these effects was substantial: PC-MIN participants rated feedback mechanisms over one full scale point lower than PC-REC participants ($M = 0.36$ vs. 1.56), with a similar gap for realism ($M = 0.36$ vs. 1.78). These quantitative findings validate participants' qualitative reports of "smoother performance" and "more natural exploration" on recommended hardware.

The selectivity of hardware effects offers insight into which user experience dimensions depend on computational resources. Ease of use, immersion, and procedural generation utility remained statistically equivalent across configurations because these factors primarily reflect interface design and content quality—aspects independent of rendering speed. Conversely, feedback responsiveness and realism are performance-sensitive: they require immediate visual updates and high-fidelity rendering that minimum specification hardware struggles to deliver consistently. This pattern informs deployment strategies: minimum specification systems suffice for basic platform functionality and training, but recommended hardware should be prioritised for high-stakes MSP workshops where tool legitimacy and immersive quality directly influence stakeholder engagement.

These findings extend the literature on 3D geovisualisation for spatial decision support [1,2]. Current geospatial tools for MSP rely predominantly on two-dimensional geoportal interfaces that constrain users' comprehension of vertical spatial relationships—such as the interactions between subsea cable routing, pelagic fish distributions, and surface-level shipping traffic [7]. The procedural generation pipeline demonstrated in this study addresses this constraint by automatically transforming standardised geospatial datasets into immersive three-dimensional environments that preserve spatial fidelity whilst enabling intuitive exploration. Unlike manual 3D modelling approaches, procedural generation scales across geographies and datasets, making immersive geovisualisation practical for operational deployment rather than bespoke demonstration. The empirical finding that core geovisualisation functionality is maintained across hardware configurations has implications for the accessibility of immersive geospatial tools. Organisations with limited computational resources can deploy the platform on existing hardware without sacrificing interactive spatial analysis capabilities. Recommended hardware should, however, be prioritised for applications where perceptual fidelity and real-time feedback quality directly influence analytical outcomes [47,48].

5.4. Limitations

The study presents several limitations. The sample comprised young, technology-proficient participants unfamiliar with MSP, limiting generalisability to domain experts; accordingly, the present findings should be read as evidence of usability among novice users rather than of efficacy for real MSP decision making by domain experts. The controlled laboratory setting may have overestimated ease of use. The modest sample sizes ($n = 9$–11 per configuration) limit statistical power for pairwise comparisons; while significant omnibus effects emerged for feedback mechanisms and realism, post hoc tests did not reach Bonferroni-corrected thresholds ($\alpha = 0.0167$), though consistent descriptive patterns suggest genuine hardware-related differences. The between-subjects design may also introduce demographic confounds despite efforts to match groups on technological proficiency. Future confirmatory studies with larger samples and within-subjects designs are needed.

The qualitative analysis relied on a single coder, introducing potential observer bias. This was mitigated through a structured protocol centred on predefined categories and systematic coding in Atlas.ti, though inter-rater reliability assessments would strengthen future analyses. Complementary studies involving domain professionals in real-world settings remain important to fully establish the platform's potential.

From a governance perspective, several limitations merit consideration. The platform has not yet been tested in multi-stakeholder negotiation scenarios where conflicting spatial interests must be reconciled—arguably the most demanding use case for participatory MSP tools. The platform was evaluated in single-user mode; multi-user collaborative sessions, central to real negotiation, are not yet supported and remain a development priority. Cybersickness was not formally measured, and although sessions were limited to 30 min, systematic assessment of VR comfort over extended use is needed. Future research should evaluate the platform with domain experts and stakeholder groups in authentic planning workshops to assess its capacity to support deliberative decision making.

6. Conclusions

This study demonstrates that procedural generation from standardised geospatial data can produce immersive 3D maritime environments suitable for spatial decision support, with empirical evidence on the influence of hardware configuration on geovisualisation quality. Performance testing confirmed stable rendering across PC and VR platforms, with consistent frame rates and efficient resource utilisation. User experience evaluation demonstrated that Immersive Ocean delivers a highly usable, engaging experience, with participants praising its intuitive design and interactive realism whilst identifying refinements for onboarding, navigational aids, and ecological fidelity. The automated transformation of 2D geospatial data into rich 3D environments was cited as a key innovation, with PC and VR modes offering complementary strengths—precision for detail-oriented tasks versus immersion for exploratory engagement.

Hardware configuration significantly affected feedback responsiveness ($H = 5.99$, $p = 0.04995$) and perceived realism ($H = 6.31$, $p = 0.04258$), dimensions critical for tool credibility in participatory MSP contexts. Participants using minimum specification hardware rated these dimensions substantially lower (>1.2 scale points) than those using recommended hardware, whilst core capabilities—ease of use, immersion, and procedural generation utility—remained consistent across configurations. These findings inform institutional deployment strategies: minimum specification systems enable basic participatory access for resource-constrained organisations, whilst recommended hardware should be prioritised for high-stakes planning workshops in which tool credibility influences stakeholder trust and decision-making efficacy.

The platform is now entering real-world deployment in offshore wind planning, floating turbine engineering, and environmental impact assessment. The present evaluation assessed usability with digitally proficient participants who were not MSP practitioners; it therefore validates the platform's accessibility and interaction design rather than its effectiveness in authentic, multi-stakeholder planning decisions. Future evaluations will involve domain experts—marine scientists, energy and shipping professionals, and regulatory bodies—to assess integration into established workflows and support for multi-stakeholder spatial trade-off analysis. As the international community advances the EU Mission 'Restore our Ocean and Waters' and the UN Decade of Ocean Science for Sustainable Development [49], immersive Virtual Twin platforms built on standardised geospatial infrastructures can contribute meaningfully to inclusive ocean governance, bridging science, policy, and practice across jurisdictional boundaries.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi15070323/s1. Supplementary Material S1: Immersive Ocean Technical Architecture and Implementation Details—detailed technical specifications of the platform, including core functionalities, the procedural generation pipeline and Procedural Rule Pack catalogue, the structural diagram, and interoperability standards. Supplementary Material S2: System Performance—full hardware/software specification, testing protocol, baseline and scenario-execution performance metrics, and GPU/memory analysis. Supplementary Material S3: User Testing Research Design—the five-phase evaluation protocol, task prompts, and questionnaire design with the source scales for each dimension.

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Appendix A

Table A1. Raw questionnaire response frequencies by hardware configuration. Note: Values represent the number of participants selecting each response level for each questionnaire item. Rows may not sum to exactly n due to missing responses (if any). Likert scale: −2 = strongly disagree, −1 = disagree, 0 = neutral, +1 = agree, +2 = strongly agree. Descriptive statistics (mean, standard deviation, median) calculated from these distributions are presented in Table 2.

Evaluation Dimension	Question	Item	PC-MIN (n = 11)					PC-REC (n = 9)					VR-REC (n = 11)				
			−2	−1	0	+1	+2	−2	−1	0	+1	+2	−2	−1	0	+1	+2
Ease of Use and Intuitiveness	Q1	"The platform was easy to use."	0	0	2	6	3	0	0	0	5	4	0	0	2	6	3
	Q2	"I felt confident navigating the platform without needing much help."	0	0	3	7	1	0	1	1	5	2	1	1	2	6	1
Feedback Mechanisms (Accuracy and Helpfulness)	Q3	"The platform responded well and provided useful information when I interacted with it (e.g., clicking, navigating, or using features)."	0	3	3	3	2	0	1	0	1	7	0	0	5	3	3
	Q4	"The information provided by the platform helped me understand maritime spatial planning concepts."	0	2	2	5	2	0	0	0	6	3	0	1	1	1	8
Immersion (perceived control and interactivity)	Q5	"I felt in control of my actions while interacting with the platform."	0	2	1	3	5	0	0	1	1	7	0	1	1	3	6
	Q6	"The platform encouraged me to actively explore and interact with the environment."	0	2	3	2	4	0	0	1	2	6	0	1	0	2	8
Dynamic Procedural Generation	Q7	"The 3D environment and its customization were useful for understanding maritime spatial planning."	0	1	2	3	5	0	0	0	4	5	0	0	2	3	6
Realism	Q8	"The 3D environment felt realistic and closely resembled real-world conditions."	1	2	3	2	3	0	0	0	2	7	0	1	1	1	8

Table A1. *Cont.*

Evaluation Dimension	Question	Item	PC-MIN (n = 11)					PC-REC (n = 9)					VR-REC (n = 11)				
			−2	−1	0	+1	+2	−2	−1	0	+1	+2	−2	−1	0	+1	+2
Overall Satisfaction	Q9	"Overall, I am satisfied with the platform as a tool for maritime spatial planning."	0	0	5	4	2	0	0	2	2	5	0	1	2	1	7

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