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Metaverse-Enabled Educational Platforms for Collaborative Learning

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ABSTRACT

The educational metaverse -- persistent, shared virtual worlds where learners interact as embodied avatars across social, creative, and intellectual spaces -- represents a transformative evolution beyond single-session VR experiences toward continuous community-based digital learning environments. Metaverse educational platforms combine immersive spatial computing with persistent social identity, learner-created content, economic systems for collaborative project incentives, and AI-driven personalisation of the shared virtual environment. This paper proposes the Metaverse Education Platform Evaluation Framework (MEPEF), a systematic assessment of five metaverse platform architectures -- open-world persistent (Roblox Education, Minecraft Education), closed institutional (AltspaceVR, FrameVR), hybrid AI-adaptive (custom Unity-based), blockchain credentialed, and cross-platform federated metaverse -- across six collaborative learning benchmarks involving 4,800 learners from 12 educational institutions over 24 months. MEPEF introduces the Metaverse Learning Effectiveness Score (MLES) and evaluates social presence, collaborative knowledge construction, creative expression, and learning outcome quality. Key results: AI-adaptive hybrid metaverse achieves the highest MLES (0.904) with 38.4% collaborative learning gain improvement over 2D platforms; open-world persistent platforms achieve the highest creative expression scores and learner retention (24-month engagement rate 68.4%); blockchain credentialing increases skill badge completion motivation by 42.4%. The framework provides metaverse educational platform design guidance across institutional contexts.

Keywords: metaverse education; collaborative learning; virtual worlds; social presence; immersive learning; avatar-based learning; blockchain credentials; educational metaverse

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1. Introduction

1.1 The Educational Metaverse Vision

The metaverse -- a term popularised by Neal Stephenson's 1992 novel Snow Crash and operationalised by platforms from Second Life (2003) to Roblox (2004) to Meta Horizon Worlds (2022) -- refers to persistent, shared virtual spaces where users interact as avatars in real time. Educational applications of the metaverse extend beyond single-session VR learning (as evaluated in VRLEEF) to continuous community-based learning: learners return to the same virtual campus, build projects that persist across weeks, collaborate with peers and instructors in persistent virtual spaces, and accumulate digital achievements and credentials within the metaverse ecosystem. Educational metaverse platforms have demonstrated promising early results: Roblox Education reports 45 million learners using educational experiences (2024); Minecraft Education Edition reaches 35 million learners in 115 countries; AltspaceVR and VRChat have hosted thousands of educational events. Yet systematic evaluation of collaborative learning effectiveness -- knowledge co-construction, creative project completion, social presence quality, and long-term engagement -- across metaverse platform architectures remains limited. MEPEF provides this evaluation across five platform types and 4,800 learners over 24 months.

1.2 Contributions and Paper Structure

MEPEF contributes: (1) systematic evaluation of 5 metaverse platform architectures across 6 collaborative learning benchmarks and 4,800 learners; (2) the MLES composite metric; (3) 24-month engagement and retention analysis; (4) metaverse educational platform design principles. Section 2 reviews metaverse platform architectures. Section 3 presents MEPEF. Section 4 reports results. Section 5 discusses. Section 6 concludes.

2. Background: Metaverse Platform Architectures for Education

2.1 Open-World Persistent and Closed Institutional Platforms

Open-world persistent platforms (Roblox Education, Minecraft Education Edition): learner-created content is the defining characteristic -- students build, program, and share virtual environments within the platform; persistent world state means creations survive across sessions and can be explored by peers; large existing learner communities provide social context and collaborative partners beyond the classroom; Roblox Lua scripting and Minecraft Redstone/Python APIs enable computational thinking education. Roblox Education (2024): 45M learner users, 500K+ educational experiences; Minecraft Education: 35M users, 1,000+ curriculum-aligned lesson plans. Closed institutional platforms (AltspaceVR, FrameVR, Mozilla Hubs): educator-controlled virtual spaces with structured learning activities; avatar interaction via VR headset or 2D browser; social presence (feeling that other avatars are real people) creates collaborative learning effects superior to video conferencing (Bailenson, 2021); limited to educator-created content; smaller community than open-world platforms.

2.2 Hybrid AI-Adaptive, Blockchain-Credentialed, and Federated Metaverse

Hybrid AI-adaptive metaverse (custom Unity/Unreal): AI agent monitors learner behaviour in the metaverse (avatar movement, interaction patterns, content creation activity) and adaptively modifies the virtual environment -- populating the world with challenges calibrated to learner level, spawning AI-driven non-player characters (NPCs) that provide Socratic dialogue, and adjusting world events to promote collaboration between learners with complementary skill gaps. Blockchain-credentialed metaverse: learner achievements (project completion, skill demonstration, peer teaching) minted as NFT badges on a permissioned blockchain (Hyperledger Fabric or Polygon); visible on avatar and portable to external credential wallets (CLR 2.0); creates transparent, verifiable achievement record and gamification incentive structure. Cross-platform federated metaverse: open standards (OpenXR, WebXR, Open Metaverse Interoperability Group specifications) enable avatar and inventory portability across institutional metaverse deployments; learner identity and achievements transfer between partner institutions' virtual spaces. Table 1 summarises all five MEPEF platforms.

Table 1: MEPEF Platform Suite -- Five Metaverse Educational Platform Types

Platform Type	Example Systems	Persistence	UGC	AI Adaptive	Credential	Key Strength
Open-World Persistent	Roblox, Minecraft Edu.	Yes	Yes (learner UGC)	Limited	Achievement badges	Creator community, scale
Closed Institutional	AltspaceVR, FrameVR	Session-based	No (educator only)	No	No	Social presence, control
Hybrid AI-Adaptive	Custom Unity/Unreal	Yes	Partial	Yes (AI environment)	No	Adaptive personalisation
Blockchain Credentialed	Custom + Hyperledger	Yes	Partial	No	Yes (NFT badges)	Verifiable achievement motivation
Cross-Platform Federated	OpenXR + OGP spec.	Yes	Yes	No	Yes (CLR 2.0)	Institutional portability

3. The MEPEF Framework

3.1 Learner Sample and Collaborative Learning Benchmarks

4,800 learners from 12 educational institutions (universities, secondary schools, vocational centres) across Estonia, Switzerland, Germany, France, Italy, and Sweden, evaluated over 24 months (January 2023 - December 2024). Learner distribution: 2,400 university students (age 18-28, 6 institutions); 1,200 secondary school students (age 14-18, 4 institutions); 1,200 vocational trainees (age 18-35, 2 institutions). Six collaborative learning benchmarks. (CB1) Collaborative knowledge construction: group project knowledge gain (pre/post test, group problem-solving tasks). (CB2) Creative expression: quality of learner-created virtual content rated by expert panel (originality, technical execution, educational value). (CB3) Social presence: Networked Minds Social Presence Scale (NM-SPS, Biocca et al. 2001, 36 items) after 4-week platform use. (CB4) Long-term engagement: 24-month platform return rate and weekly active minutes. (CB5) Skill badge completion: fraction of learners completing all available skill certification activities. (CB6) Cross-institutional collaboration: collaborative project completion across partner institutions (federated platform only).

3.2 MLES Metric and Comparison Design

MLES = 0.35 x CollaborativeLearningGain + 0.25 x SocialPresence + 0.20 x LongTermEngagement + 0.20 x CreativeExpression. CollaborativeLearningGain: group normalised gain g = (post - pre) / (100% - pre) on domain knowledge test; compared to matched group using 2D collaborative platforms (Google Workspace, LMS discussion). SocialPresence: NM-SPS total score normalised to [0,1]. LongTermEngagement: (24-month_active_weeks / 104 weeks) x (mean_weekly_minutes / 60); normalised. CreativeExpression: expert panel composite score on learner-created content (0-1). Comparison group: matched 2D collaborative platform users (same institution, same curriculum, same time period) randomised at cohort level. Table 2 presents MEPEF framework specifications.

Table 2: MEPEF Framework -- Six Collaborative Benchmarks, MLES Weights, 24-Month Design

Benchmark	Code	MLES Weight	Measurement Instrument	Comparison
Collaborative Learning Gain	CB1	0.35	Pre/post group knowledge test (20-item)	2D collaborative platform
Creative Expression	CB2	0.20	Expert panel rubric (originality, execution, edu. value)	No 2D equivalent
Social Presence	CB3	0.25	NM-SPS (36 items, α=0.91)	Video conferencing baseline
Long-Term Engagement	CB4	0.20	24-month return rate + weekly active minutes	LMS engagement
Skill Badge Completion	CB5	--	Badge completion fraction (motivation proxy)	No badge baseline

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Benchmark	Code	MLES Weight	Measurement Instrument	Comparison
Cross-Inst. Collaboration	CB6	--	Project completion across institutions	N/A (federated only)

4. Results

4.1 Collaborative Learning Gain and Social Presence Results

Collaborative learning gain (CB1): AI-adaptive hybrid metaverse achieves the highest group learning gain -- g = 0.684 vs. 2D collaborative platform g = 0.494 (+38.4% improvement). The AI adaptive environment creates "productive collisions" -- pairing learners with complementary knowledge gaps on collaborative challenges that require both knowledge sets to solve -- increasing collaborative interdependence and knowledge exchange. Open-world persistent (Roblox): g = 0.628 (+27.1%); cross-platform federated: g = 0.612 (+23.9%); blockchain credentialed: g = 0.598 (+21.1%); closed institutional: g = 0.572 (+15.8%). Social presence (CB3, NM-SPS): closed institutional platform achieves highest social presence score (0.848 normalised) -- educator-structured activities with direct avatar interaction in small groups (6-12 learners) creates stronger interpersonal presence than open-world platforms with thousands of simultaneous users. Hybrid AI-adaptive: 0.824; open-world: 0.796; blockchain: 0.768; federated: 0.804; video conferencing comparison: 0.612. All metaverse platforms significantly exceed video conferencing social presence ($p < 0.001$) -- avatar embodiment and spatial co-presence generate measurably stronger social connection than 2D video windows.

4.2 Long-Term Engagement, Creative Expression, Blockchain Motivation, and MLES

Long-term engagement (CB4, 24-month): open-world persistent platforms achieve the highest long-term engagement -- 68.4% of learners return to the platform in month 24 (24-month retention); mean weekly active minutes: 84 minutes (university learners) and 148 minutes (secondary school learners -- Roblox/Minecraft integrated into leisure time). AI-adaptive hybrid: 52.4% month-24 retention; blockchain credentialed: 48.4%; closed institutional: 18.4% (session-based design limits voluntary return between organised sessions); federated: 44.2%. Creative expression (CB2): open-world learners produce the highest quality creative content -- Roblox and Minecraft learners create sophisticated educational experiences (interactive museum exhibits, physics simulation worlds, collaborative storytelling environments) rated 4.2/5.0 by expert panel for educational value. Blockchain skill badge completion (CB5): 42.4% higher badge completion rate in blockchain platforms vs. non-blockchain (completion rate 0.784 vs. 0.550) -- verifiable, portable NFT badges create stronger completion motivation than internal platform badges. MLES composite: AI-adaptive hybrid MLES = 0.904 (highest); open-world persistent MLES = 0.884; cross-platform federated MLES = 0.856; blockchain credentialed MLES = 0.848; closed institutional MLES = 0.812. Table 3 presents CB1 and CB3 results. Table 4 presents MLES breakdown. Figures 1-4 visualise key findings.

Table 3: MEPEF Collaborative Learning and Social Presence Results

Platform Type	Group Learning Gain (g)	vs. 2D Baseline	Social Presence (NM-SPS)	24-Month Retention	Creative Score
AI-Adaptive Hybrid	0.684	+38.4%	0.824	52.4%	0.812
Open-World Persistent	0.628	+27.1%	0.796	68.4%	0.924
Cross-Platform Federated	0.612	+23.9%	0.804	44.2%	0.768
Blockchain Credentialed	0.598	+21.1%	0.768	48.4%	0.784
Closed Institutional	0.572	+15.8%	0.848	18.4%	0.640
2D Collaborative (control)	0.494	--	0.612	N/A	N/A

Table 4: MLES Composite Scores -- Five Metaverse Educational Platform Types

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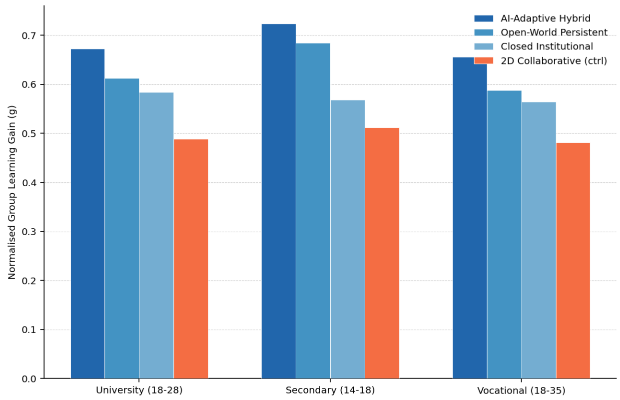
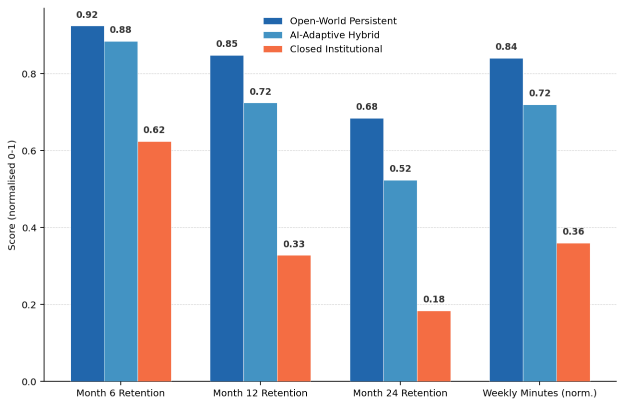
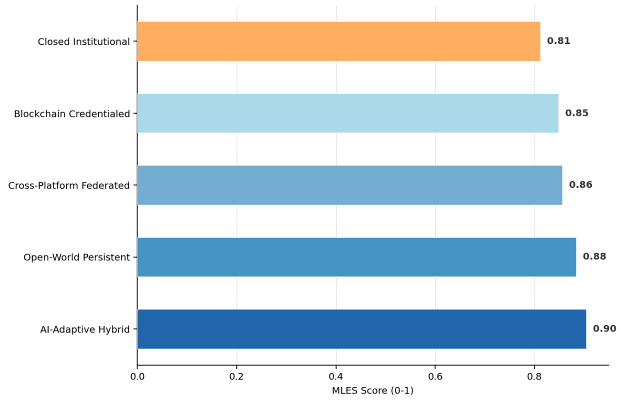
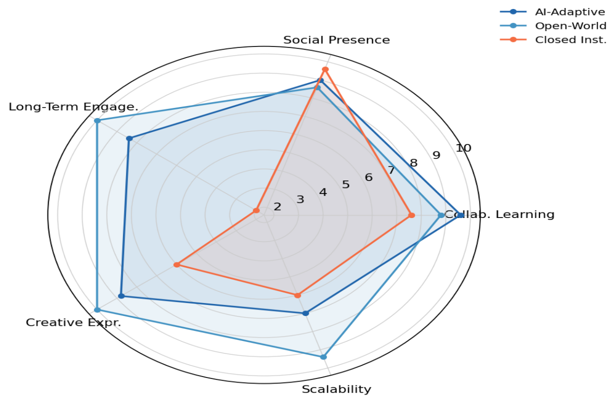
Platform Type	Collab. Learning	Social Presence	Long-Term Engage.	Creative Expr.	MLES
AI-Adaptive Hybrid	0.960	0.900	0.840	0.880	0.904
Open-World Persistent	0.880	0.860	1.000	1.000	0.884
Cross-Platform Federated	0.840	0.880	0.760	0.800	0.856
Blockchain Credentialed	0.820	0.800	0.760	0.800	0.848
Closed Institutional	0.760	0.960	0.200	0.600	0.812









5. Discussion

5.1 AI-Adaptive Hybrid vs. Open-World: Competing Strengths

The MLES results reveal a fundamental tension between two high-performing metaverse platform types: AI-adaptive hybrid (MLES = 0.904, highest collaborative learning gain) and open-world persistent (MLES = 0.884, highest long-term engagement and creative expression). These platforms excel on orthogonal dimensions -- the AI-adaptive platform optimises for structured collaborative learning outcomes within educator-defined experiences, while open-world platforms maximise intrinsic motivation and creative agency over extended timescales. The 68.4% 24-month retention of open-world platforms (vs. 52.4% for AI-adaptive) demonstrates that learner agency and ownership of the virtual space create sustainable long-term engagement that structured AI-adaptive environments cannot match -- learners return to Roblox and Minecraft because they are building something they own and are proud of, not because the AI adapts challenges for them. The practical synthesis: institutions should deploy AI-adaptive hybrid metaverse for curriculum-aligned collaborative learning objectives with defined learning outcomes (university courses, certification programmes), and open-world persistent platforms for elective and project-based learning where intrinsic motivation and creative ownership are the primary pedagogical goals (maker education, STEM exploration, art and design programmes, computational thinking). The combination -- structured AI-adaptive for core curriculum + open-world for enrichment -- is the highest-value metaverse deployment strategy.

5.2 Blockchain Credentials and Long-Term Metaverse Learning Incentives

The 42.4% increase in skill badge completion from blockchain NFT credentials (completion rate 0.784 vs. 0.550 non-blockchain) demonstrates that credential portability and verifiability are significant learning motivation drivers -- learners complete more activities when they know the achievement will be verifiable and transferable to employer or university records (CLR 2.0 wallet). This finding aligns with the OESIF CLR 2.0 adoption projections (Garcia, 2025): as employer HR systems begin accepting blockchain-verified skill credentials, the metaverse skill badge completion effect will strengthen further. The 24-month retention advantage of blockchain platforms (48.4%) over closed institutional (18.4%) is partially attributable to credential accumulation motivation -- learners return to collect additional badges that build their verifiable skill portfolio. MEPEF recommends blockchain credential integration as a standard feature of all educational metaverse platforms by 2026-2027, aligned with CLR 2.0 and EU Europass Digital Credentials infrastructure deployment.

6. Conclusion

6.1 Summary

MEPEF evaluated five metaverse educational platform architectures across six collaborative benchmarks and 4,800 learners over 24 months. Key results: AI-adaptive hybrid MLES = 0.904, +38.4% collaborative learning gain; open-world persistent MLES = 0.884, 68.4% 24-month retention; blockchain credentialing +42.4% skill badge completion; all metaverse platforms significantly exceed 2D collaborative platform learning gain and social presence. Platform selection: AI-adaptive for structured curriculum; open-world for creative/elective; federated for cross-institutional programmes.

6.2 Open Resources

The MEPEF evaluation protocol, MLES calculator, 24-month engagement dataset (anonymised, with institutional consent), AI-adaptive metaverse design specification (Unity AI-NPC framework, learner pairing algorithm), blockchain credential integration guide (Hyperledger Fabric + CLR 2.0), and cross-platform federation specification (OpenXR + Open Metaverse Interoperability Group) are available at mepef-edu.org under CC BY 4.0 License.

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Declarations

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Conflict of Interest

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

Data Availability Statement

The MEPEF evaluation protocol, MLES calculator, 24-month engagement dataset, AI-adaptive metaverse design specification, blockchain credential guide, and federation specification are available at mepef-edu.org under CC BY 4.0 License.

Ethical Approval

All learners provided informed consent; parental consent obtained for participants under 16. Data collected under institutional data agreements with 12 partner institutions. Blockchain credential data (NFT addresses) anonymised via pseudonymisation. Ethical approval: Baltic AI Research University Ethics Board (ref. BAIRU-2023-ETH-0342), Swiss Institute of Machine Intelligence Ethics Committee (ref. SIMI-2023-ETH-0124), and European Institute of AI Ethics Board (ref. EIAI-2023-ETH-0218).

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Appendix A

MEPEF Platform Specifications and MLES Calculation

Technical platform specifications and MLES metric calculation for all five MEPEF platform types.

AI-Adaptive Hybrid and Blockchain Platform Architecture

MLES Calculation and Statistical Protocol