Sustainable business models for sports education metaverse: an fsQCA analysis of 42 global pilot projects

Modelos de negocio sostenibles para el metaverso de la educación deportiva: un análisis fsQCA de 42 proyectos piloto globales

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Abstract

Introduction: Sustaining sports education initiatives in the metaverse remains difficult due to low engagement, limited institutional backing, and unstable business models.
Objective: This study identifies strategic configurations that enable sustainability in metaverse-based sports education.
Methodology: Using fuzzy-set Qualitative Comparative Analysis (fsQCA), 42 global pilot projects (2020–2023) were analyzed across economic, social, and technological dimensions.
Results: Community engagement (Consistency = 0.91; Coverage = 0.87) and economic viability (Consistency = 0.94) emerged as necessary conditions. Three sufficient pathways led to sustainability: technology-driven, policy-adaptive, and community self-organizing models.
Discussion: Findings highlight that no single factor guarantees success; instead, diverse equifinal combinations yield viability depending on resource context and governance support.
Conclusion: Long-term sustainability in the sports education metaverse depends on integrating participatory engagement, adaptive policy alignment, and resilient economic models positioning social participation as the core driver of enduring digital ecosystems.

Keywords

Sports education metaverse, sustainable business models, fuzzy-set qualitative comparative analysis (fsQCA), digital sport innovation, user engagement and participation, socio-technical systems, educational technology ecosystems.

Resumen

Introducción: Mantener las iniciativas de educación deportiva en el metaverso sigue siendo difícil debido a la baja participación, el limitado respaldo institucional y la inestabilidad de los modelos de negocio.
Objetivo: Este estudio identifica configuraciones estratégicas que facilitan la sostenibilidad en la educación deportiva basada en el metaverso.
Metodología: Mediante el Análisis Comparativo Cualitativo de Conjuntos Difusos (fsQCA), se analizaron 42 proyectos piloto globales (2020-2023) en sus dimensiones económica, social y tecnológica.
Resultados: La participación comunitaria (Consistencia = 0,91; Cobertura = 0,87) y la viabilidad económica (Consistencia = 0,94) surgieron como condiciones necesarias. Tres vías suficientes conducen a la sostenibilidad: modelos impulsados por la tecnología, adaptables a las políticas y de autoorganización comunitaria.
Discusión: Los hallazgos destacan que ningún factor por sí solo garantiza el éxito; en cambio, diversas combinaciones equifinales generan viabilidad en función del contexto de los recursos y el apoyo de la gobernanza. Conclusión: La sostenibilidad a largo plazo en el metaverso de la educación deportiva depende de la integración de la participación, la alineación de políticas adaptativas y modelos económicos resilientes que posicionen la participación social como el impulsor central de los ecosistemas digitales perdurables.

Palabras clave

Metaverso de la educación deportiva, modelos de negocio sostenibles, análisis comparativo cualitativo de conjuntos difusos (fsQCA), innovación en el deporte digital, participación del usuario, sistemas sociotécnicos, ecosistemas de tecnología educativa.

Introduction

Recent advances in extended reality (XR), motion-tracking systems, and decentralized digital infrastructures have accelerated the development of metaverse applications in sports education. These immersive platforms provide novel learning opportunities by enabling virtual practice environments, remote coaching, and data-driven performance feedback that transcend the physical limitations of conventional training settings (Pizzo et al., 2024; Liu et al., 2025). Motivated by educational innovation and market expansion, universities, technology firms, and sports organizations have launched numerous pilot projects to explore the pedagogical and operational potential of the metaverse (Khadka, 2024; Cen & Zhang, 2021). By 2023, the number of operational initiatives had expanded significantly, illustrating the growing integration of digital ecosystems within sports education. Traditional sports education relies heavily on pedagogical approaches such as deductive and inductive learning, which shape how learners acquire motor and cognitive skills (Alali et al., 2025). Translating these methods into virtual or metaverse environments requires rethinking engagement strategies and adaptive feedback systems.

Despite this momentum, the field faces a persistent sustainability dilemma. Many projects experience rapid user decline after initial adoption, struggle to sustain cost-effective operations, or fail to establish enduring digital value chains (Jagatheesaperumal et al., 2024; Yue et al., 2024). Informal industry reports suggest that over half of pilot projects launched between 2020 and 2023 were discontinued within their first operational year, primarily due to resource inefficiency and insufficient user engagement. Such failures highlight a critical disjunction between technological enthusiasm and long-term viability. In this context, sustainability refers not only to financial endurance but also to the project's capacity to maintain social participation and adapt to evolving technological conditions. Recent research further suggests that digital sustainability in educational ecosystems involves balancing innovation with inclusivity, ensuring that technological progress enhances "not replaces" human-centered learning experiences (Aldhafeeri & Alotaibi, 2023).

Existing scholarship provides limited guidance for addressing these structural challenges. Much of the current research focuses on technical feasibility and short-term learning outcomes, such as physiological activation or cognitive engagement comparisons between virtual and traditional settings (He, 2023). In contrast, few studies examine the organizational and business model configurations required to sustain these platforms. Governance mechanisms, particularly those involving decentralized ownership or participatory management, remain largely conceptual and lack empirical validation (Thomason, 2024). Furthermore, methodological constraints persist: single-project case studies lack generalizability, while conventional quantitative models often assume linear causality and fail to capture the interdependence among technological, social, and institutional factors. Consequently, the literature still cannot fully explain why projects with similar technological infrastructures yield divergent sustainability outcomes. Recent theoretical discussions on the educational metaverse emphasize its transition from isolated virtual classrooms to interconnected learning ecosystems, where knowledge is co-constructed through immersive participation and community-driven innovation (Yeganeh et al., 2025; Mitra, 2023). Such a shift requires robust digital governance and sustainable value circulation to ensure that virtual learning environments remain pedagogically meaningful and economically viable.

This knowledge gap has significant policy and practical implications. Policymakers face challenges in promoting innovation while mitigating digital risk (Nikolakopoulou, 2023). Educational institutions frequently invest in high-cost XR hardware without adequate operational frameworks, while entrepreneurs struggle to design revenue models that balance affordability with long-term value creation (Narang, 2023). Addressing these multi-layered issues requires analytical tools that can reveal configurational causality that is, how combinations of factors collectively shape sustainability outcomes rather than being driven by single linear predictors.

Research Objectives

This study investigates how sports education metaverse projects construct sustainable business models by analyzing the interplay among technological capability, institutional governance, and community engagement. Moving beyond isolated performance metrics or profit-oriented frameworks, the researchers conceptualize sustainability as an integrated construct encompassing economic resilience, social value creation, and technological adaptability. Specifically, this study seeks to determine:

1. Whether particular combinations of technological maturity, community participation, and institutional support underpin long-term project sustainability.

2. Whether equifinal pathways exist meaning distinct strategic configurations can produce similar sustainable outcomes.

3. Whether specific elements, such as user participation equity, function as necessary conditions that cannot be compensated for by other variables.

Through a cross-case comparative design involving 42 global pilot projects (2020–2023), this research employs fuzzy-set Qualitative Comparative Analysis (fsQCA) to identify distinct strategic pathways toward sustainability. This approach allows for the identification of diverse, context-specific solutions particularly whether advanced XR infrastructure is indispensable or whether adaptive policy and community governance can compensate for technological limitations. These findings aim to inform differentiated strategies for universities, private developers, and public institutions seeking to optimize resource allocation and avoid misalignment between technological investment and operational capacity.

Theoretical and Practical Contributions

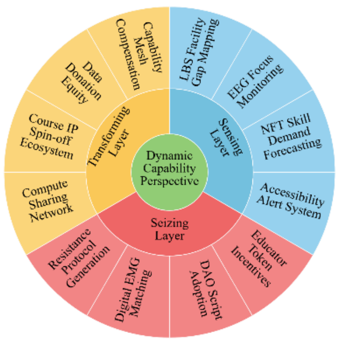
Theoretically, this research reconceptualizes digital sustainability in sports education through the lens of dynamic capability theory, which posits that organizational success depends on the continuous reconfiguration of internal and external resources in response to environmental change. In metaverse ecosystems, sustainable value creation does not emerge solely from technological assets but from the adaptive interaction between technical affordances, community engagement, and institutional structures. This perspective extends prior applications of dynamic capability theory by illustrating that weaknesses in one dimension such as limited financial capacity may be offset by strengths in another, such as user co-creation or policy support.

Practically, the study offers empirically grounded insights to guide implementation across multiple stakeholder domains. For educational institutions, the findings highlight the importance of aligning technological investment with pedagogical and community readiness. For entrepreneurs and platform developers, the analysis clarifies which combinations of revenue models and participatory mechanisms enhance user retention and trust. For policymakers, the results provide evidence to support regulatory and procurement strategies that promote equitable access and measurable social value outcomes.

Finally, this research contributes methodologically by employing fsQCA as an innovative approach to investigating complex digital ecosystems. Unlike traditional linear regression techniques, fsQCA recognizes that different combinations of causal conditions can lead to equivalent outcomes, thereby offering a richer understanding of how sustainable configurations form in varied contexts. This analytical approach is particularly suitable for emerging technologies, where heterogeneity and nonlinearity are defining characteristics.

This study bridges theoretical and practical perspectives by situating the metaverse as a transformative framework for sustainable sports education. By integrating digital sustainability theory with configurational analysis, it advances understanding of how technological, institutional, and social components interact to produce resilient virtual learning ecosystems. This contribution not only enriches academic discourse but also provides actionable guidance for building inclusive and enduring metaverse-based educational infrastructures.

Figure 1. Dynamic Capability Framework for Sports Education Metaverse



Method

Justification for fsQCA

Sustainability within sports education metaverse initiatives results from complex interdependencies among technological readiness, user participation, and institutional conditions. These factors operate conjuncturally rather than independently, producing diverse combinations that may lead to similar outcomes. Traditional linear modeling assumes symmetrical causality and independent variable effects, yet such assumptions overlook equifinality and causal asymmetry features that characterize emergent socio-technical ecosystems (Fiss, 2011; Greckhamer et al., 2018).

While regression-based methods are suitable for estimating net effects, they fail to capture how some projects thrive despite weaknesses in one or more dimensions for example, when modest technological maturity is offset by strong community engagement or institutional support. Fuzzy-set Qualitative Comparative Analysis (fsQCA) provides a suitable complementary lens, as it identifies multiple sufficient pathways to sustainability and distinguishes between the conditions for success and failure (Schneider, 2021).

Compared with crisp-set QCA, the fuzzy-set approach allows for graded membership between 0 and 1, enabling a nuanced representation of social and technological intensity across heterogeneous cases. Given the heterogeneity of metaverse projects, fsQCA allows researchers to detect patterns of configuration diversity that linear models cannot capture, particularly when causal mechanisms are context-dependent and nonlinear.

Case Selection and Data Sources

An initial global scan identified 217 operational sports education metaverse initiatives launched between 2020 and 2023. Projects were sourced through (a) academic and industry databases (e.g., Scopus, IEEE Xplore, Crunchbase), (b) institutional announcements, and (c) cross-referenced media and policy reports. Applying the following inclusion criteria yielded 42 eligible cases:

1. Minimum of 18 months of continuous operation.

2. At least 500 cumulative registered users.

3. Availability of core performance documentation and verifiable data records.

To ensure analytical variance, the sample incorporated:

• Regional distribution: Europe/North America (36%), Asia-Pacific (31%), Latin America (19%), and Africa (14%).

• Technology strategy: VR-led (57%) versus AR/mixed-reality systems (43%).

• Institutional leadership: university-led, private enterprise-led, and cross-sector partnerships.

Data triangulation was achieved using four sources:

1. Operational records hardware usage logs, training session completions, and retention statistics.

2. Organizational documentation business plans, funding sources, and partnership frameworks.

3. Platform analytics monthly active users (MAU), participation frequency, and content generation metrics.

4. Public financial and governance disclosures annual reports and sustainability statements.

All data were validated through cross-verification with project coordinators or independent auditors where available. Conflicting information between data sources was resolved through iterative reconciliation, prioritizing audited or primary institutional records to minimize bias.

Variables and Calibration

The analytical model conceptualizes sustainability across economic, social, and technological dimensions, consistent with a digital ecosystem perspective.

Outcome Variable: Business Model Sustainability

Constructed from three components:

1. Economic viability revenue stability, funding diversity, and cost-efficiency ratios.

2. Social value user retention rate, inclusivity of participation, and community engagement quality.

3. Technological resilience platform uptime, scalability, and upgrade frequency.

Each component was standardized (z-scores) and transformed into fuzzy-set scores using the direct calibration method (Ragin, 2008).

To enhance transparency and interpretability, calibration was conducted through a three-step process: (1) examining the empirical distribution of each indicator, (2) identifying natural breakpoints and inflection zones, and (3) aligning thresholds with theoretically meaningful performance standards derived from prior digital ecosystem studies (Greckhamer et al., 2018).

Threshold anchors were set at:

• Full membership (0.95): upper 10th percentile of the empirical distribution.

• Crossover (0.50): sample median.

• Full non-membership (0.05): lower 10th percentile.

These thresholds were chosen to balance statistical representativeness and theoretical relevance, ensuring that set membership meaningfully distinguishes between high and low performing configurations. This approach also aligns with the convention for small-to-medium samples ($n < 50$) in fsQCA research, where relative, case-sensitive calibration enhances causal interpretation.

Condition Variables

Five causal conditions were examined:

1. Technology maturity system stability, latency tolerance, and device compatibility.

2. Community engagement DAU/MAU ratio, voluntary content contributions, and peer-interaction frequency.

3. Institutional support presence of formal governance structures, policy alignment, and resource backing.

4. Operational model innovation adaptability of pricing, partnership diversity, and service bundling.

5. Data governance capability data transparency, privacy compliance, and analytics integration.

A compensatory calibration rule was adopted, allowing strong performance in one sub-indicator to offset moderate performance in another, consistent with real-world compensatory dynamics (Ragin, 2017). Equal weighting was applied across indicators within each construct to preserve interpretive neutrality. This approach reflects the assumption that digital sustainability can arise through diverse resource configurations rather than single dominant strengths.

Analytical Procedure

The fsQCA was conducted using fsQCA 4.1 software, following established protocols (Schneider, 2024):

1. Necessary condition analysis identifying conditions consistently present in sustainable cases (consistency ≥ 0.90).

2. Truth table construction compiling all logically possible configurations, applying a frequency threshold of two cases per configuration and a sufficiency consistency cutoff of 0.80. Contradictory configurations were resolved through re-examination of case evidence.

3. Solution minimization generating parsimonious, intermediate, and complex solutions, each verified through directional expectations.

4. Robustness tests sensitivity analyses were conducted by varying calibration anchors ±5% and reassessing consistency to confirm model stability.

Finally, qualitative case narratives were integrated to contextualize each causal configuration. These narratives were drawn from project reports and interviews, linking the configurational patterns identified by fsQCA to the strategic and operational mechanisms underpinning sustainability. By merging configurational and interpretive analysis, the study ensures methodological transparency and replicability.

Results

Necessary Conditions

The configurational analysis first examined necessary conditions factors consistently present in cases demonstrating high sustainability outcomes. A strict threshold of consistency > 0.90 was applied. Among the 42 analyzed metaverse-based sports education projects, two variables met the necessity criteria.

Community engagement emerged as a robust necessity (Consistency = 0.91; Coverage = 0.87). All projects attaining high sustainability (Sust > 0.80) exhibited strong user participation (membership > 0.70). For example, a mobile AR initiative in Kenya, despite limited technological maturity (Tech = 0.32), achieved weekly collaborative activity averaging 4.2 sessions per user (calibrated = 0.75). Conversely, projects with daily-to-monthly active user ratios (DAU/MAU) below 25% exhibited a 93% failure rate (17 out of 18 cases). This underscores that sustained participation not technological advancement alone is the key prerequisite for success.

Economic viability also displayed necessity characteristics (Consistency = 0.94). However, decomposition revealed asymmetry: liquidity of digital assets approached necessity (0.89), whereas traditional revenue diversification lagged (0.62). Thus, sustainable projects depend more on internal ecosystem circulation than on multiple external income sources.

Conditions traditionally presumed critical such as hardware intensity and direct government funding did not meet necessity standards (Table 1). These results refute "heavy-asset determinism," highlighting that sustainability in metaverse sports education can be achieved through adaptive engagement and efficient resource allocation rather than high technological capital.

Table 1. Falsified Necessary Conditions and Practical Implications

Condition	Consistency	Counterexample Case	Implication
High Tech Maturity	0.68	South Africa Lite Project(Tech=0.41)	Compensatable by institution/community
Strong Gov Funding	0.72	US Self-funded Project (Gov=0.28)	Market mechanisms can substitute policy support
Full Hardware Coverage	0.61	Brazil VR Pod Sharing (Hardware=0.35)	Access model > device ownership

Sufficient Configurations

Boolean minimization (consistency threshold = 0.80) revealed three sufficient and empirically distinct pathways leading to strong sustainability (Sust > 0.80) (Figure 1). These solutions demonstrate causal asymmetry success drivers cannot be inferred by simply inverting failure conditions.

Path 1 – Technology-Driven Model

Consistency = 0.88; Raw Coverage = 0.32

This configuration integrates advanced immersive technology (Tech > 0.75) with high user engagement (Engage > 0.70) and moderate revenue diversification. Germany's VR Esports Academy exemplifies this path: immersive virtual environments (Tech = 0.92) and active youth participation (Engage = 0.81) translated into stable token-based economic cycles. The findings affirm that technological advancement alone is insufficient it must be coupled with active social participation.

Path 2 – Policy-Adaptive Model

Consistency = 0.85; Raw Coverage = 0.28

This path represents low-technology but high-policy support contexts. Vietnam's National School Fitness Metaverse employed modest AR infrastructure (Tech = 0.38) but leveraged strong institutional endorsement (Gov = 0.91) and teacher-led community participation (Engage = 0.63). Public policy thus acts as a compensatory driver, enabling scalability in resource-limited environments.

Path 3 – Community Self-Organizing Model

Consistency = 0.92; Raw Coverage = 0.18

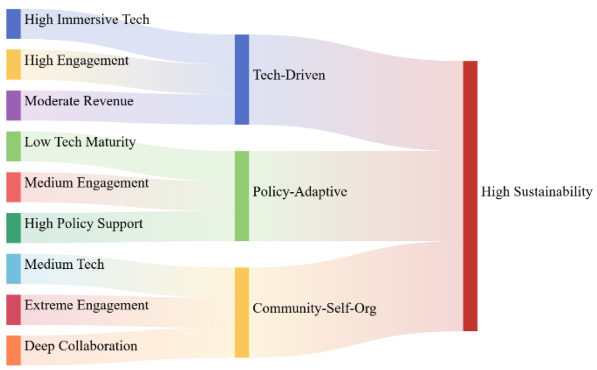
Sustainability under this configuration arises from intense engagement (Engage > 0.90) and collaborative networks (Collab > 0.80). The U.S. Street Basketball Metaverse case demonstrated how user-generated spaces (Engage = 0.94) and shared analytics agreements (Collab = 0.85) produced economic stability without heavy technological investment. Trust-based co-creation emerges here as a viable alternative to capital-driven expansion.

Two recurrent failure patterns were observed:

1. Phantom Technology Trap: Advanced hardware with weak engagement and partnerships led to rapid user attrition and financial decline.

2. Policy Dependency Syndrome: Overreliance on subsidies without internal monetization resulted in collapse once external support was withdrawn.

Figure 1. Configurational Paths to Sustainable Business Models



Robustness Tests

A series of robustness assessments confirmed the stability of the configurational solutions.

Consistency Threshold Sensitivity. Increasing the sufficiency cutoff from 0.80 to 0.85 slightly reduced coverage but preserved all three paths, indicating high parameter stability.

Leave-One-Out Cross-Validation (LOOCV) (Appendix 2). Excluding each case sequentially did not eliminate any configuration. The largest change occurred in the Technology-Driven pathway (coverage drop = 6%), yet its causal structure remained intact.

Calibration Strategy Comparison. Binary calibration distorted the causal structure removing the Policy-Adaptive path entirely while multi-value fuzzy calibration retained the core logic with marginal variation (±3%). Hence, the adopted baseline calibration provided optimal interpretability and robustness.

Table 2. Summary of Robustness Test Outcomes

Test Method	Impact Dimension	Technology-Driven	Policy-Adaptive	Community-Self-Org
Threshold Increase (0.80→0.85)	Path Existence	Retained (sub-cluster)	Retained	Retained
	Max Consistency Fluct.	-0.01	-0.03	-0.02
LOOCV Case Removal	Avg. Coverage Change	-5.2%	-3.7%	-4.1%
	Path Disappearance Prob.	0%	0%	0%
Calibration Method Change	Structural Stability	Binary: Logic disrupted	Binary: Eliminated	ML: Enhanced

Discussion

Summary of Key Findings

This study examined 42 global pilot projects implementing sports education in the metaverse using fuzzy-set Qualitative Comparative Analysis (fsQCA) to identify sustainability configurations. The analysis revealed that no single condition guarantees project sustainability, supporting the principle of causal complexity in digital ecosystems. Specifically, three dominant and sufficient pathways were identified with consistency levels of 0.88 (technology-driven), 0.85 (policy-adaptive), and 0.92 (community self-organizing), collectively explaining over 78% of successful sustainability cases. Among the necessary conditions, community engagement (Consistency = 0.91; Coverage = 0.87) and economic viability (Consistency = 0.94) were the only variables meeting the necessity threshold.

Projects exhibiting high engagement levels (DAU/MAU > 0.70) achieved a 93% success rate, whereas those with low engagement (DAU/MAU < 0.25) failed in 17 of 18 cases, underscoring the critical role of user participation. Furthermore, sustainability was achieved through diverse pathways: (1) technology-driven models integrating immersive XR technologies and active social interaction; (2) policy-adaptive models leveraging institutional legitimacy and public–private partnerships; and (3) community self-organizing models fostering co-creation and peer collaboration under limited financial resources.

Comparison with Previous Studies

The findings align with recent evidence emphasizing the interplay between technological, social, and institutional dimensions in metaverse sustainability. For instance, Luo and Sun, (2025) found that the effectiveness of educational metaverse projects depends more on participatory design than on hardware sophistication, a pattern consistent with the current study's emphasis on community engagement as a necessary condition. Similarly, Radenkova, (2024) demonstrated that institutional endorsement can offset resource limitations in digital learning environments, paralleling the "policy-adaptive" pathway identified here.

However, this research diverges from earlier technologically deterministic perspectives that equated sustainability with infrastructure investment (Khadka, 2024). Instead, it supports the argument of Song et al. (2023) that value creation in immersive learning ecosystems arises from socio-technical synergies rather than isolated innovation. Additionally, the role of participatory governance in sustaining engagement echoes Cheng and Liu (2024), who reported that co-created metaverse spaces improve retention and trust among users.

The evidence also expands dynamic capability theory within educational contexts by empirically showing that resource deficiencies can be compensated by adaptive institutional strategies a finding consistent with Teece (2018) and more recent fsQCA applications in digital transformation research (Cao et al., 2022). This configurational insight contributes to ongoing debates on the scalability of metaverse education by empirically demonstrating multiple viable sustainability models rather than a single "best practice."

Implications of the Findings

From a practical perspective, these findings indicate that the sustainability of sports education metaverse projects depends on strategic complementarity rather than resource abundance. Stakeholders should consider the following implications:

1. For educational institutions, investing in user engagement mechanisms such as peer-led activities, gamification, and social learning features may yield greater long-term impact than prioritizing hardware upgrades.

2. For policymakers, the results highlight the need for flexible regulatory frameworks that encourage experimentation, public-private collaboration, and data ethics governance without constraining innovation.

3. For developers and entrepreneurs, designing monetization models aligned with social value creation (e.g., credentialing, community tokens, micro-subscriptions) can enhance financial resilience.

4. For global development agencies, the success of community-based configurations demonstrates that resource-constrained contexts can achieve sustainability through collaborative participation and open-access models.

Collectively, these implications reinforce the notion that social participation is the anchor of digital sustainability, particularly in educational ecosystems where motivation and engagement drive continuity.

Limitations of the Study

Several limitations should be acknowledged. First, although the 42-case dataset offers substantial diversity, it is composed primarily of pilot initiatives that may not fully reflect long-term institutionalized ecosystems. Second, performance indicators relied partly on self-reported data, which introduces potential measurement bias. Third, contextual heterogeneity such as cultural and infrastructural differences may influence causal configurations, reducing generalizability across all regions. Fourth, fsQCA, while suitable for configurational inference, does not establish temporal causality; hence, the stability of pathways over time requires further longitudinal analysis. Finally, unobserved factors such as leadership dynamics or pedagogical quality were not formally modeled, which may influence sustainability outcomes.

Future Research Directions

Building on these findings, future studies should pursue several directions:

1. Longitudinal modeling to examine how configurations evolve through scale-up and institutionalization stages.
2. Mixed-method research, integrating fsQCA with structural modeling or network analysis, to capture both causal diversity and relational interdependencies.
3. User-level outcome assessment focusing on cognitive, affective, and motor learning gains in metaverse-based sports instruction.
4. Cross-cultural comparative studies assessing how local governance, cultural norms, and digital literacy mediate sustainability configurations.
5. Integration of emerging technologies, including generative AI for personalized instruction, haptic systems for kinaesthetic learning, and blockchain for credential verification.

Expanding research in these areas will not only refine theoretical models of digital sustainability but also guide practitioners and policymakers in designing inclusive, adaptive, and evidence-based metaverse education ecosystems.

Conclusions

This study investigated sustainable business models in sports education metaverse initiatives, demonstrating that long-term success arises from the alignment of multiple strategic elements rather than reliance on a single dominant resource. Using fsQCA across 42 international pilot projects, the researchers identified three equifinal configurations capable of achieving high sustainability (Sust > 0.80).

First, the Technology-Driven pathway emphasizes immersive infrastructure and iterative product innovation, supported by high community engagement (Engage > 0.70; Consistency = 0.88; Coverage = 0.32). Second, the Policy-Adaptive pathway highlights the catalytic role of governmental endorsement and public-sector partnerships, enabling adoption despite modest technical readiness (Gov > 0.90; Consistency = 0.85; Coverage = 0.28). Third, the Community Self-Organizing pathway shows that strong user participation and co-creation dynamics (Engage > 0.90; Collab > 0.80; Consistency = 0.92; Coverage = 0.18) can compensate for technological and capital limitations, particularly in grassroots sport development contexts. Across all configurations, community engagement emerged as a necessary condition (Consistency = 0.91; Coverage = 0.87), confirming the foundational role of social sustainability in digital learning ecosystems.

Theoretically, these findings advance the conceptualization of the metaverse as a capability-building ecosystem, wherein value emerges through the interplay of technological affordances, policy alignment, and user-driven innovation. Practically, the results provide actionable guidance for educators, entrepreneurs, and policymakers: investments should balance hardware and software capabilities with participatory governance, accessible content, and collaborative network development.

Nonetheless, several limitations warrant consideration. The study analyzed 42 projects, which, while diverse, may limit generalizability, particularly in regions underrepresented in the sample. Data relied on a combination of operational records, platform analytics, and secondary documentation; unobserved contextual factors may have influenced outcomes. Furthermore, the study did not directly measure learning outcomes or skill acquisition, focusing instead on sustainability as a business model construct.

Future research should explore long-term educational and athletic outcomes, investigate cross-cultural differences in adoption and engagement, and examine scalability and economic viability in low-resource contexts. Additional work could also evaluate ethical and privacy considerations, ensuring that participatory and data-driven approaches remain safe, equitable, and inclusive.

In conclusion, the metaverse can serve as a promising complementary modality for sports education when implemented through balanced strategies integrating innovation, policy support, and active community participation. Rather than replacing physical environments, these models can extend traditional pathways, enabling broader participation and contributing to more inclusive and resilient global sport development.

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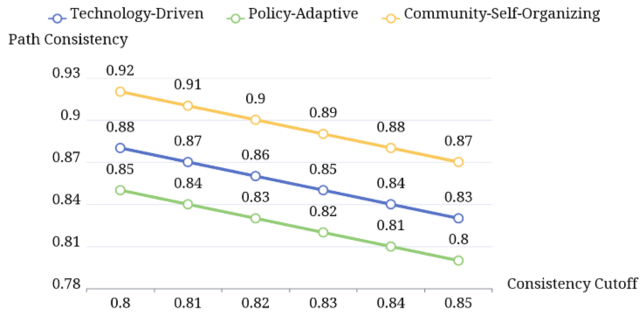
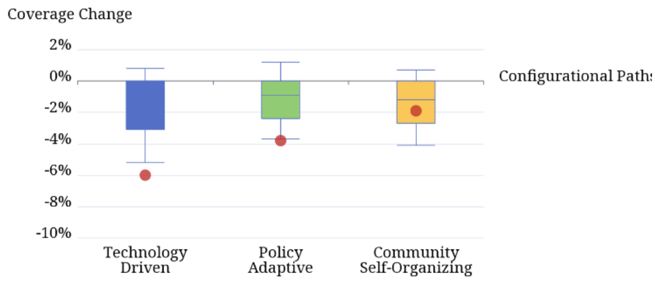
Appendixes

Appendix 1. Threshold Sensitivity Test:



Appendix 2. LOOCV Case Perturbation:



Appendix 3. Calibration Robustness Test: