Asia Pacific Academy of Science Pte. Ltd.

Metaverse 2026, 7(3), m260021.
https://doi.org/10.54517/m260021

Perspective

Toward a Tri-Axial Perspective on Smart-Space-Based Immersive Metaverse Systems: Technological Capabilities, Spatial Linkage Configurations, and Application Domains

Chang Ok Yun

ANCHOR Project Group, Dongseo University
Corresponding author: Chang Ok Yun, coyun@dongseo.ac.kr

CITATION

Yun CO. Toward a Tri-Axial Perspective on Smart-Space-Based Immersive Metaverse Systems: Technological Capabilities, Spatial Linkage Configurations, and Application Domains. Metaverse. 2026; 7(3): m260021. https://doi.org/10.54517/m260021

ARTICLE INFO

Received: 7 July 2026
Accepted: 19 August 2026
Available online: 29 September 2026

Abstract: Smart space-based immersive metaverse systems are emerging at the intersection of immersive interfaces, context-aware environments, digital twins, artificial intelligence, and networked services. However, current discussions often treat metaverse, XR, smart space, immersive content, and digital twin as interchangeable terms, making it difficult to compare system configurations across application settings. This Perspective proposes a tri-axial conceptual decision-support framework that analyzes such systems through three dimensions: technological capabilities, spatial linkage configurations, and application service domains. The framework distinguishes context-aware recognition, actuation and environmental control, immersive interface, and networked synchronization from spatial configurations such as home-centered, institution-to-institution, expert-mediated remote supervision, field-to-control, site-to-visitor, and city-scale public systems. It then connects these dimensions to application service domains including education, work and collaboration, healthcare and rehabilitation, cultural heritage and tourism, manufacturing and industry, and public and urban services. The paper contributes a conceptual vocabulary for distinguishing standalone XR, digital-twin, and smart-room applications from integrated smart-space-based immersive metaverse systems, while identifying operational, technical, ethical, legal, and social considerations that shape future implementation. Because the framework is conceptual and pre-validation in nature, future research should examine its usefulness through expert review, comparative case coding, prototype-based evaluation, and living-lab studies.

Keywords: Spatial computing; Immersive interface; Context-aware systems; Interoperability; Edge intelligence; Privacy governance; Socio-technical systems; Spatial services

1. Introduction and Related Work

The metaverse has been described in several partly overlapping ways. Stephenson introduced the term in a fictional account of persistent virtual social space [1]. Dionisio et al. later framed three-dimensional virtual worlds as an early technological foundation for the metaverse [2], while Mystakidis emphasized immersion, continuity, and social interaction in a concise encyclopedia definition [3]. Nevelsteen further clarified the technological basis of virtual worlds across games, mixed reality, and metaverse-related systems [4]. These works show that the metaverse is not a single device class but a historically evolving concept linking persistence, spatiality, interaction, and shared digital environments.

Recent metaverse surveys extend this discussion toward infrastructures and application ecosystems. Lee et al. and Ning et al. outline enabling technologies, virtual ecosystems, and application areas [5,6]. Wang et al. foreground fundamentals, security, and privacy [7], whereas Dwivedi et al. emphasize multidisciplinary implications for research, policy, and practice [8]. Shi et al. examine the technological essence and framework of the metaverse [9], and Rawat et al. discuss requirements, standards, applications, and challenges [10]. Methodologically, this Perspective does not claim to be a systematic review, scoping review, statistical synthesis, or tested predictive model, but it draws on transparency principles from scoping-review and search-reporting guidance [11–13]. These studies are important, but they often emphasize technology stacks or broad research agendas more than the relational configuration between physical spaces, digital services, users, institutions, and governance responsibilities.

The present Perspective focuses on the increasingly common situation in which metaverse-related systems are not purely virtual. Immersive classrooms, remote rehabilitation environments, factory digital-twin operations, museum AR services, and public spatial services connect physical sites, users, data, and institutions. Foundational work on ubiquitous computing and smart environments helps define this physical-contextual side of the problem [14,15]. IoT and edge-computing research further explains how sensors, connected devices, context recognition, and local computation support adaptive environments [16–18]. At the interface level, mixed-reality and augmented-reality research clarifies the continuum between physical and virtual experience [19,20], and VR/XR studies explain presence, plausibility, and embodied interaction [21–23].

Digital-twin research adds another important component. Digital twins are not merely visual models; they involve data connection, monitoring, synchronization, simulation, or operational feedback [24,25]. Manufacturing-oriented reviews and industrial digital-twin studies further emphasize operational monitoring and feedback loops [26,27]. Recent work in the built environment also shows that the definition of the digital twin continues to vary across fields [28]. For the purposes of this Perspective, a digital twin becomes metaverse-relevant only when it is linked to immersive interaction, shared networked services, and a domain-specific spatial service relation.

Examples of this direction can be found in immersive VR education and virtual field-trip studies [29,30], distributed mixed-reality collaboration [31], immersive collaborative health applications and human digital twins for healthcare [32,33], XR-enabled remote human–robot interaction [34], and smart-building digital twins that connect metaverse platforms with IoT sensors [35].

Figure 1 summarizes the conceptual evolution from standalone immersive content toward integrated smart-space-based immersive metaverse systems.

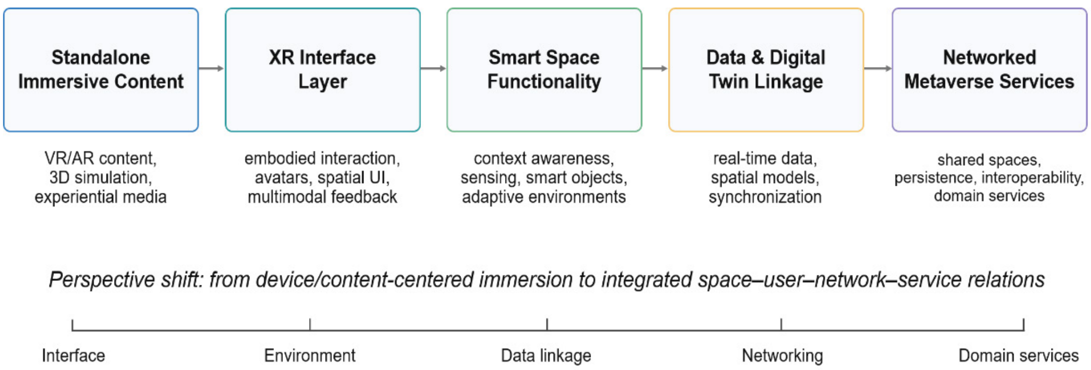

Figure 1. Conceptual evolution from standalone immersive content toward integrated smart-space-based immersive metaverse systems.

The central argument is therefore that smart-space-based immersive metaverse systems should be understood as socio-technical configurations rather than as a single platform type. They are best analyzed through three interrelated dimensions: technological capabilities, spatial linkage configurations, and application service domains. This paper develops a conceptual decision framework for such analysis and explicitly treats it as a pre-validation analytical lens rather than as a tested measurement model.

2. Conceptual Positioning and Source Basis

This article is written as a Perspective. It does not claim to be a systematic review, scoping review, statistical synthesis, or tested predictive model. The source-selection process was used to support conceptual clarification, framework positioning, and illustrative mapping. To avoid overclaiming, this article uses the term targeted conceptual source selection rather than structured review, while drawing on transparency principles from scoping-review and search-reporting guidance [11–13].

The search and source update were completed on 3 July 2026. Sources were identified through Scopus, Web of Science, Google Scholar, IEEE Xplore, ACM Digital Library, ScienceDirect, standards-organization websites, and official platform documentation. The five keyword families were: metaverse and virtual worlds; XR, AR, VR, MR, immersive interface, and spatial computing; smart space, smart environment, IoT, context awareness, and edge computing; digital twin, spatial data, 3D assets, and interoperability; and education, collaboration, healthcare, cultural heritage, manufacturing, and urban services. **Figure 2** maps the conceptual boundary of the target system in relation to smart spaces, XR/immersive interfaces, digital twins, and metaverse services.

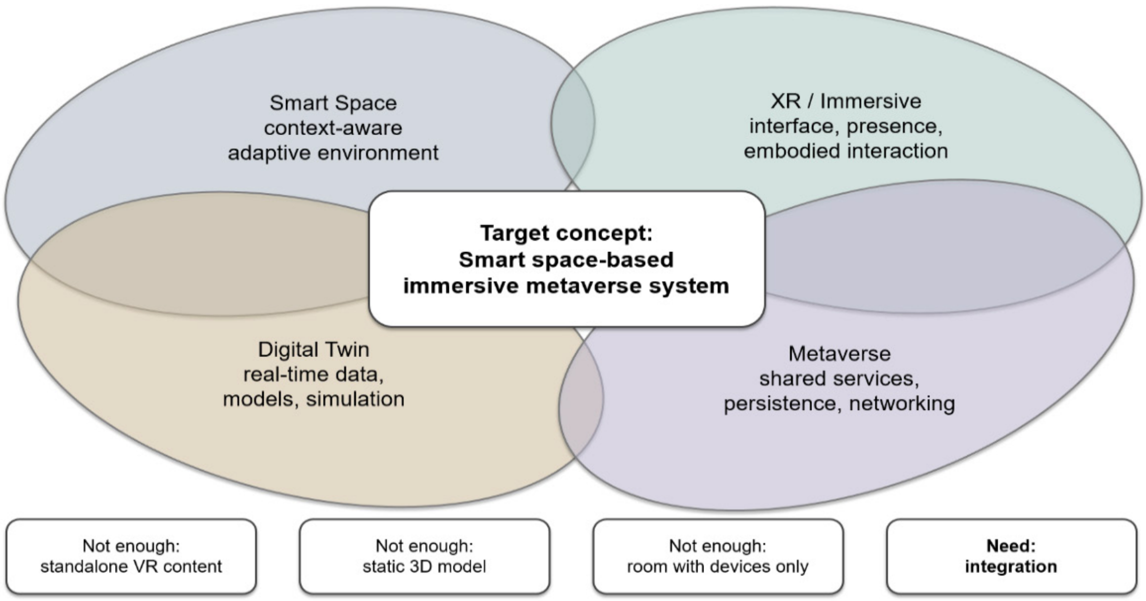

Figure 2. Conceptual boundary map for the target system.

Inclusion was based on conceptual relevance to at least one framework component: conceptual boundary conditions, technological capabilities, spatial linkage configurations, application service domains, operational or governance concerns, or future validation needs. Exclusion applied to sources that were only loosely related to immersive or spatial systems, purely promotional, non-scholarly without standards relevance, or unrelated to the tri-axial framework. Because this is a Perspective, the search was not designed to generate a complete retrieval count or formal exclusion flow.

Supplementary File S1 therefore provides a transparent source log and literature-to-framework mapping rather than a PRISMA-style screening diagram.

The synthesis was limited to English-language publications and English-language official documentation. This limitation is important because cultural-regional acceptance, interface conventions, public-sector adoption, privacy expectations, and local regulatory interpretations may differ across non-English-speaking regions. The framework should therefore be treated as a starting point for multilingual and region-specific validation rather than as a globally generalizable classification.

Conceptually, the target system is narrower than any single component. A smart space is a physical or hybrid environment that senses, interprets, and responds to contextual conditions [14–18]. XR is an interface category that supports presence, embodied interaction, and spatial visualization [19–23]. A digital twin is a data-linked representation of a physical system [24–28]. The metaverse is treated here as a persistent, shared, interactive, and spatially organized service environment. A smart-space-based immersive metaverse system emerges only when these elements are integrated for a domain-specific purpose. **Table 1** summarizes the boundary conditions that distinguish the target concept from adjacent concepts.

Table 1. Boundary conditions distinguishing the target concept from adjacent concepts.

Concept	Core meaning	Not sufficient by itself	Role in target systems
Smart space	Context-aware/adaptive physical or hybrid environment	Room with devices only	Physical and contextual intelligence
XR / immersive interface	VR, AR, MR, spatial visualization and embodied interaction	Standalone immersive content	Embodied and spatial user experience
Digital twin	Data-linked representation of physical object/process/environment	Static 3D model	Physical-digital synchronization
Metaverse	Persistent, shared, interactive spatial service environment	Any virtual application	Networked and shared services
Target system	Integration of smart space, immersion, physical-digital linkage, and networked service logic	Any single component alone	Central object of this Perspective

The inclusion rule clarifies how borderline cases should be handled. Standalone XR, static 3D models, non-immersive digital twins, and isolated IoT rooms may be relevant to metaverse research, but they are not target systems by themselves. A target case must integrate context or sensing, immersive/spatial interaction, physical-digital linkage, and networked service logic. A strong target case additionally includes persistence, interoperability, governance, workflow integration, and repeated operational use. **Table 2** presents the inclusion and exclusion rules used to classify target systems and borderline cases.

Table 2. Inclusion and exclusion rules for classifying target systems.

Classification status	Required integration condition	Examples or exclusions
Excluded / not target	Single component only; no integration among smart-space function, immersion, physical-digital linkage, and services.	Standalone VR; static 3D model; non-immersive dashboard; isolated IoT room.

Continuation Table:

Classification status	**Required integration condition**	**Examples or exclusions**
Peripheral metaverse-related case	Two or three components are present, but one minimum condition is weak or absent.	AR guide without persistence; remote collaboration without smart-space sensing; digital-twin viewer without embodied interaction.
Target case	All four minimum conditions are integrated for a domain service purpose: context/sensing, immersive interface, physical-digital linkage, and networked service interaction.	Clinic-home rehabilitation; XR-supported factory control; shared museum-remote visitor service.
Strong target case	Target case plus persistence, interoperability, multi-user participation, governance mechanisms, workflow integration, and repeated operational use.	Living-lab or operational deployment connecting users, institutions, devices, data, and services over time.

The proposed perspective does not replace existing metaverse, XR, digital-twin, smart-space, or application-domain frameworks. It instead clarifies which dimension each family tends to leave underdeveloped when integrated smart-space-based immersive metaverse systems are compared across domains. **Table 3** positions the tri-axial perspective in relation to existing metaverse, XR, digital-twin, smart-space, and application-domain framework families.

Table 3. Positioning of the tri-axial perspective in relation to existing framework families.

Framework family	**Main contribution**	**Under-addressed dimension**	**Extension by this Perspective**
Metaverse technology frameworks	Describe stacks of devices, networks, platforms, data, AI, and content.	Relational spatial configuration and domain-service purpose are often secondary.	Adds spatial linkage and application-service interpretation.
XR / immersive interaction models	Explain presence, embodiment, visualization, and interaction.	May not specify sensing, IoT control, governance, or physical-digital synchronization.	Connects immersion to context, synchronization, and service value.
Digital-twin frameworks	Explain data representation, monitoring, simulation, and feedback.	May lack embodied interaction, shared participation, and domain governance.	Treats digital twins as synchronization mechanisms within immersive systems.
Smart-space / IoT frameworks	Explain context awareness, sensors, actuators, edge computing, and adaptive environments.	May not include immersive interface, persistence, or shared spatial services.	Positions smart spaces as physical-contextual foundations.
Application-domain studies	Describe education, care, industry, culture, and urban cases.	Difficult to compare across capability and spatial configurations.	Provides a cross-domain vocabulary for comparison and validation.

3. Tri-Axial Conceptual Decision Framework

The tri-axial framework asks three questions. First, what technological capabilities make the system possible? Second, how are physical, virtual, and institutional spaces connected? Third, what service purpose, user group, institutional context, and value logic define the application domain? These questions are analytical rather than predictive: they support structured comparison and decision support, but they do not assign statistical weights or performance scores. **Figure 3** presents the tri-axial conceptual decision framework.

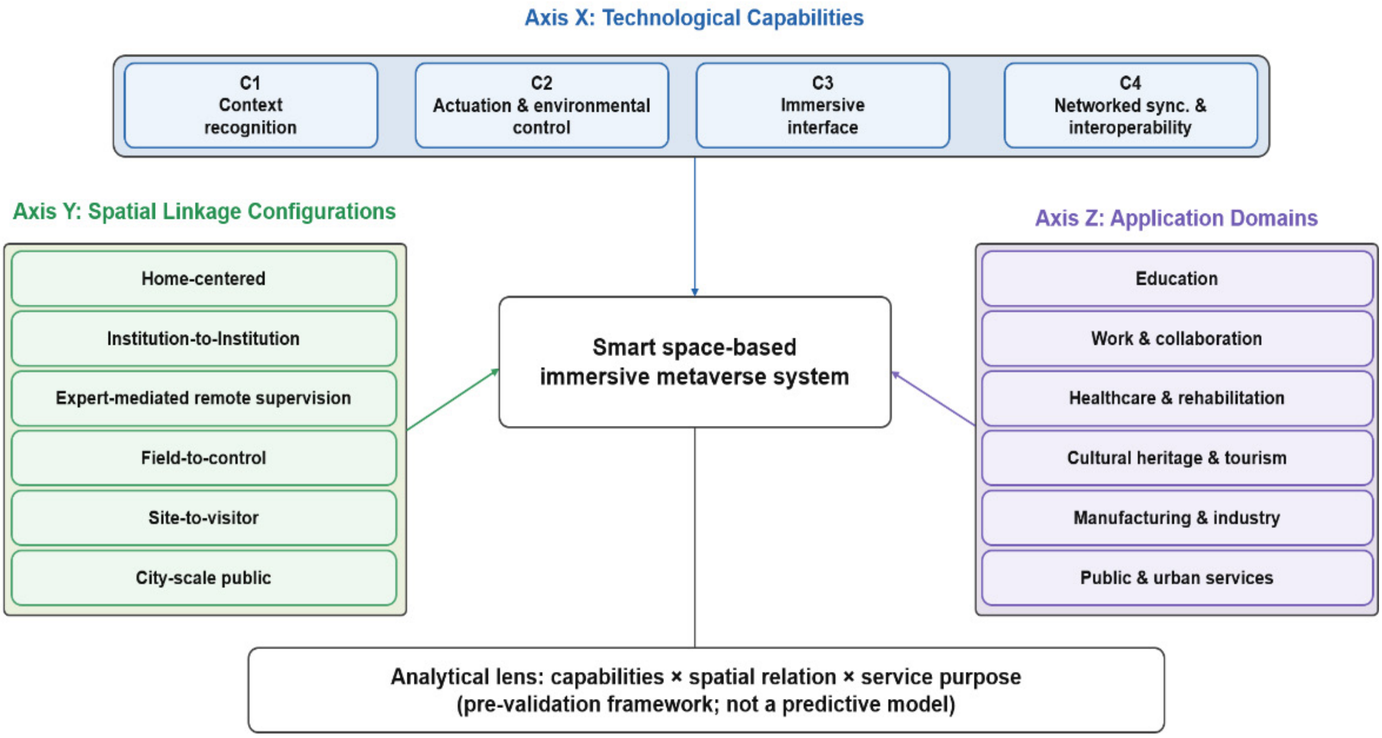

Figure 3. Tri-axial conceptual decision framework.

Axis X is defined in terms of technological capabilities rather than hierarchical layers. Context-aware recognition refers to sensing and interpreting users, objects, activities, or environmental conditions. Actuation and environmental control refers to changing or controlling devices, connected objects, actuators, or responsive environments. Immersive interface refers to the spatial user experience, including VR, AR, MR, avatars, spatial visualization, and embodied interaction. Networked synchronization and service interoperability refers to the system function that connects users, data, services, assets, and digital twins across locations [17,18,36–39].

Axis Y classifies the dominant spatial relation rather than the service sector. The key issue is how spaces and actors are connected: for example, home-centered participation, institution-to-institution coordination, expert-mediated remote supervision, field-to-control operation, site-to-visitor mediation, or city-scale public service. The label is assigned by the dominant anchor relation and service-control logic, not by the application domain.

Axis Z classifies the application service domain. Domains define why the system is deployed, who uses it, what outcomes matter, what institutional constraints apply, and what value, liability, cultural acceptance, and governance issues shape adoption. Thus, a rehabilitation system belongs to the healthcare and rehabilitation domain, but its spatial linkage may be expert-mediated remote supervision. This distinction prevents the spatial axis from duplicating the domain axis.

Table 4 defines the operational boundaries and indicators for the three axes.

Table 4. Operational boundaries and indicators for the three axes.

Axis	Operational boundary	Indicators/questions	Common ambiguity handled
X1 Context-aware recognition	Sensing and interpreting user/object/activity/ environmental context.	What is detected? How is context interpreted?	Distinguished from control: recognition reads and interprets; it does not necessarily act.
X2 Actuation and environmental control	Changing or controlling connected objects, devices, actuators, or responsive environments.	What is controlled? Is control manual, automated, or adaptive?	Distinguished from recognition by its intervention function.
X3 Immersive interface	Spatial presentation, embodied interaction, avatars, XR feedback, and user presence.	How does the user perceive and interact spatially?	Distinguished from networking: it is the experience layer, not the synchronization layer.
X4 Networked synchronization and service interoperability	Connecting users, data, services, assets, and digital twins across spaces.	What must be synchronized or interoperable?	Distinguished from interface by its system-linking function.
Y Spatial linkage configuration	Dominant relation among physical, virtual, and institutional spaces.	Who/what is connected, across which spaces, under whose authority?	Not a service sector; it is the relation structure.
Z Application service domain	Purpose, users, outcomes, institutional setting, and value logic.	Why is the system deployed and what service constraints matter?	Not a spatial relation; it is the service-purpose context.

Spatial linkage configurations are further specified by operational criteria. The categories in **Figure 4** and **Table 5** are not domain labels. They describe primary anchor space, direction of service flow, governance authority, data sensitivity, and interaction mode. When configurations overlap, classification should follow the dominant relation that controls service delivery and risk allocation.

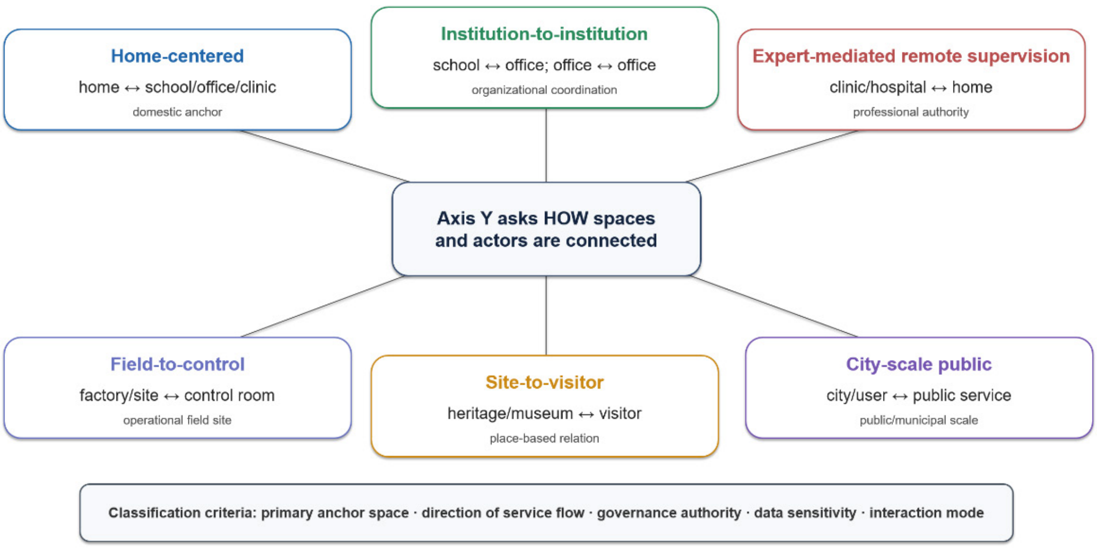

Figure 4. Spatial linkage configurations and relational classification logic.

Table 5. Spatial linkage configurations and operational criteria.

Configuration	Dominant spatial relation	Operational criterion	Design concern
Home-centered	home ↔ school/office/clinic	Home is the user-side anchor.	access, privacy, readiness
Institution-to-institution	school ↔ office; campus ↔ industry	Organizations coordinate identities, workflow, or data access.	workflow, identity, integration
Expert-mediated remote supervision	clinic/hospital ↔ home; expert ↔ client site	Professional or expert authority governs remote interaction.	safety, consent, liability
Field-to-control	factory/site ↔ control room/ expert	Operational field site connects to control or expert support.	reliability, latency, safety
Site-to-visitor	heritage/museum/city site ↔ visitor	A place-based experience is mediated for visitors.	accuracy, accessibility, culture
City-scale public	city/user ↔ public service/ infrastructure	Users interact with public data, infrastructure, or services.	scale, trust, governance

4. Applying the Framework: Operational Criteria and Worked Example

To move beyond a superficial illustration, this section applies the framework to a clinic-home immersive rehabilitation system. The example is not presented as empirical evidence. Rather, it illustrates how the axes expose operational questions that a decision maker would need to answer before treating the system as a full target case.

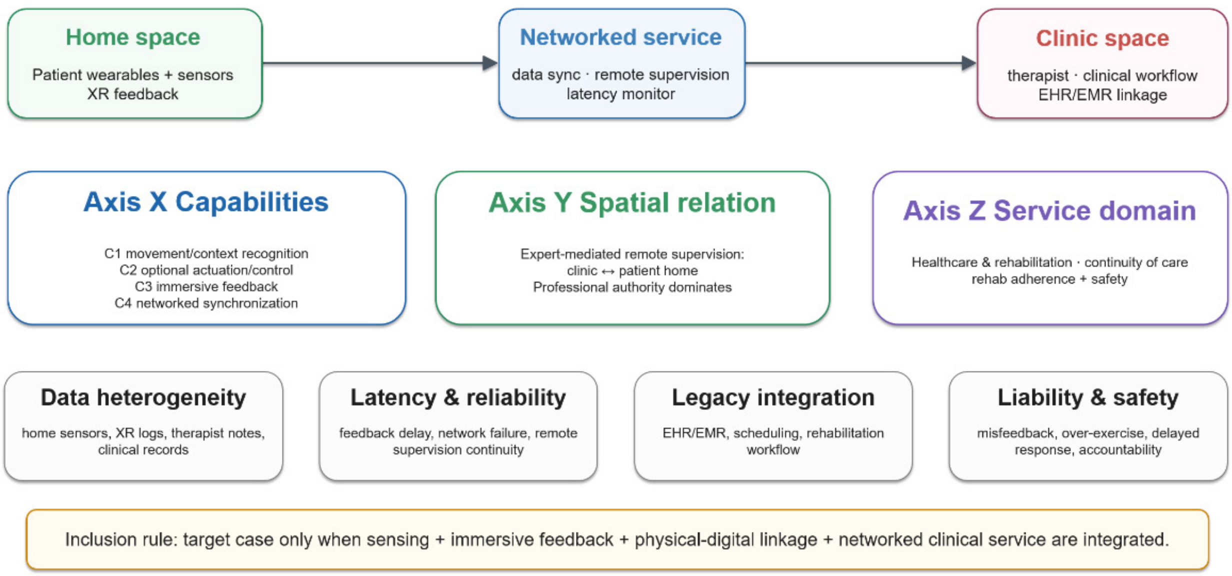

Figure 5. Worked example of a clinic-home immersive rehabilitation system.

In the example, the patient exercises at home while sensors capture movement and an XR interface provides feedback. A therapist in the clinic reviews data and supervises progress through a networked service. The system qualifies as a target case only if smart-space sensing, immersive feedback, physical-digital linkage, and networked clinical service are integrated. If it were only a video call, a standalone VR exercise, or a non-immersive dashboard, it would remain a peripheral metaverse-related case rather than a target system. **Figure 5** shows how the framework identifies capabilities, spatial linkage, service domain, data heterogeneity, latency, legacy integration, liability, and evaluation concerns. **Table 6** applies the framework to the clinic-home rehabilitation example.

Table 6. Operational application of the framework to the clinic-home rehabilitation example.

Analytical component	Clinic-home rehabilitation example	Operational issue exposed
System boundary	Patient exercises at home using sensors and XR feedback; therapist monitors from clinic through a networked service.	Boundary includes home devices, clinical workflow, data platform, and remote supervision.
Axis X capabilities	Context recognition, optional actuation, immersive feedback, and networked synchronization.	Capability gaps appear if sensing, feedback, or synchronization is missing.
Axis Y linkage	Expert-mediated remote supervision connecting clinic authority with a domestic patient space.	Classification is based on supervision relation, not simply the healthcare domain.
Axis Z domain	Healthcare and rehabilitation service purpose: continuity of care, adherence, safety, and clinical follow-up.	Domain defines safety, professional accountability, and outcome expectations.
Data and latency	Home sensors, XR logs, therapist notes, and clinical records must be aligned; delay may affect feedback quality.	Data heterogeneity and latency become design constraints.
Legacy integration	Scheduling, clinical record systems, therapist workflow, and institutional approval must be integrated.	Adoption depends on existing systems, not only XR experience.
Liability and evaluation	Errors may involve device vendor, platform provider, therapist, or institution; outcomes include safety events, usability, adherence, and clinician workload.	Responsibility and evaluation criteria must be specified before deployment.

This worked example also illustrates why broad domain tables should not be read as complete decision maps. Education, collaboration, healthcare, cultural heritage, manufacturing, and public-service systems may each involve different capability combinations, but those combinations are context-dependent. For this reason, broad domain configurations are treated as supplementary illustrations rather than as rankings, typologies with empirical weights, or comprehensive decision matrices.

5. Operational, Technical, Ethical, Legal, and Social Considerations

Operational feasibility depends on more than conceptual fit. Interoperability must be specified at multiple levels: 3D assets, scene descriptions, identity, sensor data, service APIs, digital-twin synchronization, and XR runtime compatibility. Standards such as glTF, OpenUSD, and Immersive Web work are relevant not because the framework formally conforms to them, but because they identify practical design layers through which assets, scenes, interfaces, and services may interoperate [36–39]. **Table 7** summarizes operational, technical, ethical, legal, and social considerations for applying the framework.

Table 7. Operational, technical, ethical, legal, and social considerations for applying the framework.

Dimension	Design question	Examples of design evidence
Infrastructure and cost	What devices, sensors, networks, servers, and XR endpoints are required?	bill of materials; deployment cost; replacement cycle
Maintenance and training	Who updates spatial assets, sensors, software, AI models, and user training materials?	maintenance plan; staff training; support responsibility
Latency and bandwidth	What response time is required for safe or useful interaction?	latency budget; bandwidth demand; fallback procedure
Computing efficiency	Where should processing occur: device, edge, cloud, or hybrid?	compute/energy estimate; reliability plan
Legacy integration	Which existing systems must interoperate?	EHR/EMR; LMS; ERP/MES; museum CMS; municipal data systems
Standards alignment	Which assets, data, identity, and API standards support interoperability?	glTF/OpenUSD for assets; WebXR/Immersive Web; API and identity governance
Privacy-by-design	How are data minimization, consent, local processing, and auditability implemented?	privacy impact assessment; access-control rule; retention policy
Liability and acceptance	Who is responsible for errors, and what social or cultural norms shape use?	responsibility matrix; user consultation; accessibility and cultural review

Technical feasibility also varies by configuration. Field-to-control and industrial cases may require low latency, reliable bandwidth, cyber-physical safety, and robust synchronization. City-scale public systems add scale, procurement, auditability, long-term maintenance, and public trust. Home-centered and expert-mediated remote supervision systems add device readiness, user training, data minimization, fallback procedures, and integration with existing institutional systems.

Edge AI and on-device intelligence may support low-latency context recognition, gesture interaction, environmental understanding, adaptive feedback, and personalization [40–43]. However, such systems also introduce costs, energy use, model reliability issues, privacy leakage risks, update burdens, and maintenance complexity. These constraints should be part of framework application rather than only future challenges.

Ethical, legal, and social acceptance issues should also be linked to spatial configuration. Privacy-by-design may involve local processing, data minimization, purpose limitation, access control, auditability, and retention rules [44–48]. In urban cases, privacy can conflict with public interest, safety, and municipal service goals. In healthcare and industrial cases, liability must be allocated among professionals, institutions, device vendors, platform providers, and system operators. Cultural and regional acceptance affects interface design, avatar use, heritage storytelling, public trust, accessibility, and adoption norms [49,50].

6. Discussion, Limitations, Validation Protocol, and Conclusion

The framework should be interpreted as a conceptual decision-support lens, not as a completed design standard or objective classification instrument. Its contribution is to make key distinctions explicit: capability is not the same as spatial relation, spatial relation is not the same as service domain, and a full target system requires integration among smart-space functionality, immersive interaction, physical-digital linkage, and networked service logic. **Figure 6** visualizes the staged validation protocol.

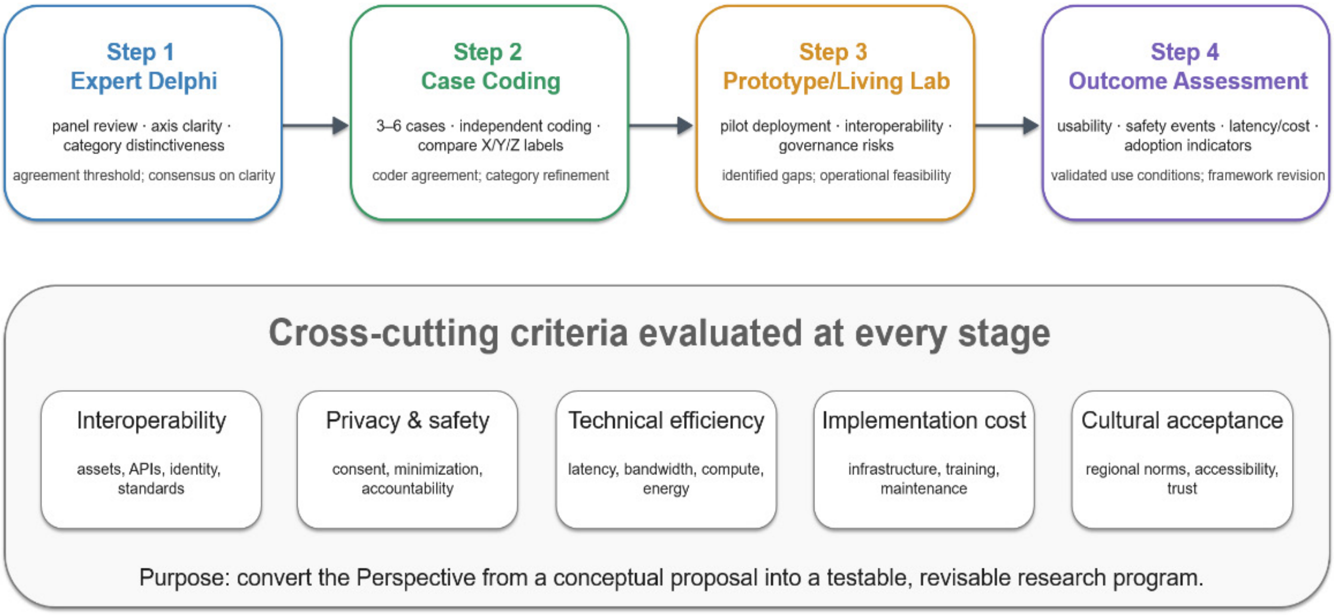

Figure 6. Staged validation protocol for future research.

The main limitation is the absence of empirical validation. The framework has not yet been tested through expert interviews, Delphi studies, systematic case coding, user studies, or statistical analysis. The tables therefore do not provide weights, rankings, or performance predictions. A second limitation is source selection. Although **Supplementary File S1** documents the targeted conceptual source basis, the process was not designed to produce exhaustive retrieval counts or formal exclusion statistics. A third limitation is language and regional scope: English-language sources may underrepresent non-English research traditions and culturally specific adoption concerns.

To make the future roadmap operational, **Table 8** converts the validation agenda into a staged protocol. The steps include expert Delphi validation, independent case coding, prototype or living-lab testing, outcome and adoption assessment, and framework refinement. The acceptance criteria are illustrative and should be calibrated by future studies; their purpose is to show how the framework can move from conceptual usefulness toward empirical validation.

Table 8. Staged validation protocol and illustrative revision criteria.

Validation stage	Methodological procedure	Illustrative acceptance or revision criterion
Stage 1: expert Delphi	Recruit domain, HCI/XR, smart-space, digital-twin, ethics/legal, and practitioner experts; conduct iterative rating of axis clarity and category distinctiveness.	Revise labels when experts identify repeated ambiguity or low agreement.

Continuation Table:

Validation stage	**Methodological procedure**	**Illustrative acceptance or revision criterion**
Stage 2: independent case coding	Apply the framework to 3–6 representative cases with multiple coders.	Refine operational criteria when coders classify the same case inconsistently.
Stage 3: prototype or living lab	Use the framework to evaluate one or more pilot systems under real workflow conditions.	Assess whether the framework identifies missing capabilities, interoperability gaps, and governance risks.
Stage 4: outcome and adoption assessment	Collect usability, safety, latency, cost, maintenance, training, workflow fit, and acceptance evidence.	Distinguish conceptual usefulness from operational feasibility.
Stage 5: framework refinement	Merge, rename, or split categories that repeatedly overlap across cases or domains.	Publish refined categories with decision rules and documented examples.

In conclusion, smart-space-based immersive metaverse systems require a more precise vocabulary than broad references to virtual worlds, XR, smart rooms, or digital twins can provide. The tri-axial perspective offers such a vocabulary by linking technological capabilities, spatial linkage configurations, and application service domains. Its value lies not in claiming a final taxonomy, but in supporting clearer classification, more transparent design reasoning, and a concrete pathway for future validation. Through further empirical work, the framework can be refined into a more robust tool for analyzing education, care, work, industry, culture, and public-service systems.

Author contributions: Conceptualization, COY; methodology, COY; investigation, COY; formal analysis, COY; writing-original draft preparation, COY; writing-review and editing, COY; visualization, COY. The author has read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: In the preparation of this work, the author used ChatGPT (OpenAI) only for language refinement, editorial organization, and formatting support. AI-assisted tools were not used to determine the conceptual axes, select or exclude sources, conduct the synthesis, classify domain examples, or generate scholarly conclusions. All conceptual decisions, source evaluation, framework development, domain interpretation, and final conclusions were made, verified, and finalized by the author, who takes full responsibility for the content of the publication.

Conflicts of interest: The author declares no conflicts of interest.

Ethical approval: Not applicable. This article is a conceptual Perspective and does not involve human participants, animal subjects, or clinical intervention.

Informed consent statement: Not applicable.

Data availability statement: No new empirical dataset was generated in this study. The figures and tables were developed through conceptual synthesis of cited literature and illustrative examples. Supplementary File S1 provides the source-selection log and literature-to-framework mapping.

References

1. Stephenson N. Snow Crash. Bantam Books; 1992.
2. Dionisio JDN, Burns WG, Gilbert R. 3D virtual worlds and the metaverse: Current status and future possibilities. ACM Computing Surveys. 2013, 45(3): 1-38. https://doi.org/10.1145/2480741.2480751
3. Mystakidis S. Metaverse. Encyclopedia. 2022, 2(1): 486-497. https://doi.org/10.3390/encyclopedia2010031
4. Nevelsteen KJL. Virtual world, defined from a technological perspective, and applied to video games, mixed reality and the metaverse. arXiv. 2015; arXiv:1511.08464. https://doi.org/10.48550/arXiv.1511.08464
5. Lee LH, Braud T, Zhou P, et al. All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda. arXiv. 2021; arXiv:2110.05352. https://doi.org/10.48550/arXiv.2110.05352
6. Ning H, Wang H, Lin Y, et al. A survey on metaverse: The state-of-the-art, technologies, applications, and challenges. arXiv. 2021; arXiv:2111.09673. https://doi.org/10.48550/arXiv.2111.09673
7. Wang Y, Su Z, Zhang N, et al. A survey on metaverse: Fundamentals, security, and privacy. IEEE Communications Surveys & Tutorials. 2023, 25(1): 319-352. https://doi.org/10.1109/COMST.2022.3202047
8. Dwivedi YK, Hughes L, Baabdullah AM, et al. Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. International Journal of Information Management. 2022, 66: 102542. https://doi.org/10.1016/j.ijinfomgt.2022.102542
9. Shi F, Ning H, Zhang X, et al. A new technology perspective of the metaverse: Its essence, framework and challenges. Digital Communications and Networks. 2023, 9(4): 801-810. https://doi.org/10.1016/j.dcan.2023.02.017
10. Rawat DB, El Alami H, Hagos DH. Metaverse survey and tutorial: Exploring key requirements, technologies, standards, applications, challenges, and perspectives. arXiv. 2024; arXiv:2405.04718. https://doi.org/10.48550/arXiv.2405.04718
11. Tricco AC, Lillie E, Zarin W, et al. PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation. Annals of Internal Medicine. 2018, 169(7): 467-473. https://doi.org/10.7326/M18-0850
12. Rethlefsen ML, Kirtley S, Waffenschmidt S, et al. PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. Systematic Reviews. 2021, 10: 39. https://doi.org/10.1186/s13643-020-01542-z
13. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ. 2021, 372: n71. https://doi.org/10.1136/bmj.n71
14. Weiser M. The computer for the 21st century. Scientific American. 1991, 265(3): 94-104. https://doi.org/10.1038/scientificamerican0991-94
15. Cook DJ, Das SK. How smart are our environments? An updated look at the state of the art. Pervasive and Mobile Computing. 2007, 3(2): 53-73. https://doi.org/10.1016/j.pmcj.2006.12.001
16. Want R, Schilit BN, Jenson S. Enabling the Internet of Things. Computer. 2015, 48(1): 28-35. https://doi.org/10.1109/MC.2015.12
17. Shi W, Cao J, Zhang Q, et al. Edge computing: Vision and challenges. IEEE Internet of Things Journal. 2016, 3(5): 637-646. https://doi.org/10.1109/JIOT.2016.2579198
18. Satyanarayanan M. The emergence of edge computing. Computer. 2017, 50(1): 30-39. https://doi.org/10.1109/MC.2017.9
19. Milgram P, Kishino F. A taxonomy of mixed reality visual displays. IEICE Transactions on Information and Systems. 1994, E77-D(12): 1321-1329.
20. Azuma RT. A survey of augmented reality. Presence: Teleoperators and Virtual Environments. 1997, 6(4): 355-385. https://doi.org/10.1162/pres.1997.6.4.355
21. Slater M. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. Philosophical Transactions of the Royal Society B. 2009, 364(1535): 3549-3557. https://doi.org/10.1098/rstb.2009.0138
22. Bailenson J. Experience on Demand: What Virtual Reality Is, How It Works, and What It Can Do. W. W. Norton; 2018.
23. Rauschnabel PA, Felix R, Hinsch C, et al. What is XR? Towards a framework for augmented and virtual reality. Computers in Human Behavior. 2022, 133: 107289. https://doi.org/10.1016/j.chb.2022.107289
24. Jones D, Snider C, Nassehi A, et al. Characterising the digital twin: A systematic literature review. CIRP Journal of Manufacturing Science and Technology. 2020, 29: 36-52. https://doi.org/10.1016/j.cirpj.2020.02.002
25. Fuller A, Fan Z, Day C, et al. Digital twin: Enabling technologies, challenges and open research. IEEE Access. 2020, 8: 108952-108971. https://doi.org/10.1109/ACCESS.2020.2998358

26. Kritzinger W, Karner M, Traar G, et al. Digital twin in manufacturing: A categorical literature review and classification. IFAC-PapersOnLine. 2018, 51(11): 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474
27. Tao F, Zhang H, Liu A, et al. Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics. 2019, 15(4): 2405-2415. https://doi.org/10.1109/TII.2018.2873186
28. Abdelrahman M, Macatulad E, Lei B, et al. What is a digital twin anyway? Deriving the definition for the built environment from over 15,000 scientific publications. Building and Environment. 2025, 274: 112748. https://doi.org/10.1016/j.buildenv.2025.112748
29. Radianti J, Majchrzak TA, Fromm J, et al. A systematic review of immersive virtual reality applications for higher education. Computers & Education. 2020, 147: 103778. https://doi.org/10.1016/j.compedu.2019.103778
30. Makransky G, Mayer RE. Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia learning. Educational Psychology Review. 2022, 34: 1771-1798. https://doi.org/10.1007/s10648-022-09675-4
31. Wong E, Sanchez Esquivel J, Gronbaek JE, et al. Practice-informed patterns for organising large groups in distributed mixed reality collaboration. In: Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24); 2024. https://doi.org/10.1145/3613904.3642502
32. Zarei T, Emery M, Saredakis D, et al. Being there together for health: A systematic review on the feasibility, effectiveness and design considerations of immersive collaborative virtual environments in health applications. Human Behavior and Emerging Technologies. 2025: 4269145. https://doi.org/10.1155/hbe2/4269145
33. Chen J, Yi C, Okegbile SD, et al. Networking architecture and key supporting technologies for human digital twin in personalized healthcare: A comprehensive survey. IEEE Communications Surveys & Tutorials. 2023. https://doi.org/10.1109/COMST.2023.3308717
34. Wang X, Shen L, Lee LH. Towards massive interaction with generalist robotics: A systematic review of XR-enabled remote human-robot interaction systems. arXiv. 2024; arXiv:2406.09264. https://doi.org/10.48550/arXiv.2406.09264
35. Masubuchi Y, Hiraki T, Hiroi Y, et al. Development of digital twin environment through integration of commercial metaverse platform and IoT sensors of smart building. In: 2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW); 2025. https://doi.org/10.1109/VRW66409.2025.00173
36. Metaverse Standards Forum. The Metaverse Standards Forum: Interoperability standards for an open metaverse. Available online: https://metaverse-standards.org/ (accessed on 3 July 2026).
37. Alliance for OpenUSD. Alliance for OpenUSD: Mission and OpenUSD interoperability. Available online: https://aousd.org/ (accessed on 3 July 2026).
38. World Wide Web Consortium. Immersive Web Working Group. Available online: https://www.w3.org/immersive-web/ (accessed on 3 July 2026).
39. Khronos Group. glTF: Runtime 3D asset delivery. Available online: https://www.khronos.org/gltf/ (accessed on 3 July 2026).
40. Huynh-The T, Pham QV, Pham XQ, et al. Artificial intelligence for the metaverse: A survey. Engineering Applications of Artificial Intelligence. 2023, 117: 105581. https://doi.org/10.1016/j.engappai.2022.105581
41. Xu M, Ng WC, Lim WYB, et al. A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges. IEEE Communications Surveys & Tutorials. 2023, 25(1): 656-700. https://doi.org/10.1109/COMST.2022.3221119
42. Zheng Y, Chen Y, Qian B, et al. A review on edge large language models: Design, execution, and applications. arXiv. 2024; arXiv:2410.11845. https://doi.org/10.48550/arXiv.2410.11845
43. Chen H, Deng W, Yang S, et al. Towards edge general intelligence via large language models: Opportunities and challenges. arXiv. 2024; arXiv:2410.18125. https://doi.org/10.48550/arXiv.2410.18125
44. ISO/IEC JTC 1. ISO/IEC TS 27570: Privacy guidelines for smart cities. International Organization for Standardization; 2021.
45. European Union. Regulation (EU) 2016/679: General Data Protection Regulation. Official Journal of the European Union. 2016, L119: 1-88.
46. Cavoukian A. Privacy by Design: The 7 Foundational Principles. Information and Privacy Commissioner of Ontario; 2009.
47. Nissenbaum H. Privacy in Context: Technology, Policy, and the Integrity of Social Life. Stanford University Press; 2010.
48. Acquisti A, Taylor C, Wagman L. The economics of privacy. Journal of Economic Literature. 2016, 54(2): 442-492. https://doi.org/10.1257/jel.54.2.442
49. Rahartomo A, Merino L, Ghafari M. Metaverse security and privacy research: A systematic review. Computers & Security.

2025, 157: 104602. https://doi.org/10.1016/j.cose.2025.104602

50. Haque AB, Islam AN, Hyrynsalmi S, et al. GDPR compliant blockchains: A systematic literature review. IEEE Access. 2021, 9: 50593-50606. https://doi.org/10.1109/ACCESS.2021.3069877